Green Gaming:
Energy Efficiency without Performance Compromise

Research performed under the project entitled:
A Plug-loads Game Changer: Gaming System Energy Efficiency without Performance Compromise - CEC/LBNL Agreement # EPC-15-023 – Task 7

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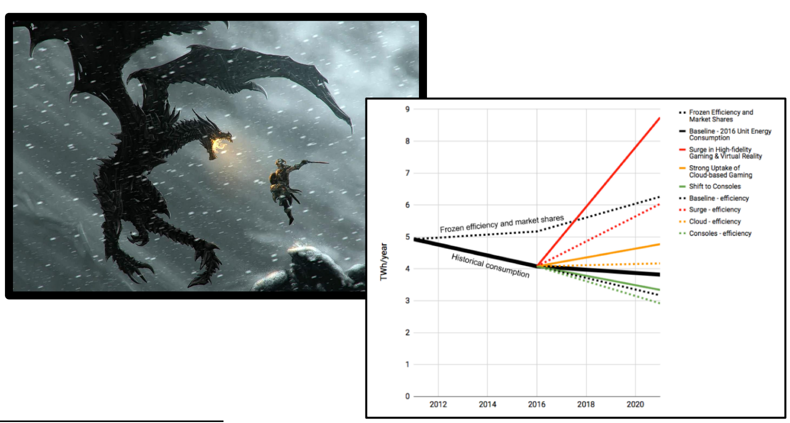

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Glossary and Abbreviations

CEC	California Energy Commission
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”.
DOE	U.S. 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 (e.g., graphics rendering in the case of gaming systems).
Firmware	A type of software that provides low-level control of a computer’s hardware. Usually 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 (e.g., 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.
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 in order 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).

1. EXECUTIVE SUMMARY

A third of humanity plays computer games,[2] and an even higher proportion does so in the U.S.—about two-thirds of the population (Nielsen 2018). Yet there are no comprehensive estimates of energy use for this widespread activity, at the national or state levels. Nor are there corresponding assessments of how the associated energy demand might evolve or the potential for improved energy efficiency. As described in this report, we find that computer gaming is one of the most significant electric plug loads and among the most complex energy end uses to understand and manage. Best practices can achieve significant energy savings.

The energy used for gaming is clearly higher today than in the early days of the activity. The extremes of this spectrum are defined on the one hand by the 1970s-era Pong game at ~10 watts when played on the original consoles versus today's highest-performance purpose-built gaming PCs, with the potential of drawing closer to 500 watts on the other hand. This trend has been accompanied by a growing installed base of gaming devices together with more and more time spent gaming. This can give rise to a perception of unavoidable trade-offs between gaming user experience and energy efficiency, yet in recent years the gaming industry has recently demonstrated an ability to improve these two factors simultaneously. That said, limited measures of *performance* increases have at times eclipsed absolute *energy use* reductions that would otherwise have resulted from efficiency improvements. While the evolution of gaming technology has been marked by improvement in metrics such as frames per second per watt, and even declining absolute energy use per system in some cases, this has not always held and thus far not translated into reductions in energy use at the macro level. Further complicating matters, as discussed at length below, although the gaming- industry and gamers themselves focus heavily on frame rate, it is an inadequate metric for characterizing user experience.

The existing literature on gaming energy use focuses almost exclusively on game consoles. Only one formal study has looked in depth at gaming on desktop computers (Mills and Mills 2015), and no work has been published regarding gaming on laptops or with television-linked media-streaming devices such as Apple TV or Android TV.[3] Neither has the energy used in data centers and associated networks for cloud-based gaming—where graphics processing occurs in a remote data center—been quantified. The energy impacts on PC gaming systems of many specific ancillary components, e.g., virtual reality (VR) equipment and high-end displays, have also not previously been

[2] We adopt 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. We add 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.

[3] Games are available for Apple TV and Android media streaming devices, and are being further developed in conjunction with Steam. See https://appleinsider.com/articles/18/06/14/valve-not-giving-up-rolls-out-new-steam-link-beta-for-ios-apple-tv

analyzed. The effect of game choice on gaming device energy use has been examined in a very limited fashion in the case of PlayStation consoles (Koomey *et al.,* 2017), but not on other consoles or gaming computers. The sensitivity of gaming energy use to user behavior (e.g., hours spent gaming) has also not been described in the open literature.

Meanwhile, no U.S. energy policies or programs have focused on the gaming end use. Voluntary Energy Star labels for displays and televisions, and the 80 Plus rating program for conventional computer power supplies targeting mainstream computers have limited spillover benefits for gaming. Computer energy labeling programs or standards do not currently consider energy use in the active-gaming mode—a key nexus of energy use in gaming computers—and the 2019 California Title-20 computer standards in effect exempt high-performance PCs used for gaming. Utility incentive programs, consumer education campaigns, public-goods R&D, and other time-tested energy policy tools have also not been applied with the goal of improving energy efficiency and otherwise managing gaming energy use. Policymakers do not independently track or forecast energy demand for computer gaming, which results in the role of this important end use being largely obscured. The lack of standardized and widely-accepted measurement protocols and energy-per-performance metrics impedes progress towards quantifying and managing gaming energy demand. The ratio of frame rate to electrical power does not consider a broad range of proxies (often unmeasurable) of user experience, and can even run contrary to other measures of user experience. As a case in point, when considered in terms of the efficiency metric fps/W, Pong would be deemed 10-times more "efficient" (at 3 fps/W) than our best High-end system (H2, at 0.3 fps/W), but this is of little significance in an energy policy context given the vast differences in actual service levels provided and user expectations.

Project Approach and Scope

To better equip stakeholders to understand gaming energy use, the research presented in this report describes the California computer-gaming marketplace (technology choice and user behavior), provides in-depth energy use measurements across the entire spectrum of representative gaming devices, quantifies the per-unit energy savings potential, and provides aggregate energy demand scenarios and policy options for saving energy while maintaining or improving performance and user experience. As an example of impactful market trends, while the overall number of desktop systems in the installed base has been declining in response to the increasing popularity of console and mobile gaming, in many cases the mix of desktop platforms and their applications is shifting towards increasingly energy-intensive configurations while time spent gaming is gradually increasing.

To develop this analysis, we established a green-gaming laboratory capable of evaluating the power requirements of 26 gaming systems carefully selected to represent the range of those in use circa 2016, the base year for our energy demand projections to the future. A subset of these systems was then modified to achieve energy savings using improved technologies and componentry available in the marketplace. We evaluated various combinations of 37 popular games, 11 simulated frame-rate benchmarks, and 9 other gaming- and non-gaming-mode tests on all of these systems. We collected one-second data on energy use and component temperatures for all tests and multiple proxies of user experience (frame rate and frame quality) for all gaming-mode tests. In all, 1109 tests were conducted, segmented into 13 categories.

To characterize the market structure, we segment PCs used for gaming into Entry-level, Mid-range, and High-end categories, based on price and computing power (discrete versus integrated graphics, grade of graphics cards, etc.) (Mills et al., 2017). We also identify four types of gamers on all platforms: Light, Moderate, Intensive, and Extreme, which reflect the differing duty cycle, i.e., numbers of hours per day of gameplay and other gaming and non-gaming modes.

We thus consider the entire technology and behavioral "ecosystem", treating gaming as an activity involving combinations of hardware and software and user behaviors rather than isolated devices with generic sets of fixed usage assumptions. These ensembles of factors comprise the core gaming platform—including computers (desktop and laptop), gaming consoles and media streaming devices—together with a variety of peripherals including external audio, graphics processing unit (GPU) docks, displays, televisions, local networking equipment, and VR headsets and associated separately powered sensors, together with a wide range of user-driven behavioral choices that also influence energy use. The core platforms are multi-function devices that perform gaming as well as other tasks for their owners. We consider purpose-built gaming equipment, as well as conventional equipment used—sometimes quite intensively—for gaming. We also assess the use of these systems during modes other than gameplay. The scope excludes low-power mobile gaming devices such as smartphones used little if at all when connected to AC power.

Findings

Not surprisingly, Mid-range and High-end desktop computers emerge as the highest per-unit energy users (with notable exceptions, however). After a period of increases in recent years, consoles have achieved absolute reductions in energy use for some time and in most cases consume less energy than desktop computers on a per-unit basis.

The ranges of energy use overlap among the various product classes. For example, the most powerful gaming laptop's power use was greater than or equal to most of the Entry-level desktops, while many of the consoles used as much or more power than all but the highest-performance laptop and Entry-level desktop.

Media streaming devices are by far the least energy intensive gaming technology *locally*, although when running cloud-based gaming services a far larger workload manifests in data centers and intervening networks. We have estimated that a 10-watt local media streaming device can entail an additional 520 watts of power (more than most local PCs) in the upstream network together with the data center hosting the servers performing the graphics processing. We estimate a corresponding 300-watt power requirement for cloud gaming on consoles. For conditions prevailing in 2016, cloud gaming adds approximately 40 to 60% to the otherwise total local annual electricity use for desktops, 120 to 300% for laptops, 30 to 200% for consoles, and 130 to 260% 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.

Aside from consideration of added network and cloud-based loads, the energy use of individual gaming system energy is declining in many cases, yet historically increasing in aggregate due to an expanding overall installed base and modal changes within the base. The adoption of increasingly large and high-resolution displays, and in some cases virtual reality, further increases energy use of the entire gaming setup. In recent years, overall demand for local gaming has held roughly constant due to a rising share of consoles over more energy-intensive desktop systems. An important unknown is whether the next generation of consoles will bring increased or decreased energy use.

Most gamers would insist that improvements in energy efficiency not compromise user experience. However, in this regard, gaming is arguably among the most difficult energy-using activities to characterize in terms of energy requirements per unit of performance. Given that most forms of user experience are not readily measurable and thus highly subjective, we focused on frame rates, together with frame quality (stutter, dropped frames, etc.), as an example of one aspect of user experience. By these limited measures, user experience and energy use do not appear to be positively correlated. Indeed, there are multiple indications that energy can be improved while maintaining or even improving user experience. We also examine temperatures as another example of also-important equipment preservation and thermal comfort for gamers, and the associated distracting fan noise deemed undesirable by gamers. We find that temperatures tend to decline as more efficient componentry is introduced.

Drivers of Demand

Per-system energy use varies significantly depending on the technology used and game-title played, as well as the intensity of gaming behavior and broader duty cycle including other uses of the systems such as video streaming. We also find that power requirements vary widely within gaming system categories (PCs and consoles) and even within product tiers that make up those broad categories.

The proportion of total system energy used during gameplay ranges varies widely. For particularly intensive gamers, gaming can be responsible for up to 70% of total annual energy use (across all system types). The effectiveness of power management (throttling power draw when workloads decline) while in idle or standby mode varies quite widely. In cases of poor power management, power requirements in non-gaming modes are comparable to those during gameplay. We find that component nameplate ratings for CPUs and GPUs do not agree well with measured maximum power use, which complicates efforts to optimally design systems and estimate energy use. Official nameplate ratings for motherboards do not exist.

Connected peripheral devices are separate energy-using plug loads in their own right, but also create increased loads within the core gaming system (typically by working the GPU harder). For example, we found high-resolution 4k displays to significantly elevate gaming system power. The number of displays is also a factor. Our tests of three lower-resolution (1080p) side-by-side displays on one High-end PC system resulted in a 25% (73 watts) increase in base system power while gaming, over and above the similar amounts of power consumed directly by the displays. Others have observed similar effects on consoles. Use of an external graphics card dock boosted one laptop's energy use by two-fold and another's by three-fold. External audio equipment (common among gamers), is relatively low power but long on-times translate into significant added energy use.

We initially expected VR rendering loads to drive energy consumption higher among High-end PCs. Energy use does increase in some of the VR configurations we measured, particularly when considering that the existing 2-dimensional display is still used in conjunction with the VR headset. However, we've found that compared to rendering on conventional 2D displays, which requires corner-to-corner high quality calculations to feed the full screen, VR rendering can take advantage of human attention factors and eye anatomy to reduce rendering load for peripheral regions of the user's field of view. Consoles were more difficult to assess, but energy use appears to be higher under VR.

Energy use for a given system varied dramatically depending on game choice. However, we discovered that game genre is not a predictor of energy use; games that appear relatively simple can use comparable amounts of energy as high-intensity games due to the quality of imagery and visual effects used. We found that even the relative *rankings* of energy use for a given game also varied according to the system they are played on.

Users' graphics-related settings also influence energy use for the desktops and laptops (consoles tend not to offer user settings that might affect energy use). Across the range of these settings, system power varies mostly by less than 5%, with the exception of VSync, which reduced energy use up to 39%. Conversely, in-game "mods" increased power by 35% in one case we evaluated.

We find that within each broad technology group (PCs, consoles, and media-streaming devices) user behavior (duty cycle, game choice, settings) is a stronger driver of unit energy consumption than technology choice.

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

Toward Improved Energy Efficiency

The great strides made by console manufacturers (50% or more gaming power reductions achieved during the lifecycle of the 7th-generation console systems) provide an "existence proof" that energy efficiency can be improved, absolute energy use reduced, and user experience and market acceptance of the products simultaneously elevated. These qualitative patterns can also be seen for best-in-class PCs, although increasing users' performance aspirations (e.g., frame rates) have tended to cancel out potential reductions in absolute energy use in many cases. However, when properly specified, we found GPU savings on the order of 50% when upgrading our base systems, without adverse effects on performance metrics.

There remain enormous variations in energy efficiency of componentry offered in the market, suggesting room for improvement in the installed base. For some games, our highest-performing desktop system used less energy than many of the lesser desktop systems and less than even the PlayStation PS4 Pro. Systems integration is suboptimal in many cases. As another indicator of the opportunities, we found dramatically oversized power supplies in almost all of the PC test systems (even at peak loads).

Key trends in energy efficiency involve graphics processing and more efficient display of imagery. Graphics processing units (GPUs) can continue to become more efficient, as can the data centers and networks being increasingly used to host and deliver gaming content. Efficiency improvements can also be achieved in central processing units (CPUs), motherboards, power supply units, and cooling. The trend towards eye-tracking foveated rendering as the standard operating mode for all head-mounted VR displays will go a long way towards managing future energy demand associated due to VR growth and, by slimming the imaging data, support a transition to allow wireless operation. Game developers can also play a role in designing games to use energy more efficiently. It is important to keep in mind that improvements in each of these areas can be offset—and even overwhelmed—by parallel trends and desires in consumer user experience that translate into increased computational workloads.

The virtual reality headsets we tested required from 15% less (52 watts) to 38% more (93 watts) power during gameplay than the same system with a similar 2D game, with the lower case presumably thanks to programmatically limiting maximum resolution to the central field of vision (foveated rendering). Some VR systems have external sensors that use 16 watts and are likely left on often when not in use.

Much of the potential for decreasing (or increasing) energy demand lies in software. In an example of software strategies, slowing down 2D screen refresh rates to match the chosen display (VSync) resulted in 14 to 39% energy savings. Conversely, overclocking of CPUs and GPUs is a popular strategy among users of higher-end systems to get faster frame rates, and can boost power use by 7% in some cases, while underclocking of these components reduced power use by up to 25% in our testing. Note that percentage savings for given measures can vary depending on the system to which it is applied, paired display, *and* the game being played. Not all measures are applicable to all systems.

In defining our efficiency packages, we 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.

Implications for Energy Use in California

We combined our power measurements for individual systems with corresponding installed base data and duty cycle profiles to estimate aggregate computer gaming energy use in California. The 15 million gaming platforms existing in the state as of 2016 consumed 4.1 TWh/year, corresponding to a $0.7 billion/year[4] expenditure by consumers, and 1.5 million tons CO_2-equivalent/year of greenhouse-gas emissions. These values include energy use on the client side for the core system as well as displays, external speakers,

Some key observations from our testing are summarized in Box 1.

Box 1. Key observations and data bank

(2016 conditions, excluding network and upstream data center energy unless otherwise noted)

Energy consumption and power during gameplay

- Across 26 systems tested, client-side electricity use ranged from 5 to over 1,200 kWh per year, reflecting equipment choice and usage pattern.
- When PCs are grouped into three product tiers (averaged across user types, duty cycle, and games played) annual electricity use varies by 3-fold over 10 desktops (248 to 648 kWh/year) and 6-fold over five laptops (45 to 249 kWh/year). Use varied 18-fold over nine consoles (10 to 182 kWh/year), and 7-fold over two media-streaming devices (8 to 51 kWh/year).
- Across individual 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. The two media streaming devices used similar amounts of *local* power: ranging from 3 to 10 watts.
- The role of GPU ranges from 45 to 77% of total energy use in gaming mode, and is surprisingly significant in short-idle mode as well (12 to 33% of total energy use).
- Some gaming laptops use more energy than Entry-level PCs used for gaming.
- Some consoles use more energy than gaming laptops.
- Power in non-gaming modes for consoles is higher than that for some PCs used for gaming.
- Unexpected spikes in PC power during short idle mode corresponded to an average of 9% of total energy use above that of the expected idle state across all systems (up to 55% on one system). This suggests a need for more realistic test procedures. We did not observe similar patterns for consoles.
- For cloud-based gaming on PCs, about 180 watts is associated with network energy and about 340 watts with energy in the data center, which is a more energy-intensive configuration than purely local gaming. The corresponding values for console cloud gaming are 180 and 120 watts.
- Being in cloud-gaming mode adds 40 to 60% to the otherwise total local annual electricity use for individual desktops, 120 to 300% for laptops, 30 to 200% for consoles, and 130 to 260% for media streaming devices.
- When cloud-based gaming is performed by PCs, 50% of total energy use (averaged over systems and user types) is in networks and data centers. The value for laptops and media-streaming devices is 75% and for consoles is 40%.
- Frame rates don't correlate with system power; high performance does not require high power.
- Energy use varies more widely by gamer type (intensity of gameplay) than by system hardware.

Operational factors

- Annual electricity use (averaged across games) varies by user type by 5-fold over ten desktop systems (236 to 1,124 kWh/year), 12-fold over five laptops (42 to 513 kWh/year), 75-fold over nine consoles (5 to 403 kWh/year), and 8-fold over two media-streaming devices (7 to 57 kWh/year).
- The fraction of statewide client-side energy used in gaming mode (across all product tiers and gamer types) varies from 29 to 32% for PCs (laptops and desktops), 41% for consoles, and 7% for media-streaming devices (rising to 70 to 75% for the "Extreme" gamer types).
- The effectiveness of gaming systems in trimming power use to maintain proportionality with workload varies widely. Power use during gameplay is the same as that in non-gaming mode for some systems, with the ratio (energy proportionality) rising to nearly 5:1 for the systems with the best power management.
- Under-/Over-clocking three PCs decreased/increased gaming power by -26% to +37%

[4] Computed at average residential electricity prices – at the marginal prices where this actually occurs, the value would be approximately 50% higher.

- Large variations in power use can occur with in-game user settings on PCs.

Game Choice

- Energy use while gaming on a *given gaming platform* varies considerably depending on game choice: by up to 3.5-fold (270 watts) across various games on PCs and by up to 1.6-fold on consoles (61 watts) 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 for the two games playable on the widest range of platforms in our sample.
- Energy requirements for PCs and consoles are not correlated with game genre.

Displays

- High-definition 4k displays result in significant increases in PC energy use (25 to 64%), and reductions in framerate, resulting in reduced energy efficiency. Consoles also experience increased power when connected to 4k.
- Multiple displays impose extra workload—all across the duty cycle—on the PC gaming system, resulting in a 25% increase in PC power for three displays in a test we conducted.

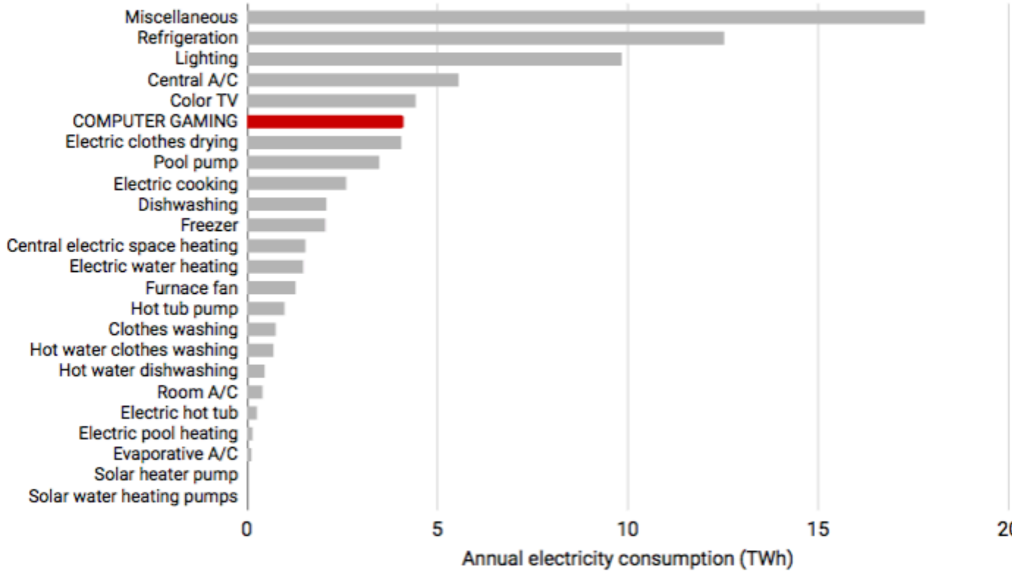
and local network equipment, as well as energy in upstream networks and data centers associated with cloud-based gaming.

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 collective energy use for computer gaming in 2016 equates to 5% of overall statewide residential electrical energy use among the investor-owned utilities in 2015 or that of about 10 million new refrigerators. Aggregate gaming energy in California is similar to that of clothes drying or televisions or that of electric cooking and water heating combined.[5] Computer gaming as a whole consumes about a fifth of all residential "miscellaneous" plug-load electricity (Figure 1).

[5] Assuming average new refrigerator uses 400 kWh/year. 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

Figure 1.
Computer gaming consumes more electricity in California than many familiar residential uses



For the purposes of this chart, unlike the other end uses, "Computer Gaming" includes multiple device types: desktop and laptop computers, consoles, and media streaming devices and associated displays, local network equipment, and speakers, and associated network and data-center energy. Values shown for Color TV are net of our 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.[6]

As of 2016, when allocating associated network energy, displays, and other peripheral loads to their respective system types, consoles are responsible for 66% of the total energy use for computer gaming across the duty cycle, followed by 31% for desktops, 3% for laptops and less than 1% for media-streaming devices, with the shares shifting toward PCs by 2021 in the Baseline scenario. 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).

We project the installed base of gaming systems will grow by about 15% as of 2021, together with a structural shift towards more energy-intensive regions of the technology spectrum for desktops and laptops, while consoles' blended unit-energy consumption declines.

With the trend towards consoles capturing an ever-larger share of total systems, and their relatively low unit energy consumption, energy demand declines slightly in the near term. In contrast, were the relative mix of device types and their unit consumption to remain frozen at 2011 levels—the beginning of our analysis period—demand would have grown by 64% to 6.3 TWh/year by the year 2021.

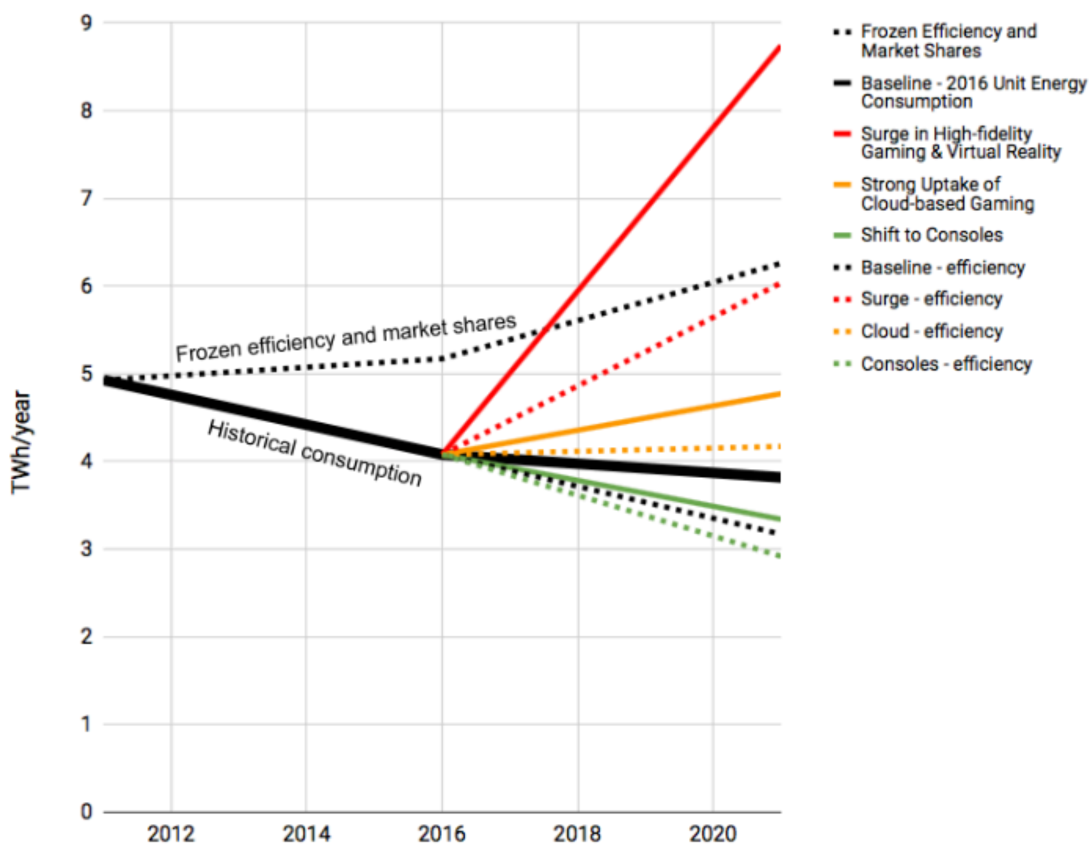
A set of additional scenarios define an envelope in which energy use, cost, and emissions rise by 114% or drop by 28% from the 2016 levels, depending on how the market evolves

[6] See http://www.energy.ca.gov/contracts/GFO-15-310/12-Attachment-12-Energy-Efficiency-Data_2015-11-10.xlsx The CEC does not further disaggregate miscellaneous.

(Figure 2). The relative shares of different gaming product families (PCs, consoles, media-streaming devices) varies substantially among these scenarios. Under these scenarios, up to 27% of total energy shifts to the data centers and supporting Internet infrastructure.

With near-term energy efficiency improvements in hardware, firmware, and software—and assuming that three-quarters of the stock turns over by 2021—aggregate demand falls to 3.2 TWh/year, a 17% reduction from the Baseline case and about 49% compared to the frozen-efficiency-and-market-share case. This scenario provides similar or improved measurable service levels (user experience) as the baseline scenario, with added benefits to users including reduced distracting noise and heat production.

Figure 2.
Enormous potential variations in California computer gaming energy driven by market structure, user behavior, and efficiency: 2011-2021



Solid lines are market-scenario 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 lines) 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.

Recommendations for Policymakers

Product manufacturers, consumers and energy policy makers will ultimately determine what portion of the aforementioned savings potential is captured in practice. Many long-used energy policy strategies are applicable in the computer gaming arena, including energy labeling, consumer information and education, voluntary ratings, improved software, and manufacturer R&D,. Mandatory system-level standards for gaming devices are highly problematic given the inability to consistently and meaningfully benchmark energy use per service (performance) delivered (most of these services are highly subjective and difficult or impossible to quantify), together with technologies and software that are evolving more rapidly than standard-making processes can adapt. Moreover, selecting a single metric upon which to base standards could stifle innovation while failing to recognize true efficiency improvements and their relation to user experience. Component-level standards may be more manageable, e.g., regarding power management in CPUs, GPUs, or motherboards. In any case, it is critical that often slow-moving policymaking does not inadvertently hobble or become irrelevant to industry's established innovation process.

Related considerations are that autonomous energy efficiency innovations in this industry are occurring at a rapid pace, while much of the projected demand growth is driven by consumer behavior rather than intrinsic component-level energy performance. With these drivers in mind, a focus on reducing absolute energy use per system and enhancing the currently deficient consumer information environment and behavioral campaigns hold particular promise.

Either PCs or consoles could drive future electricity demand growth, depending on how the market evolves. That said, energy demand is lowest in the scenarios dominated by consoles, whereas scenarios in which substantial demand growth occurs are driven by PCs. The majority of potential Baseline-scenario efficiency gains (about two-thirds) comes from PCs, which suggests policy attention to PCs is of particular importance, particularly given the paucity of such attention to-date. Irrespective of the client-side platforms chosen, the emergence of cloud-based gaming calls for increased focus on energy efficiency in data centers and networks, irrespective of customer-side gaming platform.

Solid policy as well as technological innovation require understanding the market, which calls for establishment of standardized energy test procedures, ongoing assessment of emerging energy-efficiency opportunities, improved understanding of user behavior as a driver of demand, market tracking to understand the ever-changing installed base, and incorporating the burgeoning energy use of computer gaming into energy demand forecasting.

2. INTRODUCTION

Energy researchers have long recognized the importance of miscellaneous uses of electricity, often referred to as "plug loads" (Meier *et al.,* 1992). 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. Lacking good accounting, energy used by plug loads can be missed altogether or incorrectly attributed to other end-uses.

Computer gaming, is perhaps the most extraordinary example of this challenge, as it comprises a myriad of platforms and use cases, in turn tempered by the consumer's choice of software as well as settings within the game during gameplay. While consumer electronics have emerged as a particularly important plug load (Rosen and Meier 2000), devices used for gaming have been largely overlooked by the energy research community and policymakers. Game consoles have received some attention, but desktop and laptop computers used for gaming have only recently come into focus (Mills and Mills 2015). While once true, the casual perception that these devices are used only on the "fringe" of society has dampened curiosity about their role in energy use.

Given that proper characterization of any energy use requires a coordinated assessment 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 that certain kinds of policy can be developed.

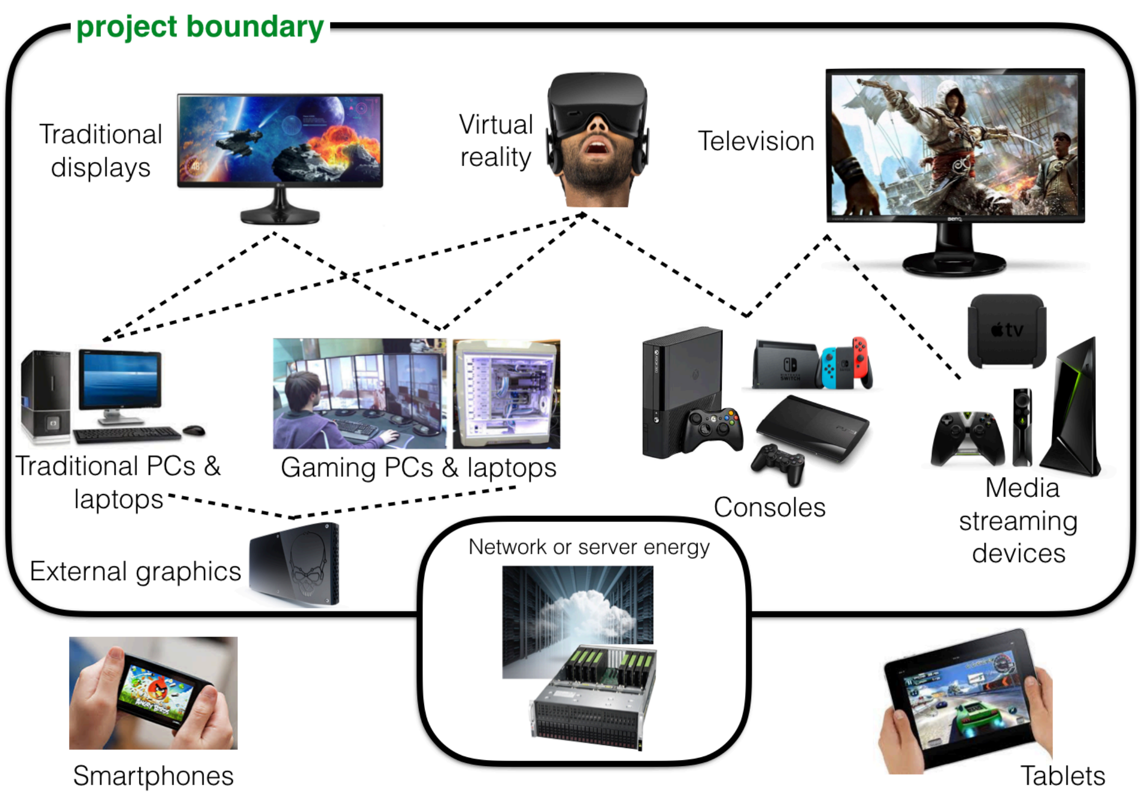
What is known is that the evolution of PC gaming technology has been marked by exponential improvement in a variety of performance metrics (Orland 2013), per-unit energy use in desktop and laptop gaming equipment has been rising, and the installed base has expanded and shifting towards energy-intensive product tiers. While gaming computer performance has improved at a faster rate than energy use has increased—suggesting improved efficiencies—absolute power requirements have been rising. Consoles have exhibited fundamentally different behavior, with energy efficiency gains outpacing the simultaneous growth in performance, often resulting in a net reduction in per-unit energy demand.

This report documents major findings from the Lawrence Berkeley National Laboratory's "Green Gaming" project which has characterized the California marketplace and constructed baseline estimates of energy demand in California and an outlook for the future.

The technical underpinning of the work is the development of rigorous energy and performance-measurement protocols, and applying them to a wide cross-section of gaming equipment in a laboratory setting under both simulated frame-rate benchmarks and actual gameplay conditions.

To understand the implications for California, we assess the gaming market structure, followed by development of historic and present energy demand estimates for gaming, highly segmented across different tiers of equipment as well as types of users and their utilization habits. We then evaluate energy efficiency opportunities at the macro level, and explore how computer gaming energy demand could develop in the near term under varying scenarios of consumer preferences and resultant structural change in equipment choice and user preferences marketplace. The report concludes with a review of policy mechanisms that could prove helpful in managing energy demand without compromising user experience. We consider all grid-connected game devices and their displays, including associated network and data-center energy, but do not address gaming on battery-only mobile devices such as smartphones (Figure 3).

Figure 3.
Boundary conditions for technology included in this study: Plug-in gaming devices with external display, or VR, and supporting Internet infrastructure and servers



This report answers a wide array of critical questions not addressed in the existing public-domain literature. These include quantifying the 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 settings on energy use, and the savings potential for modifiable desktop systems through hardware as well as firmware and software settings. The influences of behavior and technology are identified independently, shedding light on the roles of each independently and in combination. Gaming systems should be regarded as multi-function devices, that perform gaming as well as other tasks for their owners.

For analysis purposes, we define the gaming "system" as the core client-side gaming device (i.e., desktop, laptop, console, or media-streaming device). Unless otherwise noted, power use (in watts) and energy use (in kWh) are expressed for the system alone. The rendering load placed on the central system by the paired display is included, but plug load of display itself is not. We use a two-dimensional 1080p display in conjunction with VR, unless otherwise noted. Averages are for all games played with a given system (excluding simulated frame-rate benchmarks, unless noted) across the entire duty cycle, which varies by user type in some cases. When we extend the analysis to aggregate energy use at the California level, the entire gaming end use is considered, including external displays and the contributions of data centers where cloud-based gaming workloads are centered and the networks connecting these processes to the client-side system.

3. CHARACTERIZING THE COMPUTER-GAMING MARKETPLACE

Gaming has emerged as a major social and technological phenomenon, engaged in by almost a third of humanity (estimates range from 2.2 to 2.5 billion gamers in 2017).[7] In the U.S., 66% of people over the age of 13 engaged in gaming in 2018, up from 58% just five years earlier (Nielsen 2018). The average gamer is 35 years old, and 41% of gamers are women (ESA 2016).

The associated energy use has been understudied, and passed over in most energy policy and planning initiatives. A prior report from this project focuses on available energy-relevant information on the computer gaming marketplace, including associated technology trends and gaps in the consumer information environment (Mills *et al.,* 2017).

Although extensive information can be found on broad economic dimensions of the gaming marketplace (sales of equipment and gaming software), little information has been developed with energy considerations in mind. Virtually no such data is assembled at the state level.

Consumer Energy Information Environment

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

Most related information is based on rough proxies of power requirements, with virtually nothing available on measured power and energy use (the latter of which arises from a combination of power and duty cycle assumptions). These proxies include Thermal Design Power (TDP), rather than measured electrical wattage, coarse ratings on certain

[7] See https://newzoo.com/insights/articles/newzoo-2017-report-insights-into-the-108-9-billion-global-games-market/ and https://www.statista.com/statistics/293304/number-video-gamers/

power supplies,[8] and Energy Star ratings on displays and televisions. Internal power supplies for gaming laptops, consoles, and media streaming devices are not rated/labeled for consumers. There are no energy-relevant ratings for central processing units (CPUs), graphics processing units (GPUs), or motherboards, which consequently makes it impossible to rigorously right-size power supplies. Lastly, the selection of type and number of case fans is as much art as science.

Comparisons of actual system-level power to TDPs illustrate the difficulties facing consumers in knowing the energy implications of their design choices. Actual CPU power cannot be measured independently of the particular motherboard and power supply it happens to be paired with. GPUs are also difficult to isolate. Manufacturers do not include measured power data in product literature, and third-party reviews are sparse and use non-standardized test methods.

Insights into energy per unit of performance are also highly approximate. Metrics for graphics cards such as Teraflops[9] are only very loose proxies for performance. Numbers of cores and clock speeds for CPUs may or may not be meaningful, depending on how an application is coded, and frame rates are only one of many factors determining user experience and enjoyment.

There are at present no game-specific standardized energy test procedures or ratings for gaming equipment. Thus, consumers cannot know with confidence how their choices among different titles or genres will affect their energy use and costs. Third-party test results for identical components and systems vary across the consumer-oriented literature.

The combined effect of these conditions results in little transparency regarding the energy implications of gaming hardware and software choice for consumers, policymakers, or other stakeholders such as energy utilities.

Technology Families 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 Urban *et al.* (2017), we developed a detailed profile of the California gaming marketplace for the purposes of performing energy analysis.[10] We specified a set of pre-built and custom-built gaming systems that encompasses the range of functionality and user

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[8]Products are labeled with one of several grades of 80-Plus rather than discrete efficiency information, but exact numbers are available at https://www.plugloadsolutions.com/80PlusPowerSupplies.aspx

[9] Floating point operations per second (FLOPS, flops or flop/s), is a measure of computer performance for processes that utilize floating-point calculations, such as graphics image processing. Tera prefix designates a trillion (10^{12}) multiplier.

[10] Note that the Nintendo Switch hadn't been launched before Mills *et al.,* (2017) went to press. Introduced soon thereafter, the product has seen large sales numbers. We introduced it into the 2021 scenario, assuming a stock equal to the average of the PS4/Xbox One 2021 stock. We assume the same duty cycle and mix of user types for the Switch as for the Wii U.

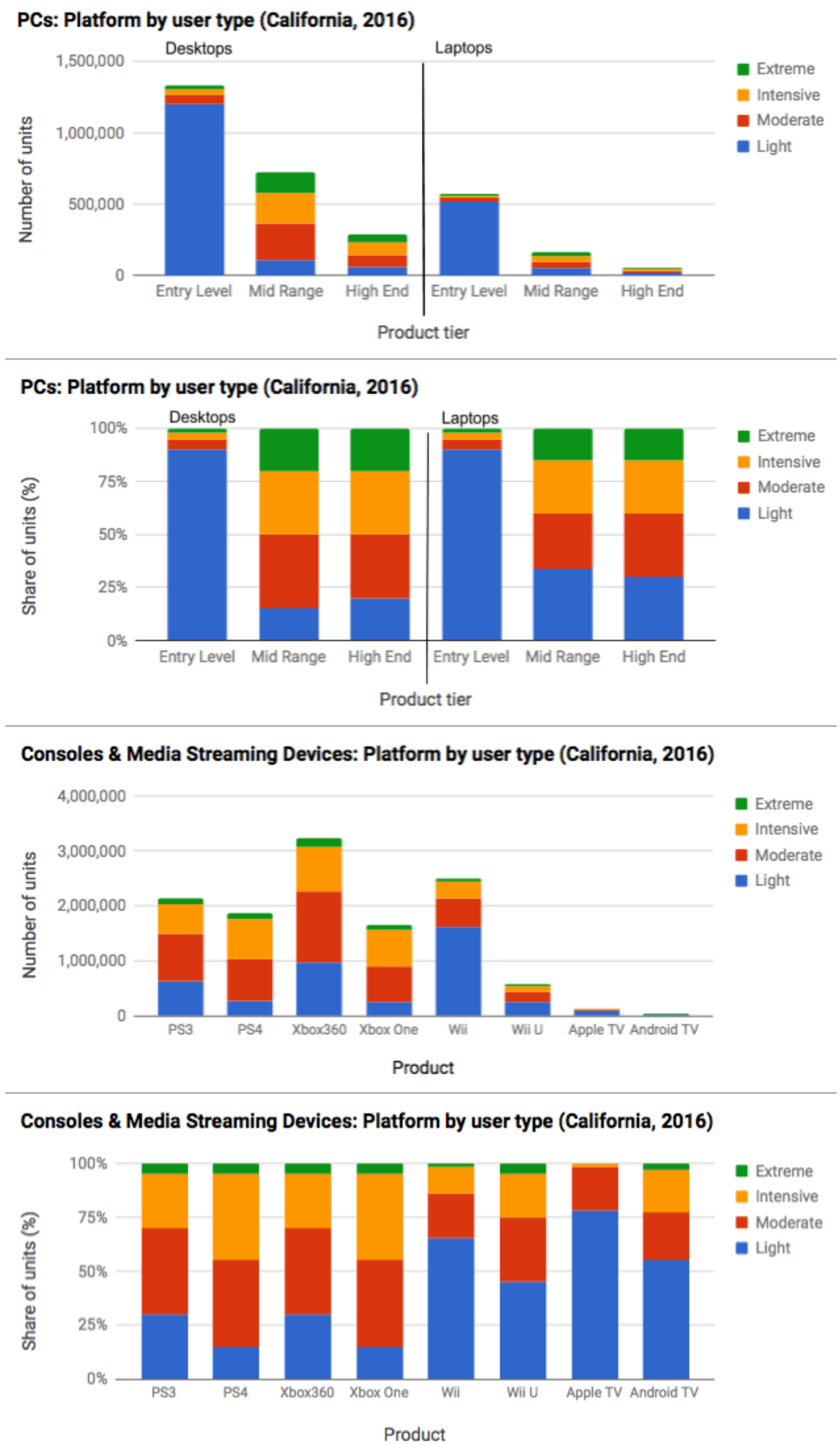
requirements sought in today's marketplace. The broad categories are desktop computers, laptop computers, game consoles, and media streaming devices (which can stream games and other media content via the Internet). The desktop computers include those purpose-built for gaming as well as "mainstream" systems. Both desktop and laptop computers can have either discrete graphic processing units or graphics integrated into the CPU. We further group gaming computers into Entry-level, Mid-range, and High-end categories, based on price and computing power. We also identify four types of gamers: Light, Moderate, Intensive, and Extreme, which reflect the differing duty cycle (numbers of hours per day) of gameplay and other gaming and non-gaming modes.

The resulting analytical platform includes an array of 26 individual gaming systems, operated by various user types across multi-step duty cycles, and running a large representative assortment of game titles and simulated frame-rate benchmarks. The resulting market segmentation spans the spectrum of gaming experience, system performance, and power requirements, and is leveraged to develop a characterization of the installed base of gaming equipment and its use.

Our decision rule for inclusion in the analysis excludes systems used less than one hour per week for gaming, thus excluding incidental use and out-of-service equipment. We find that there are currently more than 15 million computer-gaming devices in use in California meeting this definition (See Appendix A for details). We associate each user type with a segment of the installed base. Light gamers dominate among Entry-level desktop and laptop PCs, while they represent a small minority of users of Mid-range and High-end systems (Figure 4a-d and Appendix B). Consoles and media-streaming devices have somewhat lighter use regimes than PCs. Note that only systems located in homes and in use are considered here; we do not include commercial types of uses such as video editing or scientific simulation or cryptocurrency mining.

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 (extrapolated from Urban *et al.,* 2018), of which 15% are used for gaming. Of the 10 million laptops, 8% are used for gaming.

Figure 4a-d.
California gaming system installed base by user type by platform (2016)

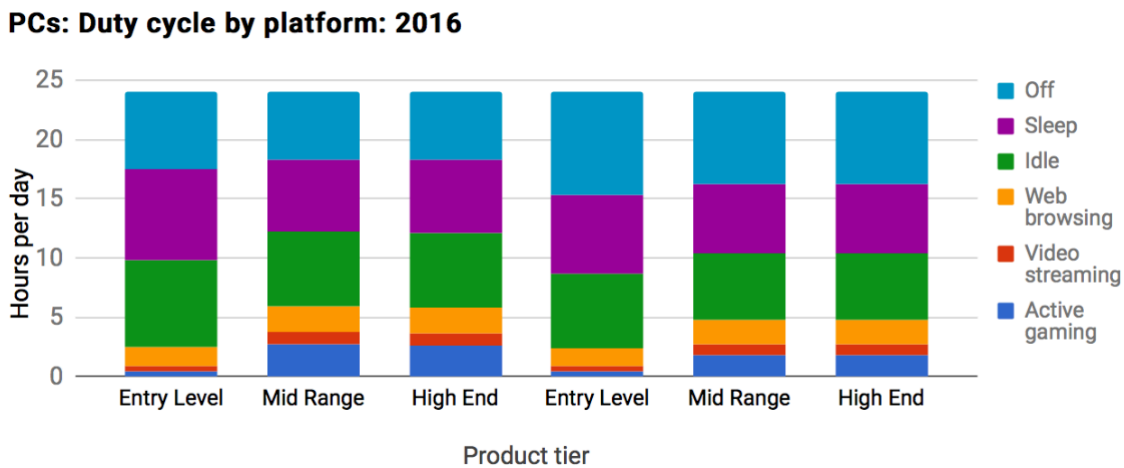


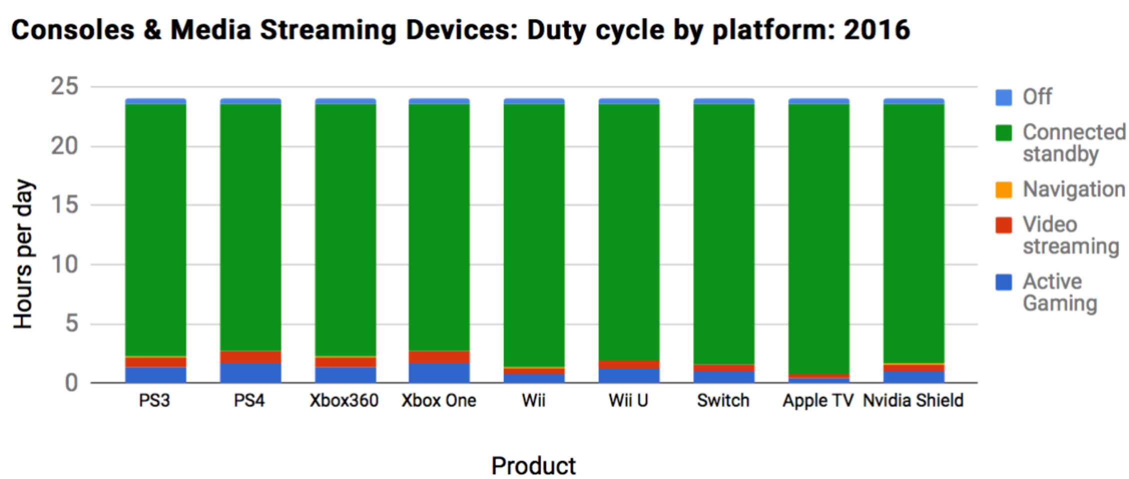
"Android TV" represented by the Nvidia Shield. The Nintendo Switch not yet introduced as of 2016, but is considered in the forward-looking scenarios presented later in this report.

Duty Cycle and User Behavior

While the most energy-intensive part of the duty cycle is time during gameplay, gaming devices also consume energy across a variety of non-gaming activities. In order to fully characterize their energy demand of these systems, we developed profiles for the entire duty cycle, disaggregated across each of the baseline systems and user types. We divide utilization into a series of modes ranging from "off" to "active gaming" (Figure 5a-b; Appendix C). Mid-range and higher-end PC systems tend to be used more intensively for gaming than the Entry-level ones.

Figure 5a-b.
Duty cycle by platform: PCs, consoles, and media streaming devices

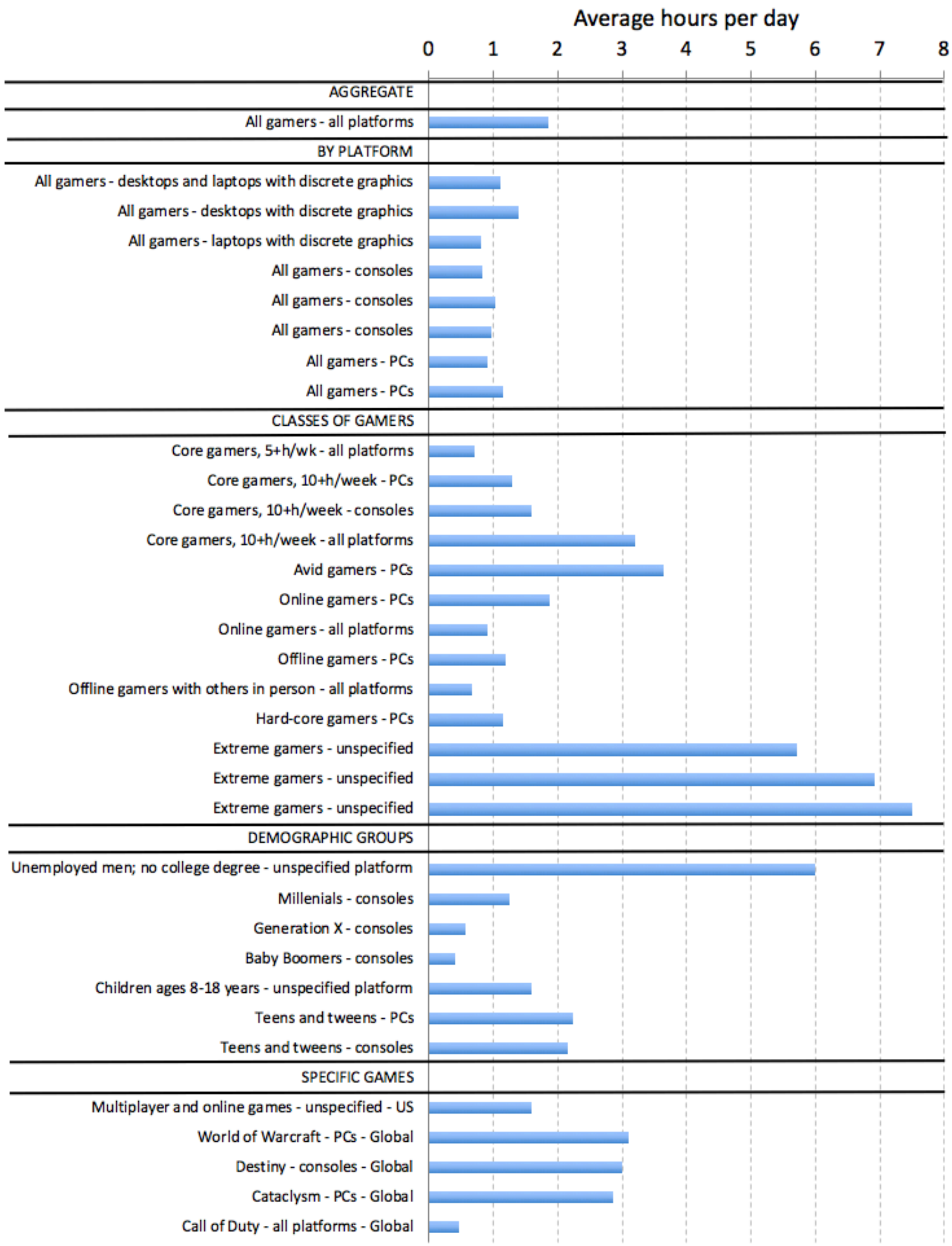




"Android TV" represented by the Nvidia Shield. The Nintendo Switch not yet introduced as of 2016, but is considered in the forward-looking scenarios presented later in this report.

Across the literature, we found estimates of time spent in gameplay that ranged from just a few minutes daily to nearly than eight hours (Figure 6), with most reports focusing on specific platforms and/or demographics. For the intensive gamers, time in non-gaming modes is proportionally lower.

Figure 6.
Time in daily gameplay varies widely by user and system type

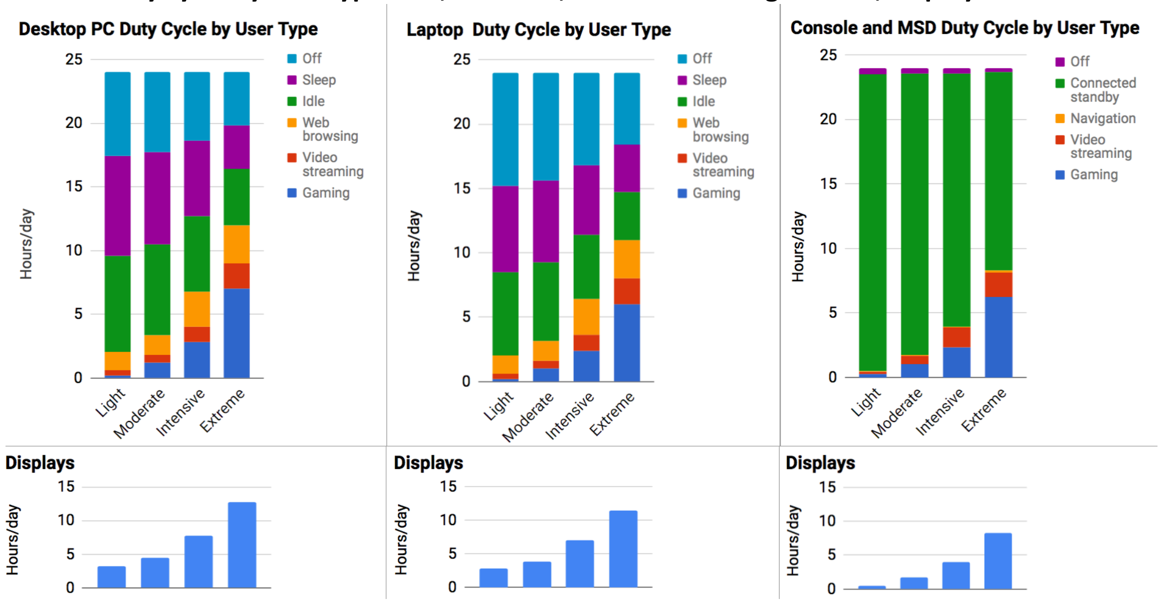


Values, notes, and sources provided in Appendix D.

Since publication of our initial market assessment (Mills *et al.,* 2017), the Consumer Technology Association's periodic survey of a nationally representative sample of U.S. households has been updated with new questions to assess time in gameplay for desktop and laptop computers. The survey found an average time in gameplay at 1.4 h/day for desktops and 0.8 h/day for laptops with discrete graphics (Urban *et al.,* 2017). The survey also yields estimates for other parts of the video-game console duty cycle, with fine-grain distinctions among makes, models, and technology generations. We adopt these values in our analysis as an improvement over the prior estimates in Mills *et al.,* (2017).

In our final characterization of PC user types, average time in gameplay ranges from approximately 30 minutes per day for Light users to 5 hours per day for Extreme users. For users of consoles and media streaming devices, the time in gameplay varies from 15 minutes to 6 hours per day, respectively. The dominant state for consoles is connected standby (Figure 7a-c).[11] Display on-time varies accordingly with user type.

Figure 7a-c.
Duty cycle by user type: PCs, consoles, media streaming devices, displays: 2016



Gaming in Conjunction with the Internet

Gaming has expanded into the Internet in three key ways, creating complex and far-ranging implications for the associated energy use. The original use of the Internet for gaming, now quite common, involves multiplayer games during which networks transmit small amounts of data so that players can share a given gaming environment in real time. Digital distribution of games has also become a popular alternative to physical disks, creating larger usage of energy within networks due to the greater amounts of data involved. Lastly, and more recently, the underlying graphics-rendering workloads of gaming are also shifting to the Internet, hosted on servers in data centers, which also

[11] See Appendix C for our definitions of "Off" and "Connected standby" for consoles.

requires transmission of large amounts of data. We refer to this as cloud gaming, although also known as “game streaming” or “on-demand” gaming.[12]

An indirect use of the Internet in association with gaming is known as ESports – projected to have an audience of nearly half a billion people globally by 2019 – in which people simply watch professionals game in real-time (NewZoo 2016). ESports has energy implications similar to those of streaming video.

As far back as 2012, PC gamers reported spending 34% of their total gaming time in online mode (PwC 2012). The more recent Entertainment Software Association survey finds that 51% of the most frequent gamers play online games at least once weekly (ESA 2016), for an average of 0.9 hours per day.[13] According to Statistica, among college students, approximately 35% play daily and 75% play at least weekly (Statistica 2016c). NPD finds that 70% of the 34 million “core gamers” (Siegal 2014) game online. An entire gaming genre—Massively Multiplayer Online Role-Playing Games (MMORPG)—is played by one third of all U.S. gamers (Statista 2016).

Nielsen data suggest[14] that the shift towards online gaming is occurring among console users as well, with 21% of 7th-generation console hours used in that mode in 2010, increasing to 28% for 8th-generation consoles in 2014. Console players now spend more time playing online games than offline games. Statistica placed the value at 46 million online console gamers in the U.S. in 2014.

To place this form of gaming activity a broader context, online gaming is projected to be the fastest-growing segment of residential Internet service, with the 1.1 billion users worldwide in 2015 growing to 1.4 billion by 2020 (Cisco 2016a).

The global volume of online gaming traffic was estimated at 76 petabytes per month in 2016, and projected to grow seven-fold by 2020 (Cisco 2016c). These estimates are up sharply from values produced just three years earlier (Figure 8). Notably, online gaming is one of only four segments of consumer Internet traffic data that Cisco disaggregates in their reports, the others being Internet video, web/email/data, and file sharing, and is the fastest-growing at 47%/year. Gaming devices are also used for other cloud-based activities such as web-browsing and video streaming.

Online digital distribution of games requires vastly more data transfer than online gaming. It is generally preferred for convenience and ease of updates. Services like Steam distribute all of their games in this fashion. Digital distribution is more popular among PC gamers than console gamers, the latter group preferring to download games 2:1 over purchasing physical disks (Nielsen 2017).

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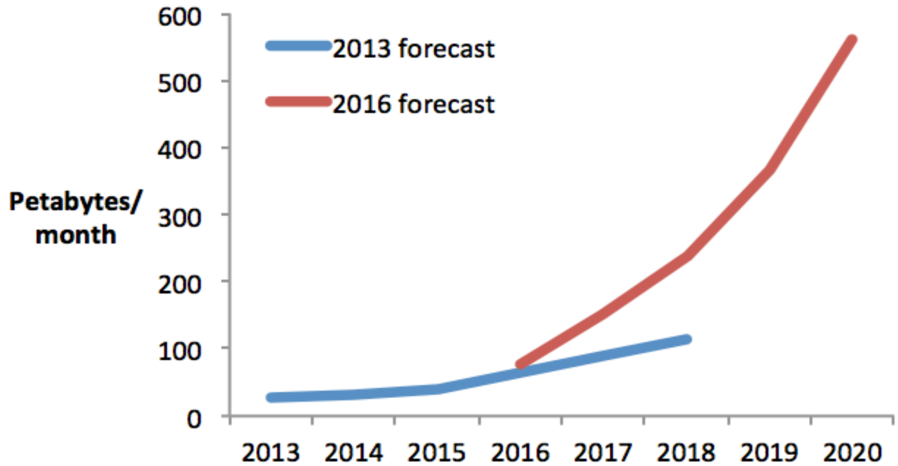
[12] In the case of GeForce NOW, content is streamed at 1080p resolution and 60 fps at 40 Mbps, which matches the local playing experience for most users (Eisler 2017).

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

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

Figure 8.
Rapidly escalating global online gaming throughput



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.

Online gaming retains heavy workloads on the local client, while exchanging meta-data among gamers. Cloud gaming stands to be far more energy-intensive. 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 (which we refer 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).

About a dozen cloud-based gaming service offerings are currently active.[15] As of early 2017, Nvidia had installed several hundred thousand of its high-power GeForce graphics processing units in data centers, which can be "rented" via its GeForce NOW service by gamers seeking a peak gaming experience.[16] Sony's PlayStation Now service offers a similar cloud-based game streaming service for PlayStations and PCs, with over 600 titles available for their consoles as well as PCs as of spring 2018.[17] The Xbox Game Pass is a similar service, with approximately 100 titles as of early 2018.[18] Some gaming equipment manufacturers are exploring the establishment of data centers dedicated solely to hosting gaming infrastructure.

We explore the energy use under of various forms of Internet-based gaming later in this report.

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[15] See https://en.wikipedia.org/wiki/Cloud_gaming

[16] See https://www.polygon.com/2017/1/5/14176032/geforce-now-1080-1060

[17] See https://www.playstation.com/en-us/explore/playstationnow/

[18] See https://www.dailydot.com/parsec/xbox-game-pass-cost-games/

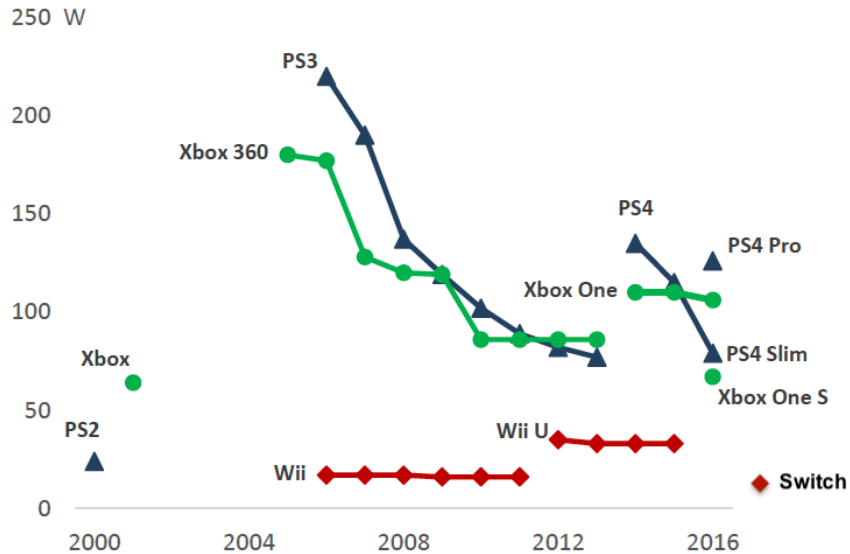
4. BASELINE ENERGY USE AND PERFORMANCE

The existing literature on gaming energy use focuses almost exclusively on game consoles, and is most recently summarized in Mills *et al.,* (2017). Only one formal study has looked in depth at desktop computer gaming (Mills and Mills 2015), and no work has been published regarding gaming on laptops or with television-linked media-streaming devices such as Apple TV or Android TV. Neither has the energy used in data centers for networked-based gaming been quantified. The energy use of many specific ancillary components, e.g., virtual reality equipment and high-end displays, has also not previously been analyzed. The effect of game choice on gaming device energy use has been examined in the case of four games run on one brand of console (Koomey *et al.,* 2017), but not on gaming computers. Making new measurements and drawing together all these lines of data, we have developed a more comprehensive set of energy use estimates.

Measurements of console power requirements are available over a sixteen-year period. During the beginning of this period, per-unit power use increased nearly ten-fold in the jump from Sony's PS2 to PS3, while that from Microsoft's Xbox to Xbox 360 rose about three-fold. Since that time, most consoles have demonstrated particularly rapid reductions in energy use. Urban *et al.* (2017) charts nearly 50% reductions in power use during active gameplay over the Xbox 360 and PS3 product cycle and the current console generation (Figure 9). As the next generations of each product were introduced, power consumption initially increased, doubling in some cases—but not nearly to the introductory levels of the previous generation--then dropped again with time. The minimum values achieved as of the most recent points in each product cycle were similar to the final release of preceding generations. Power requirements for the Nintendo Wii were virtually unchanged over their product cycles, until the recent release of the Switch, which marked a substantial proportionate drop. Power requirements in other modes (video playback, navigation, standby/off, etc.) have also trended lower over time. Common to all these systems is a dramatic improvement in performance and user experience over time. Thus, console efficiencies (performance per watt) have improved dramatically over time.

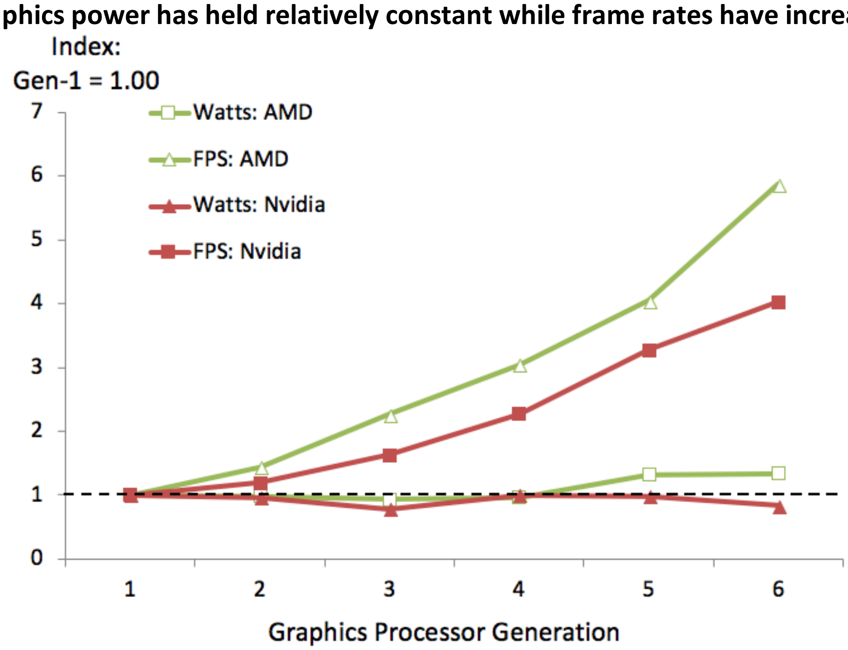
Gaming computers are much more diverse in terms of product choices and less well characterized in terms of energy use. Limited multi-generational comparisons of the dominant graphics cards brands (the most energy-intensive component in these systems) over the last 10 years shows performance increasing many-fold with energy use relatively unchanged (Figure 10). That is to say that efficiency, measured as power per unit of performance, has improved rapidly, while absolute energy use has remained relatively constant. There are important exceptions, e.g., cases where new generations of GPUs yield significant absolute power reductions while improving efficiency (AMD 2016).

Figure 9.
Console power during gameplay has seen substantial improvement



Note more than halving of initial gaming power requirements between launch date and final generation of PS3 and Xbox 360 products. Subsequent launch versions for PS4 and Xbox One drew less power (and had far greater performance) than prior-generation launch versions. Measurements exclude display and network energy. Source: Urban et al., (2017) with Nintendo Switch added based on LBNL measurements.

Figure 10.
Graphics power has held relatively constant while frame rates have increased



The time period reflected here is 2010-2016. Source: Walton (2016 and 2017)

The Daunting Complexities of Performance Metrics and Benchmarks

Ideally, the energy performance of gaming systems could be readily compared with one another. 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. Moreover, as we have found in this study, the choice of game (or simulated frame-rate benchmark) strongly influences energy use as does in some cases the selection of display technology (2D versus virtual reality) and the specific choice of display within these two broad display families. Some systems (laptops and consoles) allow for internal or external display/TV use as well. 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. They can be delineated as component-level services inside the system and visual characteristics of the user's gaming experience.

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-active 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 in order 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 (e.g., 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. We 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 (Table 1), 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.[19] More importantly, 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. 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".

Table 1. Factors affecting gaming performance and user experience

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

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.*

[19] 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.

Irrespective of the preferred metric, it is important to identify test methods that apply an appropriate workload to the system. In practice, as will be explored in detail later in this report, workloads vary significantly by game. To allow for a more standardized test methodology, the industry has created a wide variety of simulated gaming-benchmarking software applications (automated stress-tests emulating intensive human gameplay); yet the energy implications of these, too, vary. To be comparable across platforms, efforts to compare gaming devices should ideally encompass PCs (both Windows and Mac OS systems) as well as game consoles designed for use with televisions. A significant obstacle at the time of our product testing was that simulated frame-rate benchmarks are not available for consoles or media streaming devices (or virtual reality systems)[20], which thus required non-standardized human testing.[21] Further confounding efforts to compare one gaming system to another, there is no single game or simulated frame-rate benchmark that can be run on all platforms. Meanwhile, many game titles on PCs are purchased through online digital licenses and undergo constant centralized version updates, potentially negating the ability to comparably repeat tests for some titles over time.

A parallel issue concerns limits to human perception: just because one can measure a given performance metric does not mean that humans can discern or appreciate it across the entire potential measurement spectrum. For example, are faster and faster frame rates indefinitely perceptible? Does the gamer detect each and every dropped frame? Because each gamer is unique, there is no ground truth regarding the level of services being noticeably received. This creates yet another set of confounding factors for efforts at energy-per-performance metric standardization.

PC energy use in non-active modes is reasonably well defined by Energy Star and other test methodologies. PC energy use and efficiency in gaming and other active modes, however, is poorly defined, and not considered in Energy Star or other existing rating systems (IEC 62623 does define an active work mode and how to use it in the calculation of TEC, but this is not used by Energy Star or CA Title 20 standards). Power requirements can vary considerably during gameplay, as a function of underlying workload created by the application and the gamer's choices as they move through the storyline. For example, Figure 11 shows the power levels of three different five-minute active gaming tests on the same system. Note how not only are the average power levels quite different, but also the pattern of power use is unique to each. In addition, users may under- or over-clock the CPU or GPU and implement a variety of in-game settings, or game modifications ("mods"), each of which will simultaneously influence the system power draw and user experience. The choice of display can also influence system energy use—and of course user experience as well—particularly in the case of virtual reality.

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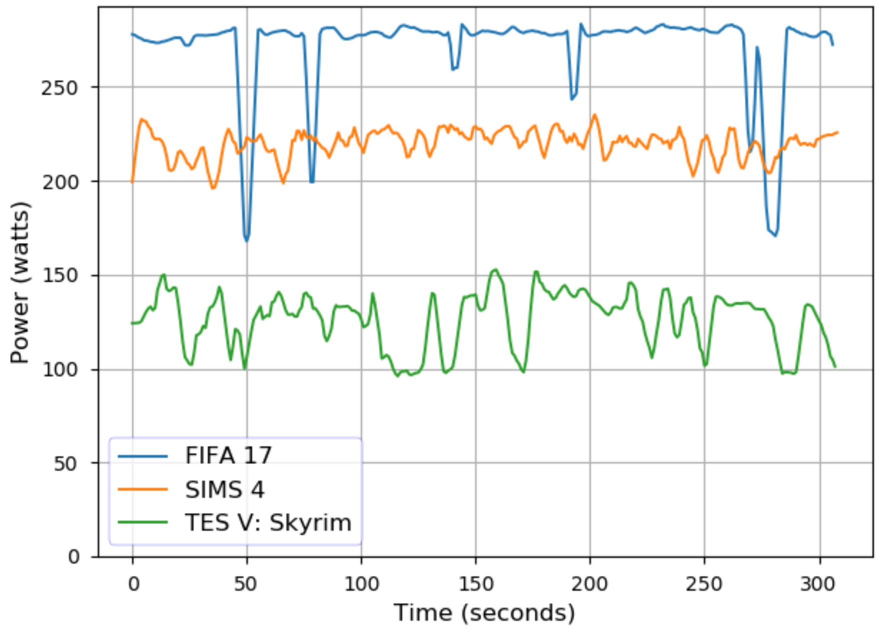
[20] 3DMark released a VR testing protocol after our testing process had begun.

[21] Futuremark (now named "UL Benchmarks") has subsequently released VRMark, https://benchmarks.ul.com/vrmark.

Figure 11.
The level and pattern of energy use varies considerably by game, even on a given platform: System M4



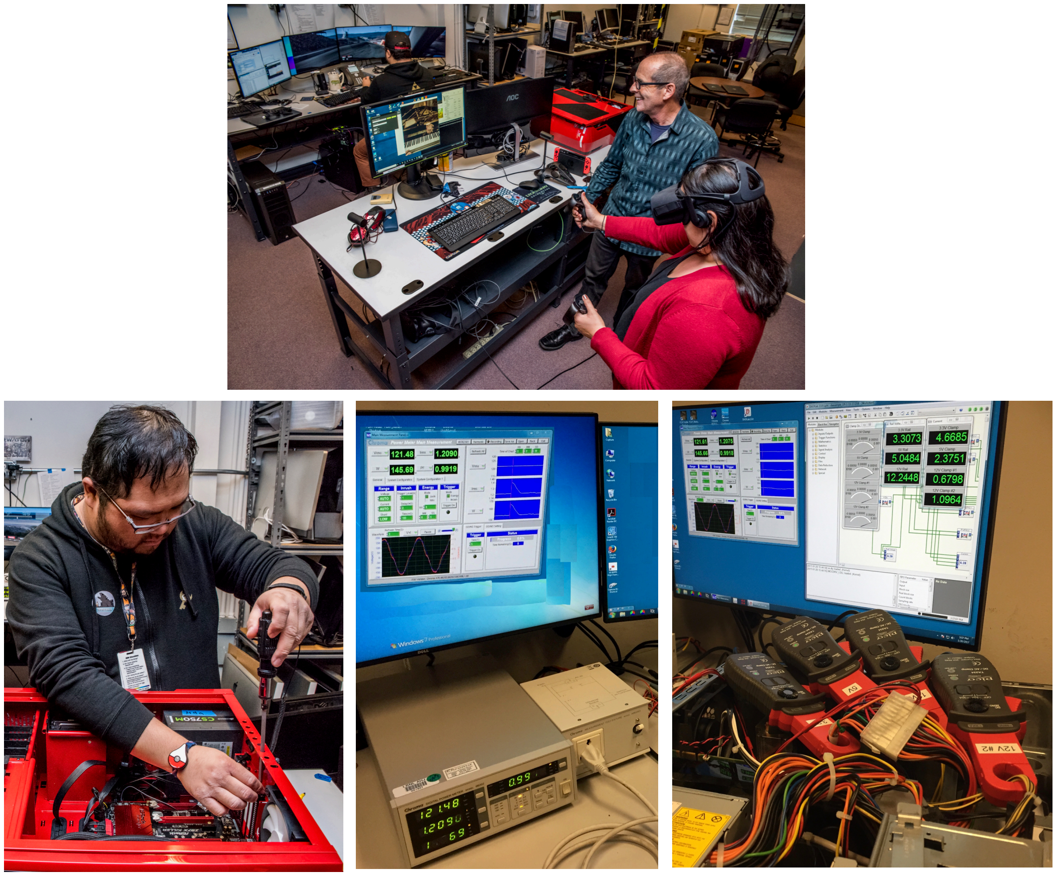
Koomey *et al.,* (2017) offer a valuable addition to the literature on the challenges of energy-per-performance developing metrics. Their discussion raises important pragmatic and conceptual issues concerning the ability to meaningfully benchmark energy use for gaming consoles in particular. The authors express doubt that energy-per-performance metrics can be consistently and repeatability applied across the range of available gaming platforms, and that representative games or combinations of games can be identified and revised on an ongoing basis for this purpose. Methods must be deemed neutral to competing technology platforms.

In light of the foregoing discussion, it has been necessary to limit our assessments to frame rate and frame quality. One weakness of the fps metric is that given absolute changes at the higher end of the performance spectrum correspond to proportionately low percentage improvements compared to the same change at the lower end of the spectrum (e.g. 20 vs 25 fps versus 120 vs 125 fps).

Green Gaming Bench Testing Lab

We established a Gaming Systems Test Lab and associated procedures at LBNL for the purposes of analyzing specific gaming devices and software variables (Figure 12) (Bourassa *et al.,* 2018a and 2018b). The lab allowed us to log power use and frame-rate/quality for each gaming system in both gaming and non-gaming modes. A data acquisition platform was also developed to aggregate and analyze the large volumes of information collected.

Figure 12.
Green gaming laboratory and test equipment



Key measurements and the equipment used include:

- **System Power** was measured using a Chroma 66202 Digital Power Meter which can measure power to 0.1mW resolution with an accuracy of 0.1% of reading + 0.1% of range. Power of just the gaming system was measured and did not include any external display, peripherals, or network equipment power. Data were recorded on a 1-second basis and included power (watts), rms voltage, rms current (amps), power factor, THDi (%), and THDv (%).
- **Component Power** (such as CPUs and GPUs) was measured using a Measurement Computing USB-1608FS-Plus data acquisition system, which samples at 50 kHz. Currents were measured using Pico TA234 30-amp current clamps. Voltage, current, and power (V x A) were recorded on a 1-second average basis.
- **Video Image Output** was captured using a Datapath VisionSC-DP2 capture card capable of capturing 4k Ultra HD video at up to 60 fps. Video was stored in a RAID 0 (data striping) array of three 500GB SSD drives with a maximum write speed of 450 GB/sec. The maximum amount of data coming through with 4K 60 fps video, uncompressed and uncropped, is about 1.39 GB/sec.

- **Frame Times** were measured using multiple methods including FRAPS, PresentMon, and FCAT VR software running on the PC system under test. The Nvidia FCAT testing process, which includes the VitualDub video software analysis application was used to analyze the video capture test files.[22] Statistics recorded for each test are summarized in Table 2. In addition, the following statistics were calculated from the frame times for each test: 97th percentile frame time, 99th percentile frame time, frame time RMS error (the RMS error between the actual frame times and the frame times smoothed using a Gaussian filter).
- **CPU and GPU Temperatures and CPU Power** were recorded using OEM embedded sensors together with Open Hardware Monitor software running on the test system.

Table 2. Frame statistics recorded (all times in milliseconds)

Software	Period	Variable
FRAPS	Whole test	Average frame time
		Minimum frame time
		Maximum frame time
PresentMon	Each frame	Time Between Presents
		Time Between Display Change
		Time in Present API
		Time Until Render Complete
		Time Until Displayed
	Whole test	Dropped
FCAT	Each frame	Frame time
	Whole test	Average original frame time
		Average calculated frame time
		Number of frame runts
		Number of frame drops
FCAT VR	Each frame (HTC Vive)	Total GPU render time
		App Miss Count
		Number Dropped Frames
	Each frame (Oculus)	Total GPU render time
		App Miss
		Warp Miss

System Selection and Testing

We 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 circa 2016 (Figure 13 and Table 3).[23] Each system is designated using an alpha-numeric system ID: For desktop PCs, in order of increasing computing power, E-series are Entry-level systems, M-series are Mid-range, and H-series are High-end. The L-series are laptop PCs, the C-series are consoles and the V-series are media streaming devices. Desktop systems E1, E2, M1, and H2 were pre-built commercially available systems. We 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

[22] See https://www.geforce.com/hardware/technology/fcat and https://github.com/GameTechDev/PresentMon/releases

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

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 gaming "benchmark") or by a person using a real game. We experimented with 11 frame-rate benchmarks and 37 actual popular games drawn from 8 broad genres, together representing 206 game-system combinations (Bourassa *et al.,* 2018a) (Table 4) Games were selected to reflect popularity and matched with compatible systems for testing.

Figure 13.
Baseline systems: desktops, laptops, consoles, and media streaming devices

VR headsets are also shown: HTC Vive (left) and Oculus Rift (right). System ID codes can be cross-referenced to more technical information in Table 3.

All gaming-mode tests were conducted with external high-definition (HD) 1080p Dell 24in 1080p display (desktops, laptops, and consoles). In the case of C7 (Wii) we used a Samsung 60 1080 TV monitor because the device only has separate video and audio RCA photo connectors (aka "composite out"). These values reflect findings from our earlier market research (Mills *et al.,* 2017).

The investigation involved conducting a total of 1109 tests segmented into 13 different categories of tests. 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 "active gaming"). Detailed results of all the tests are presented in Bourassa *et al.* (2018b).

In addition to baseline equipment tests, we examined a variety of permutations, including trials using virtual reality rather than 2D displays, external graphics card "docks" fitted to laptops (available for both PCs and Apple computers), and a range of software and firmware variations.

Table 3. Baseline system descriptions: PCs, consoles, & media streaming devices

Product Category	System ID	Make and Model	Motherboard	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
High-end desktop PC	H1	DIY	EVGA X99 Classified	Intel Core i7 5820K	AMD 2x R9 Fury X	Discrete	80+ Gold
	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					

Table 4. Array of frame-rate benchmarks and games used while measuring gaming power

Type of game or benchmark		System																									
		E1	E2	E3	E4	M1	M2	M3	M4	H1	H2	L1	L2	L3	L4	L5	C1	C2	C3	C4	C5	C6	C7	C8	C9	V1	V2
BENCHMARK	Prime 95	X	X	X	X		X	X	X	X	X	X	X		X	X											
	Sky Diver		X				X			X					X												
	Cloud Gate		X				X			X					X												
	Unigene Heaven		X				X			X					X												
	Unigene Valley		X			X	X			X				X	X												
	Cinebench		X			X	X			X				X	X												
	Catzilla		X				X			X					X												
	Furmark		X				X			X					X												
	NovaBench		X				X			X					X												
	Geekbench 4 Pro		X				X			X					X												
	P-Test9		X				X			X					X												
PUZZLE	Candy Crush Saga		X	X	X							X	X														
SIMULATION	The Sims		X				X			X			X														
	The Sims 4	X	X	X	X	X	X	X	X			X	X	X	X												
	Farmville 2		X				X			X					X												
SPORTS & RACING	FIFA 17						X	X	X						X		X	X	X	X	X	X					
	Project CARS		X				X			X					X			X	X		X	X					
	Project CARS VR									X	X					X											
	Rocket League					X								G													
	Wii Sports																						X				
	Mario Kart 8																						X	X			
	Real Racing 3																									X	X
	Mario Kart Wii																						X	X			
	Gran Turismo 5																X										
	Forza Motorsport 4																			X							
	Super Mario Brothers																						X	X			
	Super Mario Odyssey																								X		
	Super Smash Brothers																						X	X			
OPEN WORLD	Middle-Earth: Shadow of Mordor					X				X	X			X		X	X	X	X	X	X	X					
	Minecraft		X				X			X					X												
	Skyrim TES	X	X	X	X	G	X	X	X	X	X	X	X	G	X	X	X	X	X	X	X	X			X		
ROLE PLAYING	The Witcher 3: Wild Hunt					G				X	X			G		X											
	Borderlands																										G
	Bioshock Infinite					X								X													
	Fallout 4									X	X					X											
	Legend of Zelda: Twilight Princess																						X	X			
	Zelda: Breath of the Wild																								X		
	Batman Arkham VR									X	X					X		X	X								
SHOOTER	Overwatch						X	X	X						X			X	X		X	X					
	Call of Duty Black Ops 3						X	X	X						X		X			X							
	Fortress 2					G								G													
	Modern Combat 5: Blackout																									X	X
	Splatoon 2																								X		
MASSIVELY MULTIPLAYER ONLINE	League of Legends	X	X	X	X							X	X														
	World of Tanks	X	X	X	X							X	X														
PLATFORM	Despicable Me: Minion Rush																									X	
	Super Smash Bros - Brawl																							X			
	Super Smash Bros - WiiU																								X		

Note: Game selection reflects popularity and fit to a given platform. No frame-rate benchmarks are available for consoles or media streaming devices. The "G's" indicated games implemented on GeForce NOW.

At least one representative desktop PC system in an Entry, Mid-range and High-end market segment was subsequently modified to achieve energy savings and retested.

Our energy use measurements were made primarily at the system level because system integration determines ultimate energy use and our 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 affected by the choice of power supply.

Note that the per-system results pertain *only* to the core gaming system. Energy use by external displays (including VR peripherals) and network/cloud-related energy are not counted in the assessment of individual systems, but are considered when the aggregate statewide energy use is estimated.

Defining the power requirements of a gaming device is thus no easy task. Simulated frame-rate benchmarks are appealing because they are automated and highly replicable. Human gameplay is ostensibly more realistic, but less repeatable. We evaluated both. To minimize "noise" caused by variations in human gameplay, we developed a detailed test procedure 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 The Elder Scrolls V: Skyrim, this period involved an approximate 6-minute test of the introductory tunneled (explicit path, "Helgen Keep", ideal for the sake of test replicability) section of the game.

We also recruited 22 experienced gamers to play 89 individual game sessions (11 different game titles) in an unscripted manner on the some of the computer gaming systems (Bourassa *et al.,* 2018). Figure 14 compares the average power use during each user test to that for a bench test of the same combination of game and system for 23 PC tests and 13 console tests. The average power during the tests was a good match, with the PC bench tests only 1.6 watts higher and the console bench tests only 1.1 watts higher. These findings provide high confidence in the generalizability of our scripted testing, with differences less than the error test procedure uncertainty (Vaino *et al.,* 2018).

System Power Requirements, by Usage Mode

At the outset of the testing process, we sought to determine the variation in test results that might be encountered for gaming mode depending on test procedure. We ran 11 frame-rate benchmarks on desktop computers selected from each of our three product tiers and one Mid-range laptop and compared the results to those for 10 actual game titles (Figure 15a-b).

The exercise made it evident that power requirements vary considerably (a factor of more than two) depending which frame-rate benchmark or game title is chosen. That said, contrary to a popular perception that these benchmarks don't approximate real-world gameplay, we found that all but two of the benchmarks bracketed a range of power requirements very similar to those of the range of real-world games that we tested. However, these benchmarks yield widely varying energy use estimates for given gaming systems.

Given that actual games are as or more intrinsically representative of actual utilization and energy use, we have focused on those results over those of simulated frame-rate benchmarks. As discussed below, we find that disciplined human testing of actual games to be highly reproducible.

We compared the measured energy under the frame-rate benchmarks to that under actual gameplay. Figure 16 compares the system power use under each benchmark test to the mean power of the aforementioned 10 games. Although the benchmark that best fits (almost perfectly) the mean game power distribution is Cloud Gate, this benchmark is designed for notebooks and home PCs and thus we chose to use the next higher power benchmark, Fire Strike, as our representative benchmark for all subsequent tests as it is designed for high performance PCs used for gaming and would help to differentiate the systems more meaningfully.

Figure 14.
Agreement between measurements during structured bench testing and open gameplay: 22 players

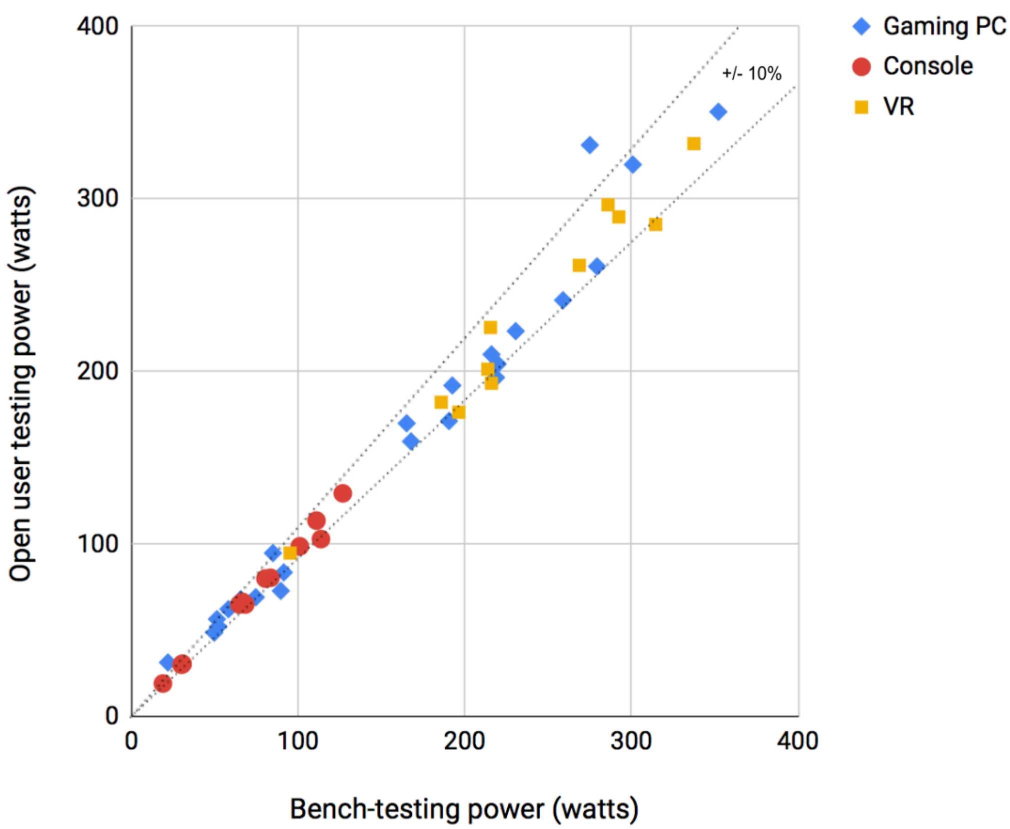
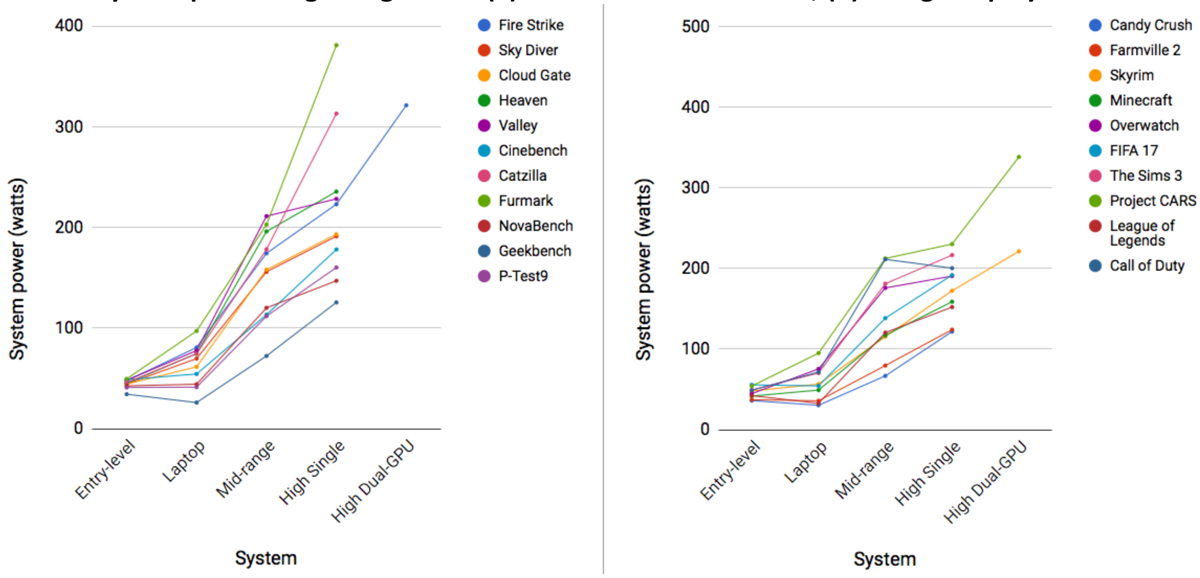


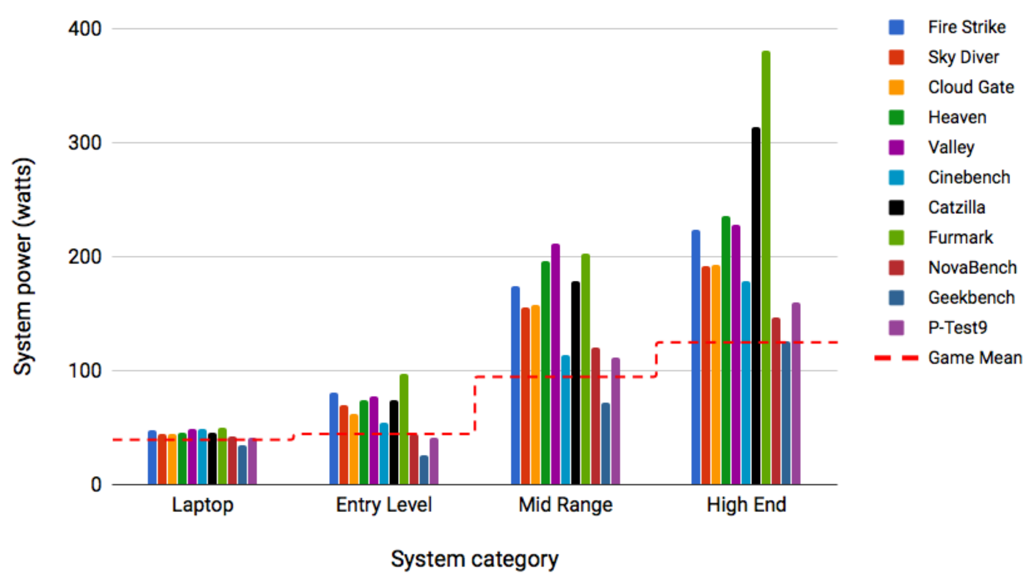
Figure 15a-b.
System power in gaming mode: (a) frame-rate benchmarks; (b) real gameplay



Values for systems L4, E2, M2, and H1.

The Fire Strike frame-rate benchmark is made up of four consecutive tests (Graphics 1, Graphics 2, Physics, and Combined), which are each from 14 to 40 seconds long. An average of the Graphics 1 and Physics power levels was found to best represent typical power during gameplay. While this benchmark provides our best fit to actual gameplay, there are cases (e.g., with system H1) where it consistently over-predicts actual use (Figures 17-18).

Figure 16.
Active gaming power varies widely depending on chosen benchmark



Values for systems L4, E2, M2, and H1. The average across all Fire Strike tests is shown here, as this testing predated our search for a proper weighting of those four test modes.

Figure 17.
Improved predictive power of Fire Strike metric when sub-tests are weighted

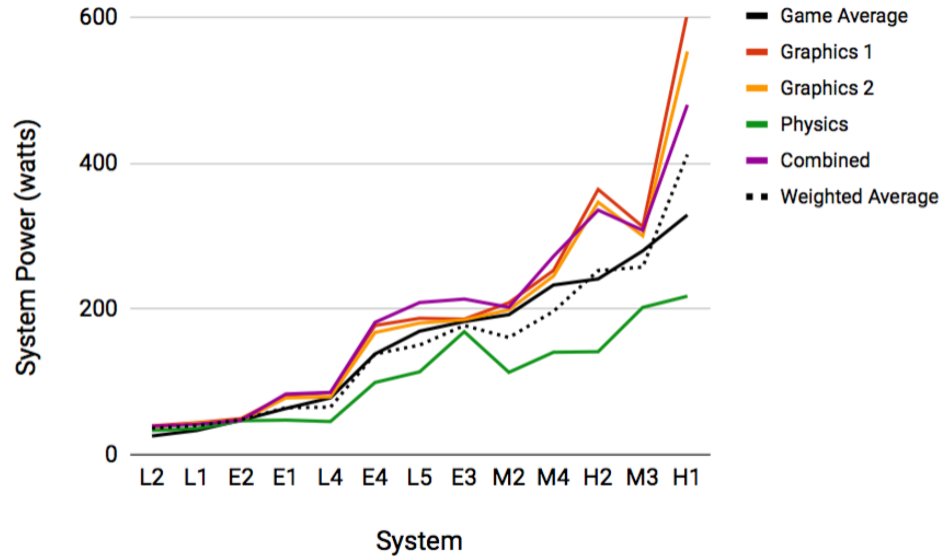
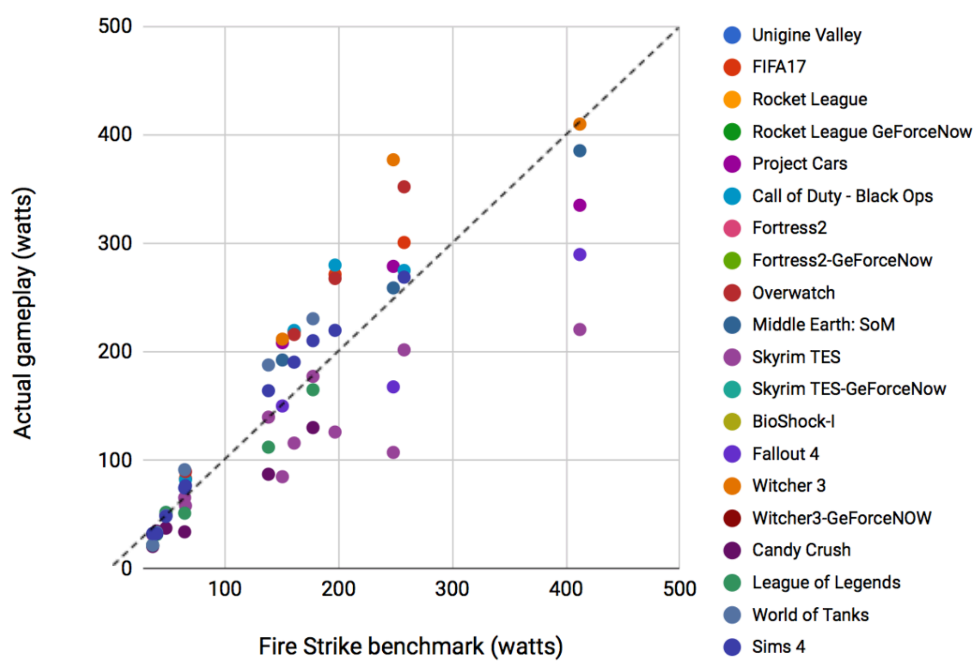


Figure 18.
Power under simulated benchmark is a reasonable proxy, although results under actual gameplay vary



Each "column" of values represents a given system with its weighted Fire Strike result and the associated game-specific results, e.g., the set to the far right represents system H1 with the five games tested on that platform. Includes Windows desktop and laptop PCs able to run Fire Strike.

We subsequently tested the full range of desktop and laptop computers as well as consoles and media-streaming devices (Figures 19a-d). 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.

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.

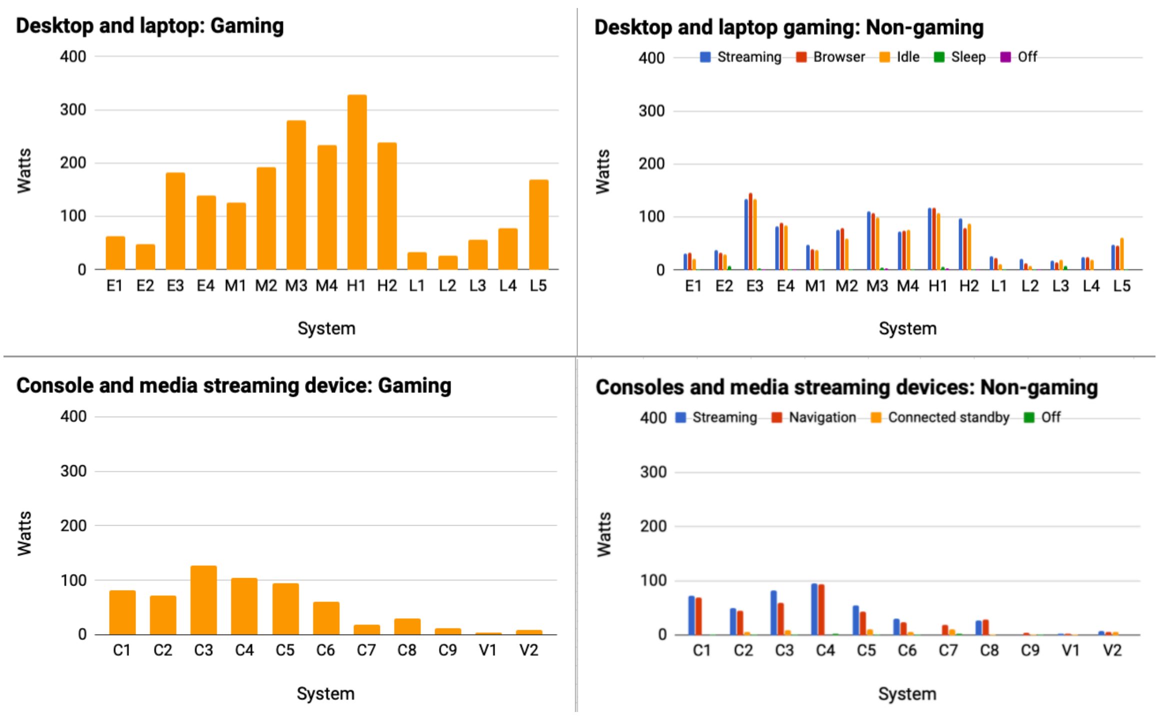
Among the more interesting gaming-mode observations are that the most powerful gaming laptop's power use was greater than or equal to most of the Entry-level desktop computers, while many of the consoles used as much or more power than all but the most high-performance laptop and Entry-level desktop.

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. For example, when in non-gaming modes, the Entry-level desktop E3 uses far more power than the two high-end Desktops: 10 to 20% more—depending on mode—compared to system H1 and 40 to 90% more compared to system H2. Reasons for this include poor systems integration, discussed further later in the report.

Idle[24] power also varies considerably in relation to more compute-intensive modes such as gaming. In some cases, idle power consumption is only slightly lower than that for browsing or streaming, and in many cases draws significantly more than half the power of gaming mode. These latter findings are presumably a reflection of power management strategies with varying levels of effectiveness. It can also be observed that 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. Non-gaming power among the High-End laptops is on a par with some of the Entry-level and Mid-range desktops.

[24] All "idle" mode tests for PCs notes in this report used the short-idle test.

Figure 19a-d.
Average system power during gameplay and non-gaming modes: 2016



Gameplay power levels are the average power measured across all games.

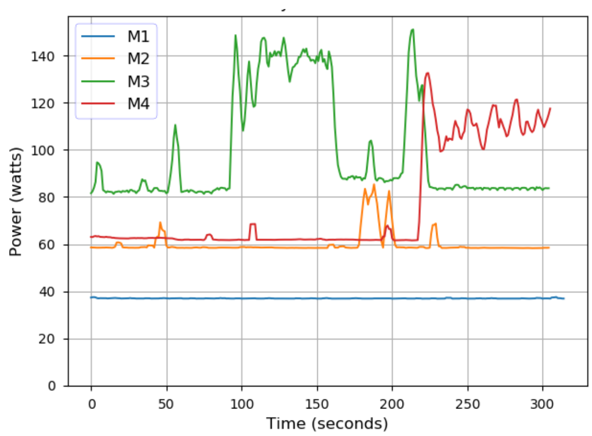
Media streaming devices consume notably less energy *on the client side* than all other products evaluated here. As a case-in-point, the Apple TV draws 0.8 watts of standby power, while the Nvidia Shield TV draws 5.7 watts. When reduced to standby, the Shield exhibited a reduction of only 0.2 watts, thus effectively operating in a 'Display Off' modality when set to nominal standby.[25] For comparison, idle power for most desktops is in the 60- to 100-watt range. PC sleep mode power (the closest equivalent mode to standby) is in the range of one to five watts.

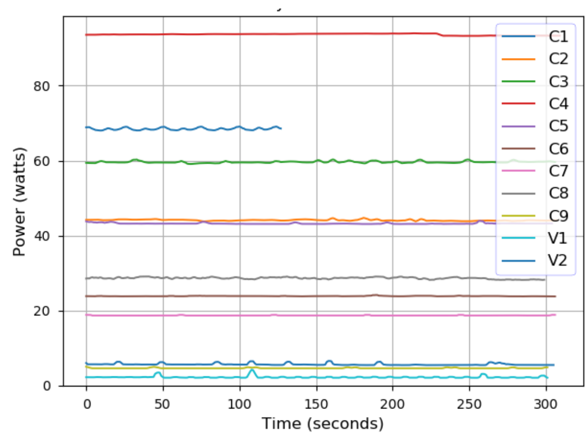
Our one-second data enabled us to closely examine variations in PC idle and console navigation mode power levels. For the consoles we observed the expected constant power levels but for the PCs we observed frequent increases, often of significant duration (Figures 20a-b). For each system we estimated the average increase in measured power due to these variations by calculating the difference between the mean and the lower tenth percentile power level (a proxy of base idle power). For PCs we believe these increases are due to OS operations such as updates and can be significant, with average increases in power ranging up to 33 watts with an average of 4 watts over all systems, corresponding to 55% and 9% of total energy use above the idle state. In the case of the

[25] The "off" button had been removed on the latest model (offering only "standby" and "restart" options). Interestingly, the Shield uses the Nvidia Tegra X1 System-on-Chip, which is also used in some mobile devices and the Nintendo Switch. These devices have the ability to turn off networking and other non-critical components to save power, suggesting that even more efficient operations are possible with the underlying technology.

“M-series” systems shown in Figure 20a, the fraction of energy use spent above the pure idle state ranged from 0% (system M1) to 23% (system M4). For consoles and media streaming devices the increases were very short and regular and do not significantly affect average power, with increases ranging up to 0.4 watts with an average of 0.2 watts over all systems. These results indicate the need to qualify and perhaps rethink the established idle mode test methods for PCs, which do not provide repeatable results and can significantly underestimate power requirements in real-world conditions. There are a few cases where the expected “flat-line” power profile is exhibited, suggesting that avoidance of these increases and their associated energy use is possible in practice.

Figure 20a-b.
Substantial deviations from idle power on Mid-range PCs (left); stable navigation power on consoles and media streaming devices (right)



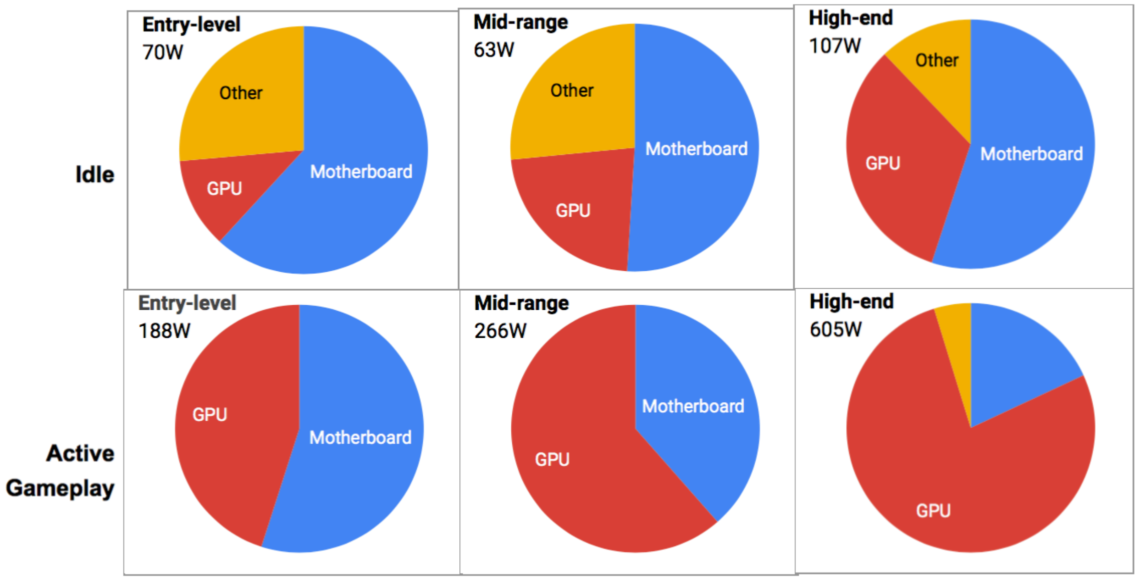


Nameplate Versus Measured Power Requirements

Nameplate ratings are important insofar as DIY gamers use them to size power supply units, and energy analysts may erroneously use them to estimate energy use in lieu of measured values.

As the first step in this process, we performed direct measurements of GPU and CPU/motherboard component power for a cross-section of our base systems. As seen in Figure 21, 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% (System E3) to 77% (System H1) in gaming mode, and is surprisingly significant in idle mode as well (12 to 33%).

Figure 21.
Measured gaming desktop component loads: The role of components varies significantly depending on duty cycle and product tier



Average power during 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. As described in Figure 20, system E3 exhibited considerable power draw during idle mode for extraneous activities.

Unfortunately, data such as these are rarely available to gamers. In fact, the nameplate values typically relied upon are based on thermal design point (TDP), which is a thermal rather than electrical metric of power. TDPs for the specific components we measured varied from the measured values. While TDPs are not in fact an electrical measurement, they are the only "nameplate" information remotely accessible to gamers. As seen in Table 5, nameplate and measured values tend not to be in close agreement. Measured maximum values do not agree well with nameplate, varying from 63 to 113% of actual for GPUs and 45 to 76% of actual values for CPUs for the units we measured. Nameplate values tend to run higher than measured values, although we observed the reverse in some cases. Manufacturers do not publish nameplate ratings for motherboards, although we have observed undocumented third-party ratings in the 70 to 100-watt range.[26]

Manufacturers have brought to market external graphics-card docks for boosting laptop gaming capability. Tests of the Razer Blade Stealth with a GTX970 GPU on L2 resulted in a four-fold increase (by 102 watts) in laptop power in gaming mode while a similar product (Alienware) with the same GPU on the system L4 more than doubled gaming power (by 110 watts).

[26] See PCPartpicker.com

Table 5. Measured maximum and nameplate values vary significantly for many components.

	System	E3 Base	E3 EE	M4 Base	M4 EE	H1 Base	H1 EE
	ID	Radeon R7 360	Radeon RX Vega 56	GTX 970	GTX 1070	ASUS R9 Fury (2)	AMD RX Vega 64
GPU	Nameplate (TDP)	100	210	148	150	550	295
	Max Measured	87	236	168	94	515	227
	Ratio	0.87	1.12	1.13	0.63	0.94	0.77
	ID	AMD FX-6300	AMD FX-8350	Core i7-4790K		Core i7-5820K	
CPU	Nameplate (TDP)	95	125	88		140	
	Max Measured	N/A	N/A	67	N/A	63	65
	Ratio			0.76		0.45	0.46
	ID	MSI 970 Gaming		Fatal1ty Gaming Z97X Killer		EVGA X99 Classified	
Motherboard	Nameplate	unknown	unknown	unknown	unknown	unknown	unknown
	Max Measured	121	110	105	87	118	90
	Ratio	unknown	unknown	unknown	unknown	unknown	unknown

Note: GPU and Motherboard power is measured, CPU power is reported by the system (and not all CPUs report power). Systems followed by "EE" indicate the energy-efficiency configuration.

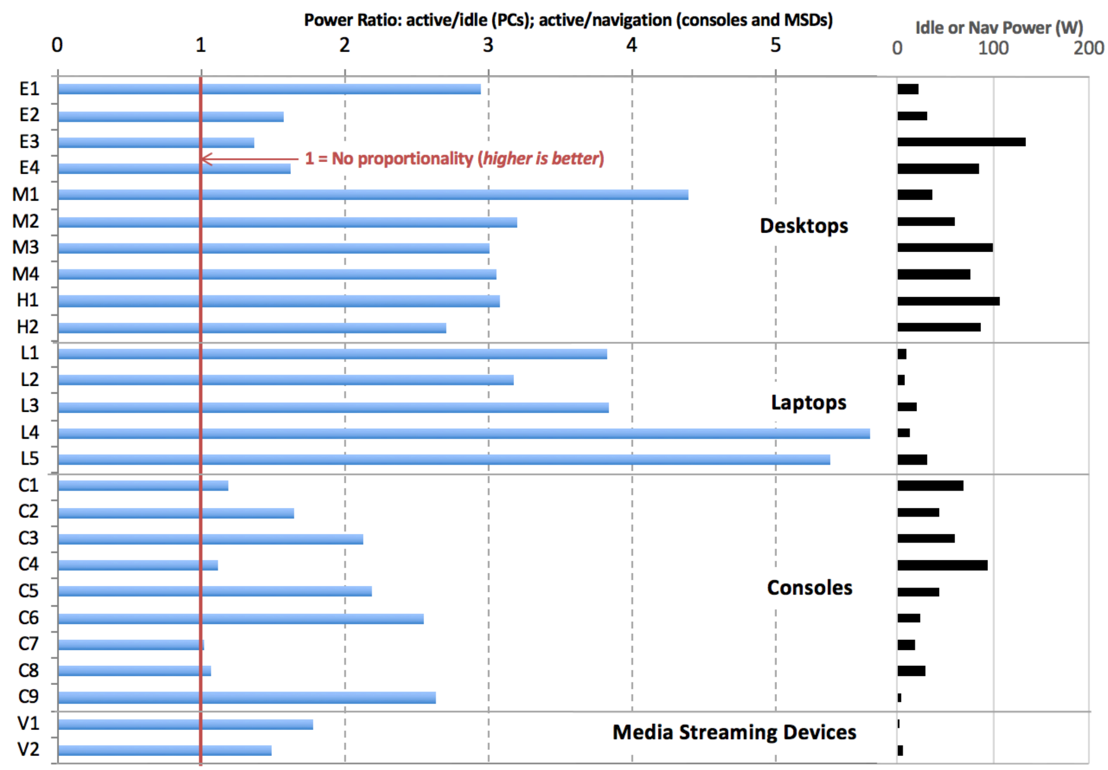
Power Management

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 consumption in keeping with these varying workloads.

While not in itself a measure of power efficiency, the concept of "energy proportionality" has been used to signify the degree to which energy use scales with the workload in computing equipment (Nordman 2005; Barroso and Hölzle 2007). The degree to which this factor has been considered in the design of our test systems clearly varies. Their relative efficacy in this regard can be characterized by the ratio of gaming to idle power use in the case of PCs or navigation mode in the case of consoles and media-streaming devices. Figure 22 compares energy proportionality for the systems. The higher the value the better the device is at scaling energy use in response to workload. Ratios of 1:1 indicate no proportionality. 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. Moreover, consoles entail certain workloads while in Navigation mode and spend very little time in that mode.

We found some of the systems to perform barely better than a 1:1 ratio, with the best desktop PCs operating in the range of 4:1, laptops 5:1, consoles 2.5:1, and media streaming devices 1.5:1. For the E3 desktop system, a poor ratio corresponded to idle power of 134 watts (the highest among systems we tested), which is a significant amount of power given no workload.

Figure 22.
Energy proportionality of baseline gaming devices: Some systems use nearly as much energy in non-gaming mode as while gaming



The metric shown here is the ratio of gaming power under gameplay to idle power (PCs) or navigation power (consoles). Laptop values taken with top closed, while attached to external display. Gaming power levels are the average power measured across all games. PCs and consoles should be assessed independently, as some workloads are undertaken when consoles are in Navigation mode.

The question remains as to where and to what degree within these systems power is used and scaled to follow workload. As noted in the preceding section, we measured three motherboard-CPU assemblies (one each from Entry-level, Mid-range, and High-end systems). Gaming power ranged from 83 to 120 watts while idle power ranged from 27 to 59 watts. Gaming-to-idle power ratios ranged from 2.0 to 3.1. The corresponding ratios for GPUs, ranged from 10.3 to 18.2, indicating that motherboard-CPU configurations do not scale nearly as well as GPUs, likely because many more functions of idle mode must still be handled by the motherboard.

Of note, the three major consoles manufacturers have now implemented automatic power-down features.

Effect of Display Choice on Power Requirements

While an independent component in all but the laptops, we view the display as integral to the gaming system, as without it there is no user experience. The choice of display affects power use in two distinct ways: the first being that of the display itself, and the second being the effect the display characteristics have on the workload presented to the gaming system. Size and resolution are the two primary characteristics that affect display power use, and resolution and refresh rate are the two primary characteristics that affect system power. Displays for gaming can be categorized in three ways: Conventional two-dimensional (2D) monitors are used for PCs, TVs for consoles, and virtual reality headsets (also known as Head Mounted Displays, or HMD) for both PCs and consoles (Mills *et al.,* 2017).

Two-dimensional monitors for computer gaming

Gamers seek monitors with higher refresh rates (up to 240Hz compared to mainstream values of 60Hz), and faster pixel response times (15ms down to 1ms) than those used for conventional computer tasks. Some games offer a setting called VSync, which locks the graphics processing rate to the monitor's refresh rate. This can create "smearing" or "tearing" effects in the image. G-Sync and FreeSync are proprietary systems that enable monitors to adapt their refresh rate to follow the game's rate.[27]

One metric of 2D monitor energy performance is the ratio of peak power requirement (in "on" mode) to corresponding pixel count. For reference, measured power consumption varied between 15 watts and 77 watts across a sampling of 1080p gaming monitors found in the market between 2014 and 2016, with a factor-of-two variation within the constraints of a given monitor size and resolution (Mills *et al.,* 2017).

Among gaming-related energy intensive trends is the transition in resolution from VGA/SVGA to HD/1080p, to 4K monitors (2160p), as well as the use of multiple monitors in tandem. Monitors can also be overclocked to increase their refresh rates.[28] Our measurements for five games and the Fire Strike frame-rate benchmark found that while frame rates decline when switching from 1080p to 4k resolution, PC system power requirements typically rise (in systems that can handle the added processing load), sometimes very significantly (up to 64% in our testing), resulting in a significant reduction in efficiency expressed in terms of fps/W, which in this case users choose to trade off against higher pixel densities (Figures 23a-c). Measurements of PlayStation4 Pro consoles exhibited, i.e., 10% higher power use in Navigation mode, 32% Blu ray, 51% in streaming; gaming mode not specified (Microsoft, Nintendo, and Sony Interactive Entertainment 2017).

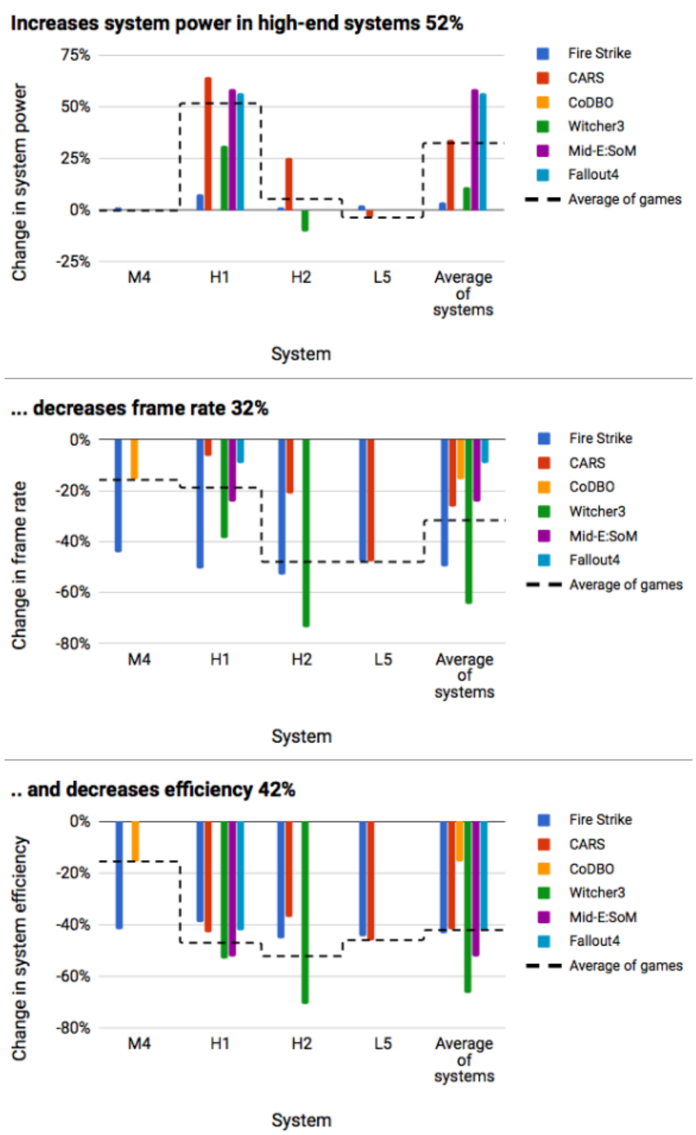
While power use by displays is driven primarily by size and resolution, other factors such as color gamut, response rate, display frequency, technology, and features have additional effects. Survey results published by Urban *et al.,* (2017) put the average computer monitor at just under 22 inches. Gamers tend to prefer larger and higher-resolution monitors (1080p or higher) than conventional computer users.

[27] See https://www.tomsguide.com/us/refresh-rates-vs-response-times,news-24345.html

[28] See http://www.pcgamer.com/how-to-overclock-your-monitor-to-a-higher-refresh-rate/

We standardized on a 24” 1080p-resolution, 60 Hz refresh rate monitor for our baseline gaming system tests (Dell U2417H). This monitor is representative of the most popular display size and resolution among gamers (Mills *et al.,* 2017). We conducted extensive testing on various other gaming-grade monitors to estimate the effect of changes in resolution and other characteristics, but we relied on previously published data on display power to estimate the energy use impacts (see Table 6). Monitor power was estimated using weighted combinations of Energy Star criteria from V5, V6, and V7. TV power was estimated using curves from Urban *et al.,* (2017) for existing stock and Energy Star V8 criteria for future. Efficient display power was estimated using the top 10% from the 2018 Energy Star list of certified monitors and TVs.

Figure 23a-c.
Conversion from HD (1080p) displays to 4k displays increases PC system power (a), lowers framerate (b), and reduces efficiency (c)



Tests include one frame-rate benchmark (Fire Strike) and five games. Not all games were played on all systems. Efficiency defined here as fps/W. Values do not include display energy.

Table 6. Average display power by year

Year	*2011*	*2016*	*2021*	
Resolution	HD (1080p)	HD (1080p)	HD (1080p)	4k (2160p)
Monitor power (watts)	34	25	17	29
TV size (inches)	37	43	46	46
TV power (watts)	134	94	45	68

Some gamers employ multiple displays and the net effect is that GPUs must drive many more pixels than was the case just a decade ago. Our market research indicated that this occurs 15% of the time on High-end desktops, 2% time on Mid-range desktops, and less than 1% of the time on other platforms. The preference is for odd numbers of displays in order to avoid a centered bezel, the most common occurrence of which is three displays, although five or even more are used by Extreme gamers. For our energy analysis we assumed that the use of multiple displays increased display energy use by 5% in aggregate over a single display.

Laptops can be used either with their native displays and/or with an external display and gamers often connect their laptops to external displays. Some laptops, e.g., L5, have native 4k and can actually use more power than when connected to a lower-resolution external display. For our energy analysis we assumed that external displays were used for gaming on laptops 50% of the time.

Numerous advanced monitor and television technologies and control software have emerged. The wide-ranging energy use and efficiency opportunities have been well-documented elsewhere (Park *et al.,* 2011; Howard *et al.,* 2012), although rarely in the context of gaming applications. The dramatic technology transitions that have occurred in displays (e.g., CRT to LCD), resulting in significant energy benefits, have been driven more by the desirable form factors and image quality than by energy savings.

Televisions for console gaming

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.[29] This is substantially more than the device-specific gaming-mode power use of most of the consoles we tested. Among 55” 4k displays, measured on-mode power use varies from 60 to almost 170 watts, and, among

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

the simpler measures, automatic brightness control can reduce on-mode power requirements from 10-50% (NRDC 2015).

Virtual reality for PC and console gaming

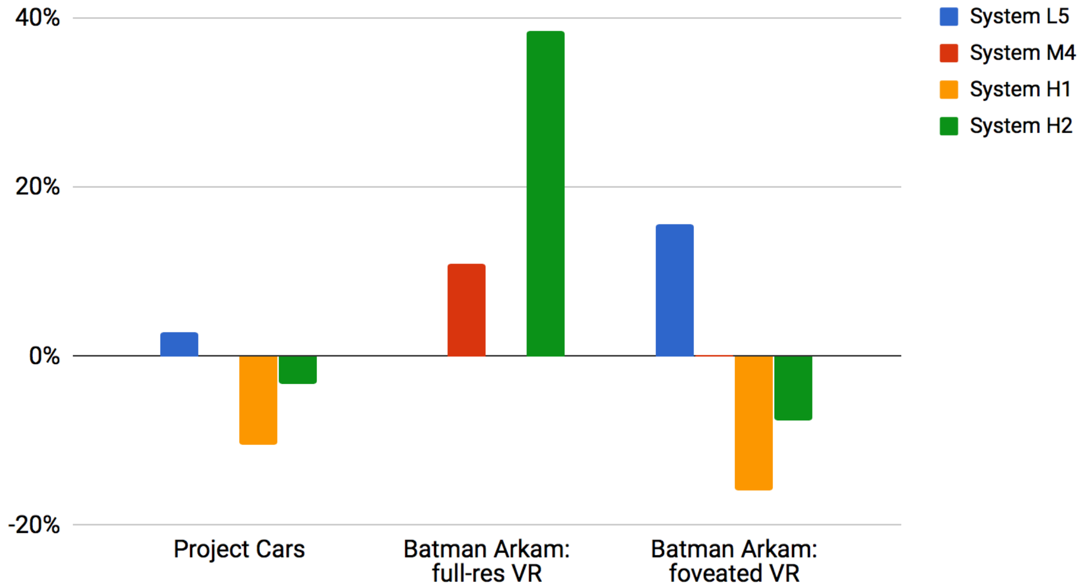
Virtual reality (VR) is gaining considerable interest among gamers, with several manufacturers bringing products to the market for gaming computers and consoles. Initial consideration suggests an intrinsic potential energy savings, due to the smaller active display area which is rendered to the full 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. Thus, system-level energy use is likely to be higher with VR.

We have produced the first publicly available measured data on gaming computer and console energy use under VR. Figure 24 shows gaming power over a scripted gaming session for two VR games—Project Cars and Batman Arkham VR— on two popular VR technologies: Oculus Rift and HTC Vive, as played on our three desktop and one laptop systems. In the case of Batman Arkham VR, the VR system was run under full-resolution and foveated-rendering modes. The variations in PC energy use between viewing gameplay on 2D displays and VR headsets are notable. The direction of change varies, ranging from an increase of 38% (93W, System H2 running Batman Arkham VR) to a reduction of about 15% (52 watts, System H1 running Batman Arkham VR with foveated-rendering mode).[30] Averaged across all the systems, power in gaming mode was 22% (53 watts) higher for Batman Arkham VR with full-resolution. When foveated rendering is activated, power drops by 5% (9 watts) compared to the 2D display. Average power for Project Cars is 5% (13 watts) lower in VR, display mode, likely due to the fixed foveated-rendering which is always on.

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

[30] Foveated rendering is the process of gradually reducing the precision of rendering along a gradient from the center of view to the periphery of view, as the eye's Fovea is most sensitive in the central area. See https://www.tomshardware.com/news/oculus-fixed-foveated-rendering-technology,36781.html

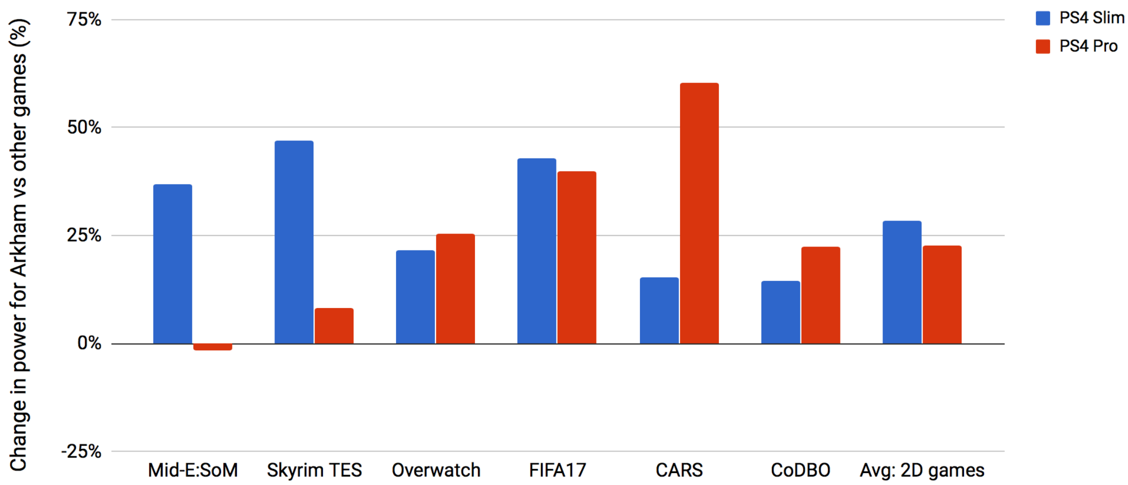
Figure 24.
PC Gaming power changes when shifting from 2D to foveated and full-resolution virtual reality



Project CARS appears to be using Foveated Rendering, hence the different pattern of energy use. Missing bars signify that system was not tested.

Virtual reality is also available for the PlayStation consoles. Energy use for the Batman Arkham VR title under 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. Instead, Figure 25 simply displays the difference in power for PlayStation Batman Arkham VR to that of a variety of popular 2D games on the PlayStation. These values are 32% and 22% above the average baseline gaming-mode measurements we made on six other PS4 games. Foveated rendering appears to be embedded in the Playstation VR system, but with no user control or settings. At 95 watts and 155 watts in gaming mode, for PS4 Slim and PS4 Pro respectively, absolute power use under console VR use is lower than that of the PC VR cases we measured (170 to 337 watts). Batman Arkham VR varied from 190 to 337 watts depending on system and headset technology.

Figure 25.
Console gaming power is higher for Batman Arkham VR vs other 2D games



Headsets are powered through the console, so their consumption is included here.

Behavioral Determinants of Energy Use

Gamers heavily influence the ultimate energy use of a gaming system through their usage choices. These include the time spent in the various tiers of the duty cycle (from "off" to time spent in gameplay), overriding manufacturer settings for factors such as processor speed and in-game settings, allocation of their time across game titles, quality settings within a given game, and the style/intensity of gameplay. Our testing has made it possible to quantify the effects of each category of these choices.

Duty cycle

Each of our four categories of gamer (Light, Moderate, Intensive, and Extreme) spends varying amounts of time in various stages of the duty cycle. These are further differentiated by type of platform and summarized previously in Figures 4, 5, 7, and 19. The translation of these duty cycles in to annual energy use is further described below.

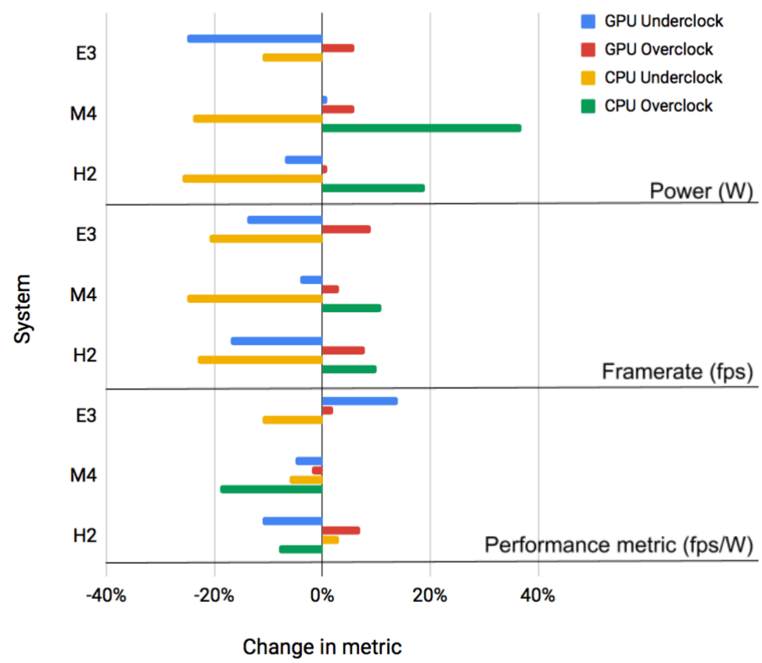
Over/under-clocking

We conducted exploratory tests to determine the effect of over-clocking the GPU and underclocking the CPU using Fire Strike "Stress" test for GPUs and "Physics" test for CPUs. The results are shown in Figure 26. GPU underclocking had a greater effect on system power than overclocking (range -25% to +6%), while CPUs responded strongly in both directions (-26% to +37%).

GPU underclocking had a greater effect on power and frame rate than overclocking, while CPU's responded strongly in both directions. Power use tended to change more rapidly than performance, resulting in declining efficiency metrics (fps/W) in most cases.

Underclocking can serve as a legitimate energy-savings measure, particularly in cases where changes in framerate are not particularly noticeable to the gamer.

Figure 26.
Over- and under-clocking significantly influences system power and frame rate



Clock-speed changes (E3/M4/H2, in %): GPU underclocking (-20/-8/-28), GPU overclocking (14/20/14), CPU underclocking (-20/-20/-19), CPU overclocking (17/18/19). We limited overclocking to 20% or the maximum value the interface would allow, if lower. We limited underclocking to maintain stability.

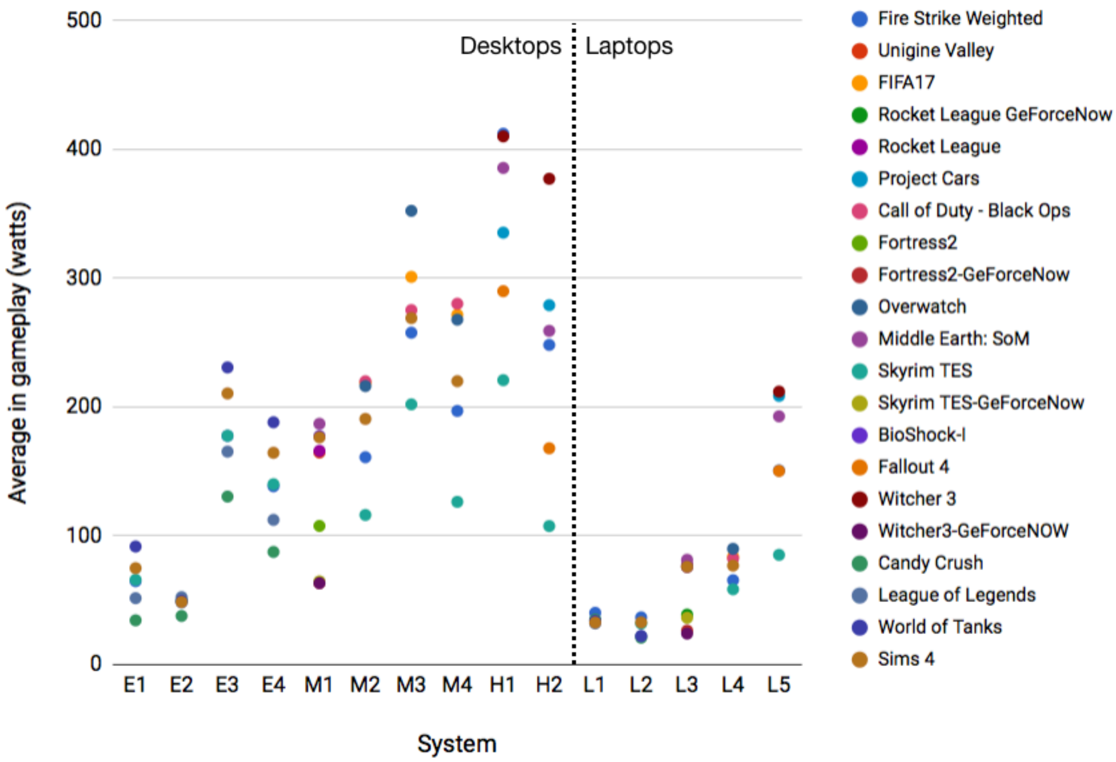
Game choice

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 remained largely unquantified. Our database of test results allows for investigation of this question for PCs, consoles, and media streaming devices. We measured gaming power while running 37 games on selected systems (none can be run on all platforms) and 11 frame-rate benchmarks. Table 4 identifies which games and benchmarks were paired with which platforms in our testing.

As noted above, given constant centralized version updates on the Windows PC games, a test at one time with a particular game will not necessarily be replicable in the future if the game is automatically updated by a centralized service such as Steam or Blizzard.

We conducted tests of 19 popular game titles across our 16 base PC systems (further described in Bourassa *et al.*, 2018a). The range of average desktop power requirements during gameplay across game titles was 21 to 410 watts (and was 21 to 212 watts for laptops and 34 to 410 watts for desktops) (Figure 27). Within many 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. The relative rankings of the results varied across machines, making it hard to generalize about the energy intensity of any particular game. The choice of software clearly has significant implications for energy use

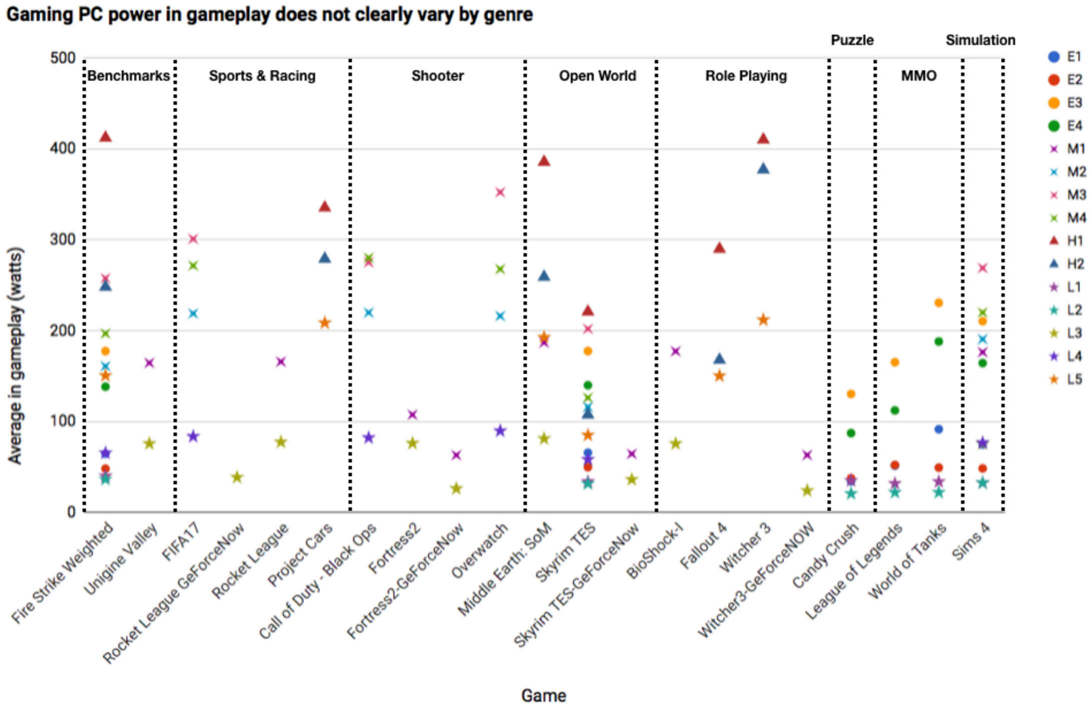
Figure 27.
Gaming PC power in gameplay varies widely by system type and game: 19 popular games and 2 frame-rate benchmarks



Not all systems are able to play all games.

Somewhat surprisingly, among the PC game titles we tested, energy use does not correlate with game genre (Figure 28). 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 (e.g., compared to Skyrim TES and League of Legends). Some systems (particularly H2) exhibited far less variance in energy use by game, both in absolute and relative terms.

Figure 28.
PC power in gameplay often does not vary by genre: 19 popular games

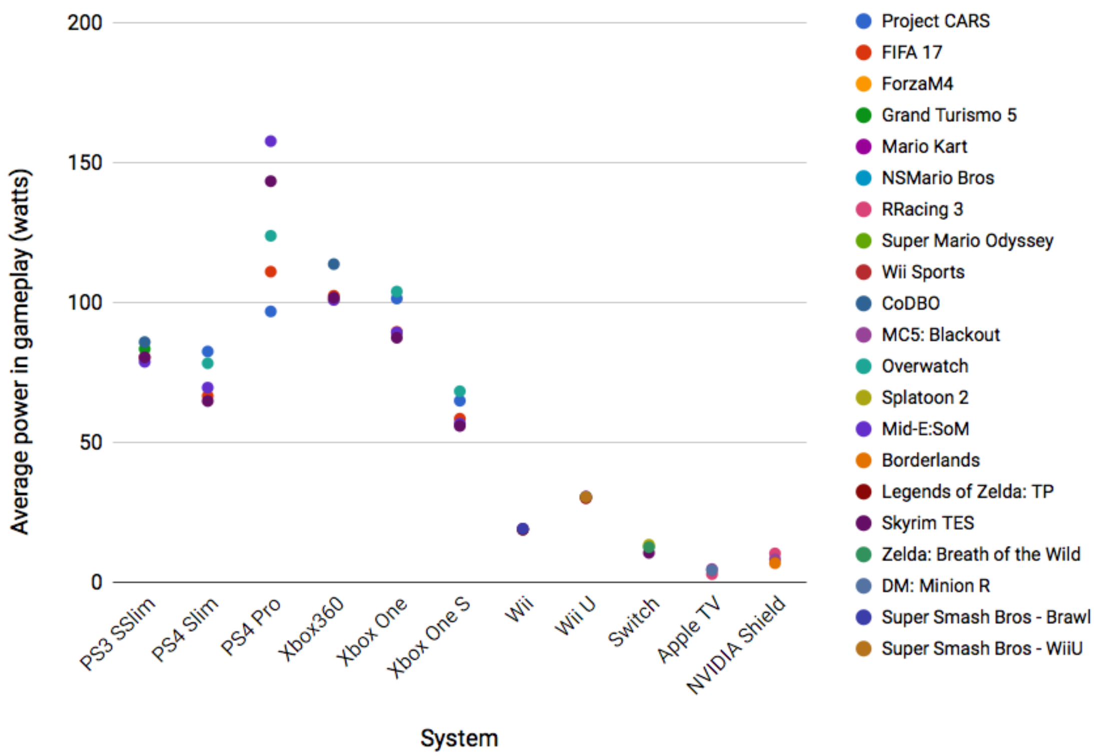


Not all systems are able to play all games. The Fire Strike frame-rate benchmark is included for reference.

Here, we evaluated 9 consoles and 2 media streaming devices across 21 popular games. We find qualitatively similar outcomes to those for PCs, although with largely lower absolute power levels. The range of average power requirements during gameplay across console game titles was 3 to 158 watts (Figure 29).

The PS4 Pro drew the greatest amount of power (97 to 158 watts). A downward trend in power during gameplay was observed when comparing successive console generations, consistent with previous Figure 9. 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.

Figure 29.
Console and media streaming device power in gameplay varies widely by system type and game: 21 popular games

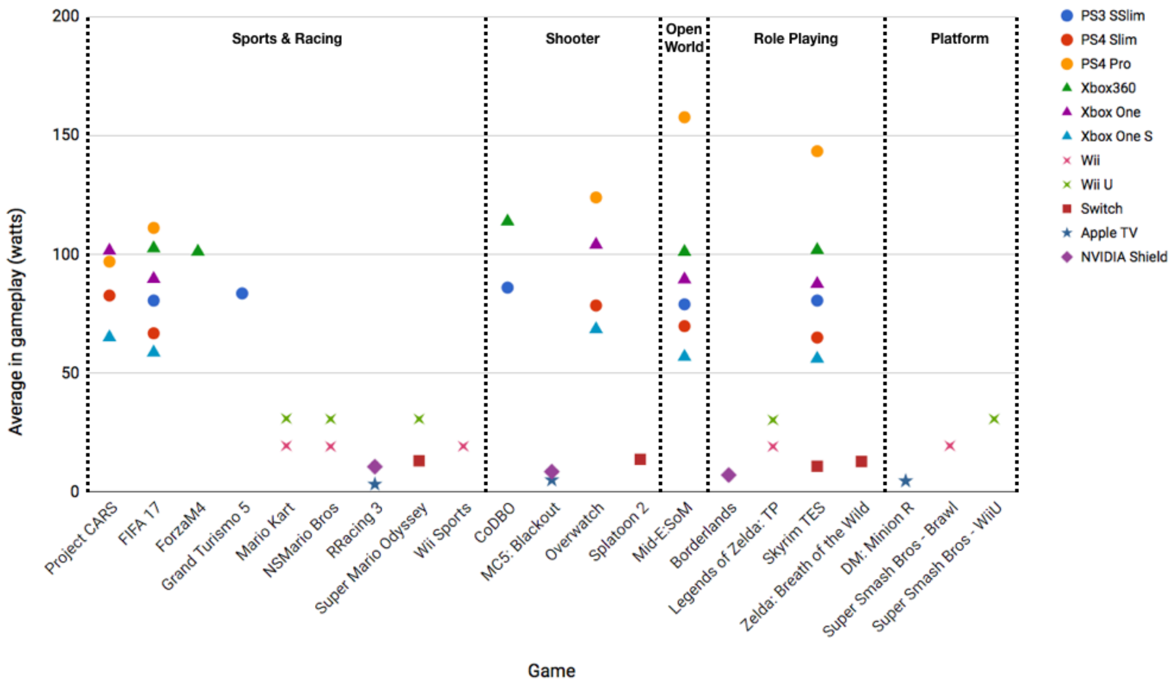


Not all systems are able to play all games. The Fire Strike frame-rate benchmark is included for reference.

With one exception, the relative spread of results across games for a given system was far less than for the PCs, i.e., a factor of approximately 1.25 in many cases. The PS4 Pro exhibited the greatest absolute and relative variance in gaming power across games, from 97 to 156 watts, a factor of 1.6. As observed for PCs, among the console and media-streaming-device game titles we tested, energy use does not track with game genre (Figure 30). The Nintendo systems exhibited far less variance in energy use by game, both in absolute and relative terms.

As was the case for PCs, the results for particular games varied widely across machines, making it hard to generalize about the energy intensity of any particular game.

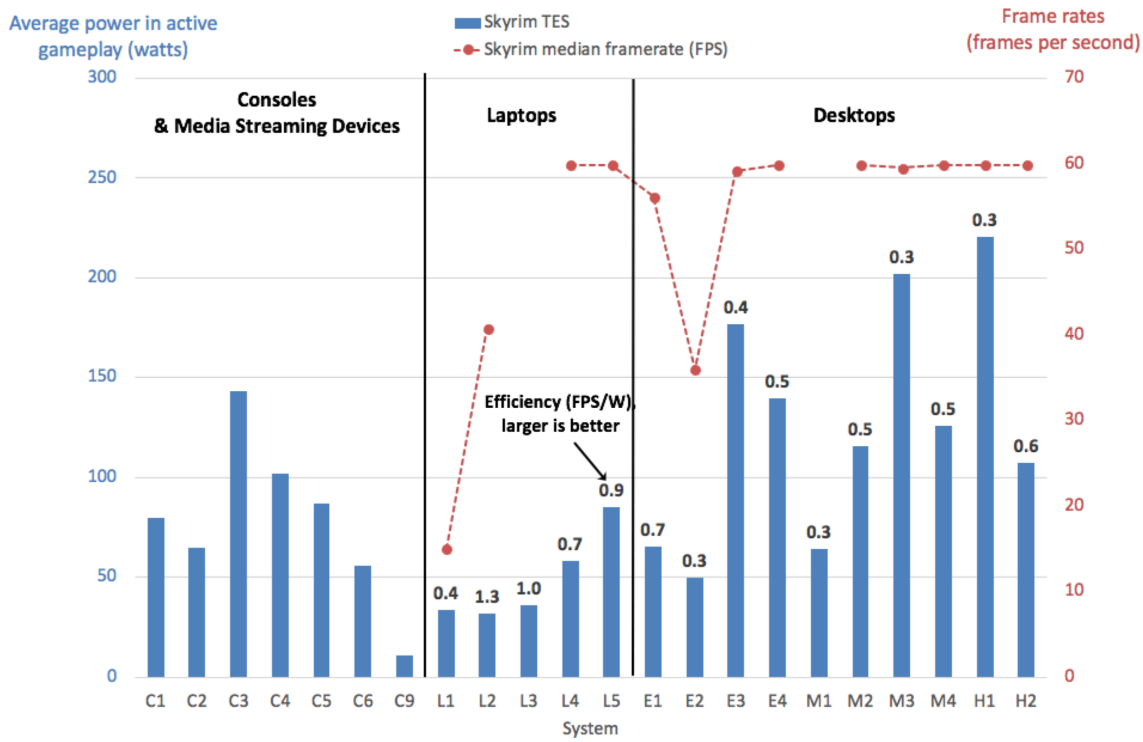
Figure 30.
Console and media streaming device power in gameplay does not vary by genre: 21 popular games



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

To provide a more in-depth view of how power for a given game varies across PCs and consoles, we evaluated power use for Skyrim across the 22 of our 26 systems with which it is compatible (Figure 31). 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 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). We 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 31.
Gaming power for Skyrim TES varies 21-fold (from 11-221 watts)



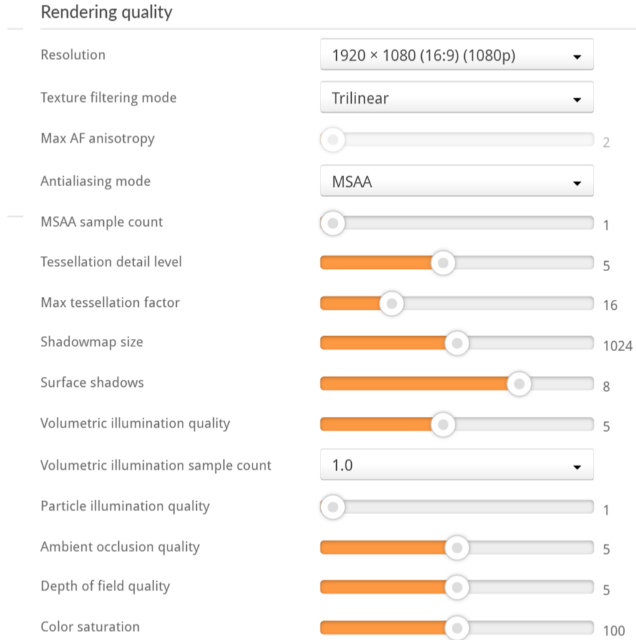
Note that Skyrim is one of the least energy-intensive games evaluated in our testing, but is available over the broadest variety of systems and hence appropriate for the analysis depicted here and the gameplay "route" (Helgen Keep) is very highly constrained and replicable. Skyrim is generally capped at 60 fps, but laptops L1 and L2 and desktop E2 experienced bottlenecks that resulted in lower frame rates.

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 our highest-performing system, yet under Skyrim TES uses less energy than many of the lesser desktop systems and less than the PlayStation PS4 Pro.

Graphics settings & in-game "Mods"

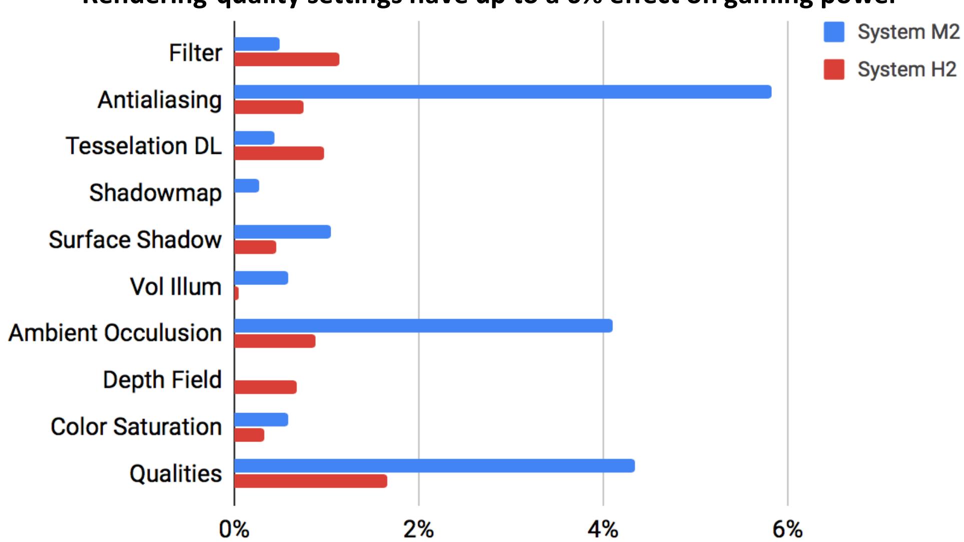
Gamers can control a myriad of games' visual characteristics. Examples include resolution, depth of field, quality of reflections, depth and continuity of shadows, particle rendering, smoothness of edges (known as 'antialiasing', the degree to which complex shapes are broken up into smaller and smaller polygons (known as 'tessillation'), and much more. Figure 32 provides a granular view of the types of attributes a gamer can control, in this case as applies to the Fire Strike simulated frame-rate benchmark.

Figure 32.
Rendering quality settings for the Fire Strike simulated frame-rate benchmarks



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. We examined the effect of multiple in-game settings for the M2 and H2 systems. The range of effects shown in Figure 33 are applied individually and are not simply additive; energy impacts would likely be greater when applied in combination.

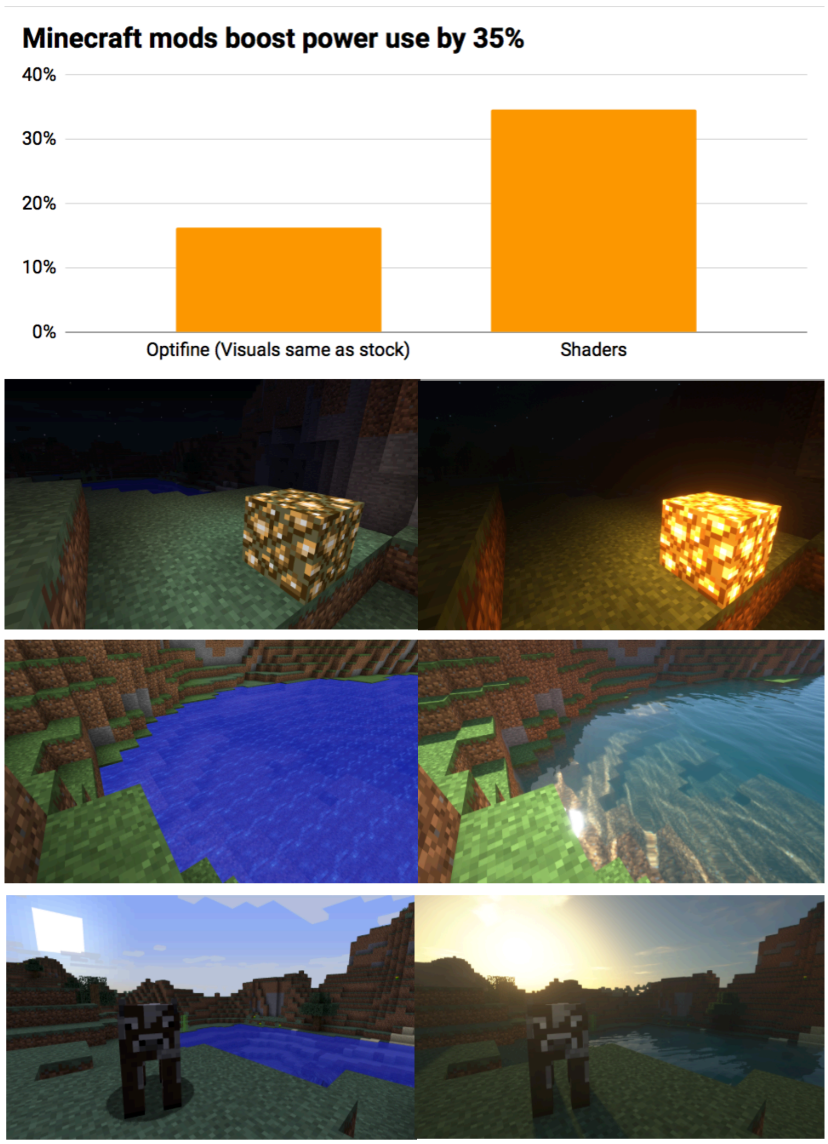
Figure 33.
Rendering-quality settings have up to a 6% effect on gaming power



Examples for the M2 and H2 systems with Fire Strike frame-rate benchmark. The full limits of these settings may not have been tested, particularly in the case of "Qualities". Moreover, frame rates varied far more than power for Antialiasing (32%) and Qualities (50%).

Games often support unique "Mods" installed by the user to enhance the gaming experience. The energy effects of these settings have not previously been described. We examined a series of mods for Minecraft and discovered significant impacts on gaming power requirements (Figure 34).[31] In particular, the Optifine mod (which increases framerate but has no other visual impact) increased base power by 31 watts (a 16% increase). Adding shaders (which dramatically enhance illumination quality, shadows, and other details) increased power by 65 watts (a 35% increase from the base settings).

Figure 34.
Effect of Minecraft "Mods" on power levels during gameplay



Electricity measurements made with Watts-Up ES Pro, measured using Vernier Logger Lite. Note differences in cube illumination pattern, water surface and transparency, and cow shadow and sky realism. Base value 187 watts; Optifine 218 watts; "SEUS Renewed 1.0.0" shader 252 watts.

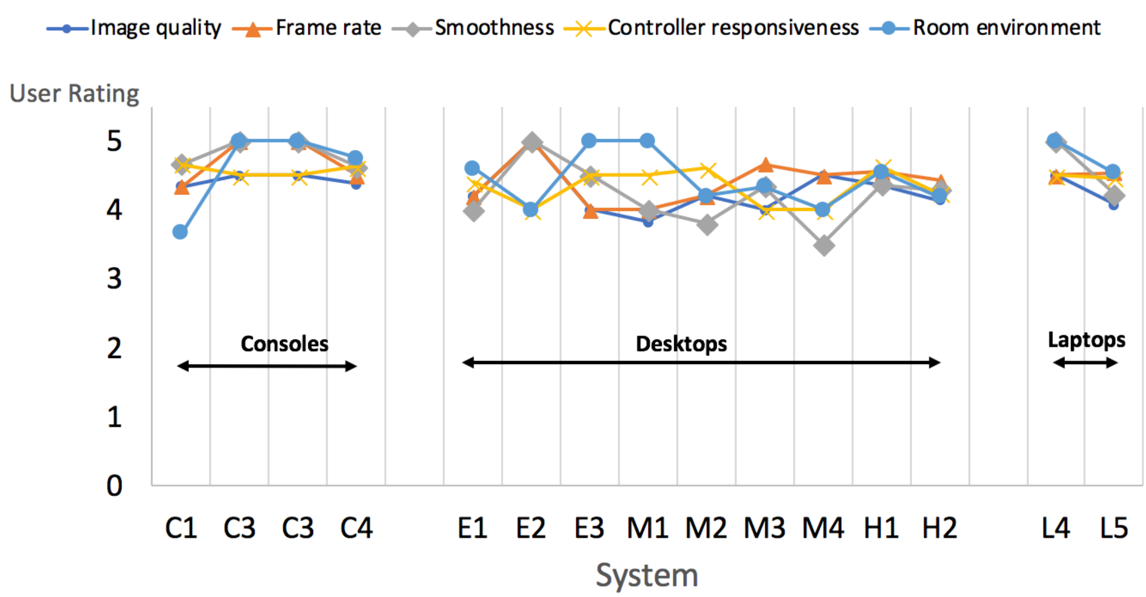
[31] These were implemented on the energy-efficient PC described in Mills and Mills (2015), and measured using a Kill-a-Watt meter rather than the Chroma used for other measurements in this study.

Variations in gameplay power requirements among actual gamers

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

We assessed the potential real-world variance around our lab-based measurement results by engaging real-world gamers in unscripted gameplay. Testers were drawn from Lawrence Berkeley National Laboratory employees who responded to a Lab-wide request for volunteers and who were established gamers. Sessions involving 22 testers ran from 15 to 45 minutes with energy use data collected using the same equipment and methods used in our formal analysis. 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. In all, a total of 87 tests were completed. Most testers participated in multiple sessions, playing those games that they had experience with. Testers then self-reported their user experience by providing scores for image quality, speed of framerate, quality/stutter of graphics and animation, quality/responsiveness of controller responsiveness, and annoyance related to noise and heat emanating from the gaming equipment. Remarkably, no particular correlation emerges between user experience and system type or nominal performance level (Figure 35).

Figure 35. Gamer experience shows no obvious correlation to system type or quality tier



The User Experience Survey asked testers to rate those user experience features on a scale of 1-5, with 1 = lowest quality and 5= highest quality (Bourassa et al., 2018b). Results reflect 87 trials across 22 gamers during 2018.

Average power during gameplay was highly similar to the Fire Strike frame-rate benchmark and human-gameplay measurements during our scripted lab-bench trials (Figure 14, above). As expected, energy use per user varied around these averages for a given hardware-game combination. Average results for given system-game combinations for PCs were on a par at 2.5% lower (4 watts) with our average bench tests and 1.7% lower (1 watt on average) for consoles. These discrepancies are within the measurement error of our testing process.

These results give us 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.

Annual Energy Use of Individual Gaming Systems

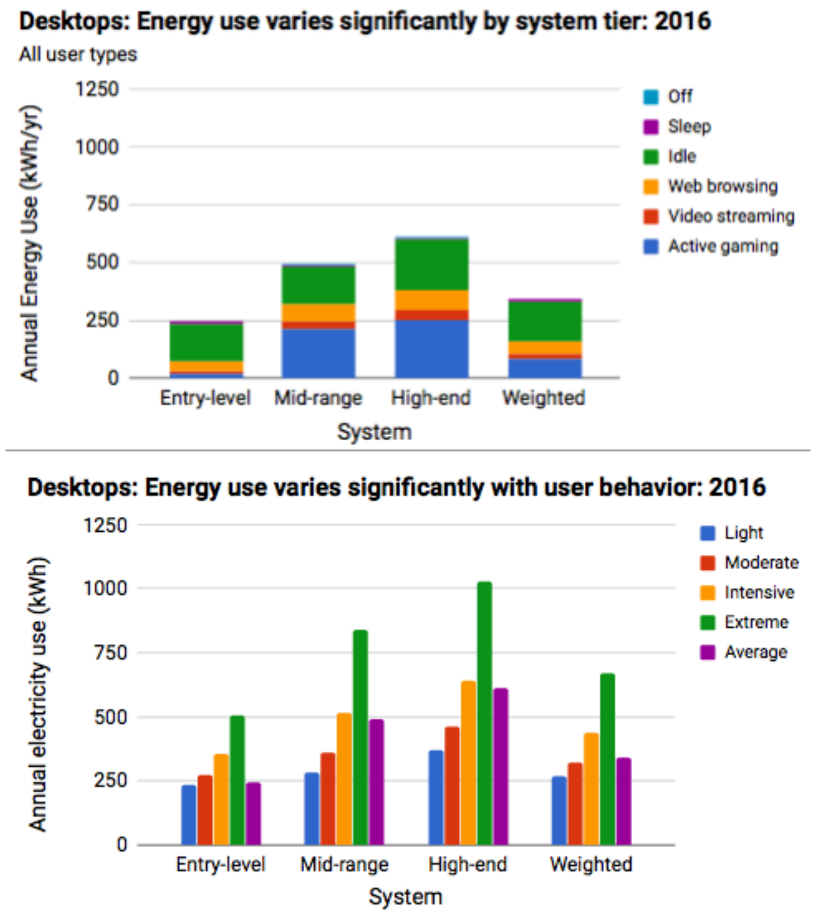
The preceding assessments of power requirements by mode together with the duty cycles and other behavioral factors can be integrated in order to estimate annual energy use for gaming. The results represent an enormous envelope of unit energy consumption, driven by many technological as well as behavioral variables (Figures 36 to 38). As with the power consumption data provided in preceding sections, here we continue to focus on client-side energy (no network or data center consumption), and exclude peripheral uses such as displays, local networking equipment, and external audio.

In many cases we found that energy use during gameplay is on the order of 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%. 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.

For desktops, absolute and relative energy use across the duty cycle varied substantially (Figure 36a), with particularly low relative active gameplay energy among the Entry-level systems. Total annual energy use varied by 3-fold (248 to 648 kWh/year) across the three broad categories of systems and their stock-weighted average duty cycle (and much more across individual systems comprising these tiers). The highest use was by system H1, with client-side electricity use of 1,237 kWh/year for the Extreme user type. These values exclude connected devices such as displays associated network or data center energy.

Behavioral factors also strongly influence outcomes (which vary approximately five-fold), as indicated in Figure 36b. Variations are even high within product tiers (which group together similar products). 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.

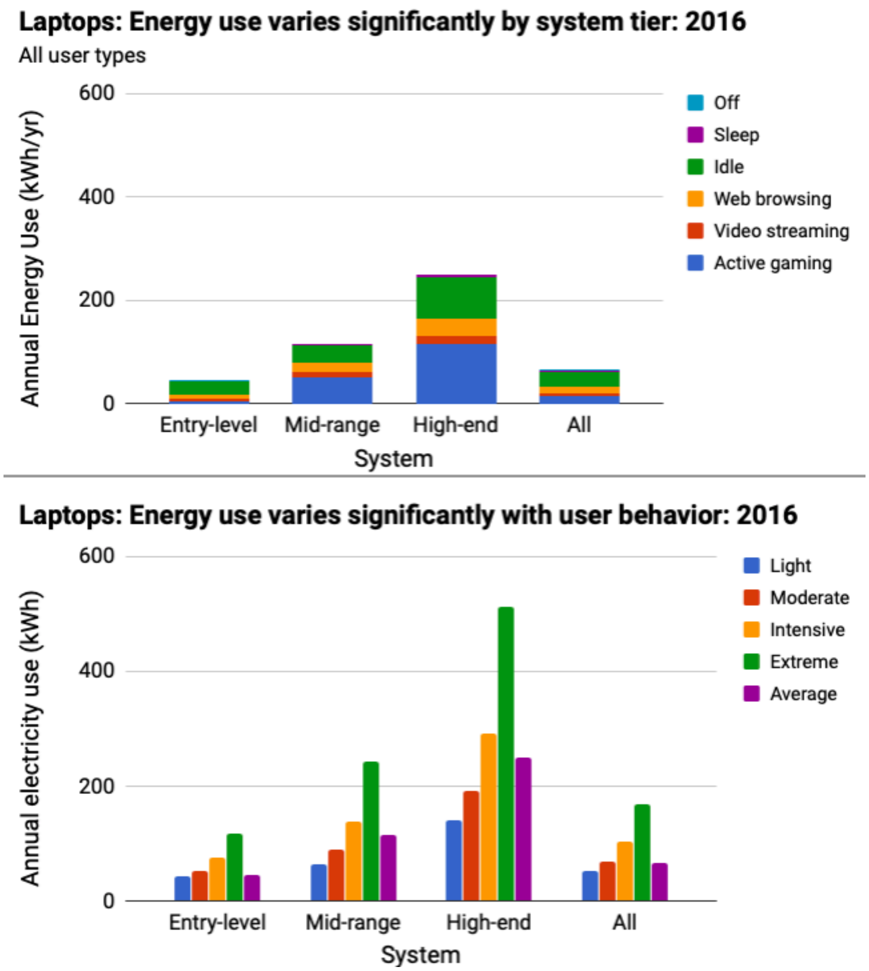
Figure 36a-b.
Baseline unit energy consumption for desktops by user type and duty cycle



Upper panel (a) is absolute energy; lower panel (b) apportionment by system.

For laptops, absolute and relative energy across the duty cycle also varied substantially (Figure 37a), with particularly low relative active gameplay energy among the Entry-level systems. 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 37b. 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.

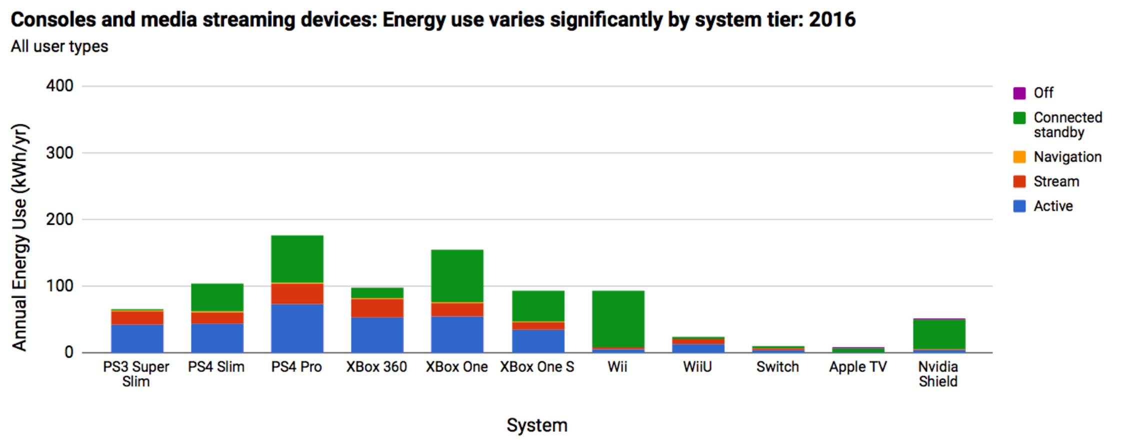
Figure 37a-b.
Baseline unit energy consumption for laptops by user type and duty cycle

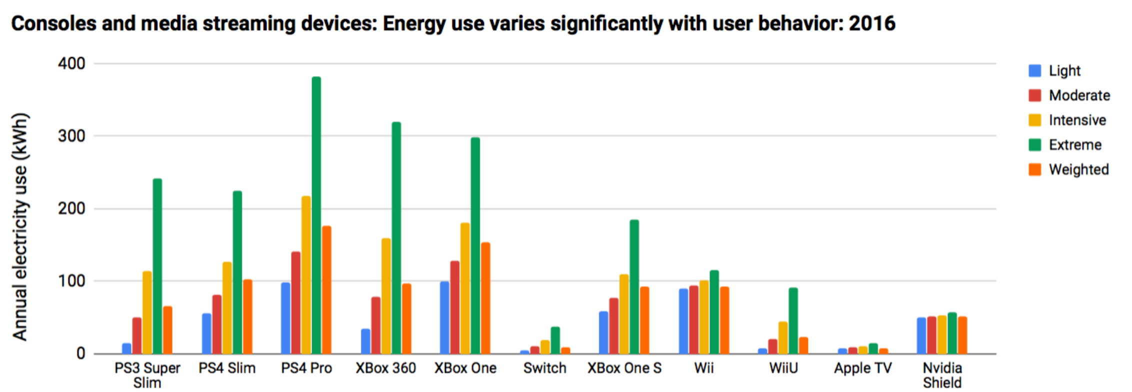


Upper panel (a) is absolute energy; lower panel (b) shows apportionment by system. All laptop testing conducted with batteries removed or fully charged. Thus we have not included energy losses associated with charging.

For consoles, absolute and relative energy use across the duty cycle varied substantially (Figure 38a). 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 38b. 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 we evaluate 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. If the past technology maturation patterns are indicative, the current-generation systems (e.g. PS4 Pro and Xbox One) will likely exhibit further improvements as their market lifecycle progresses.

Figure 38a-b.
Baseline unit energy consumption for consoles by user type and duty cycle

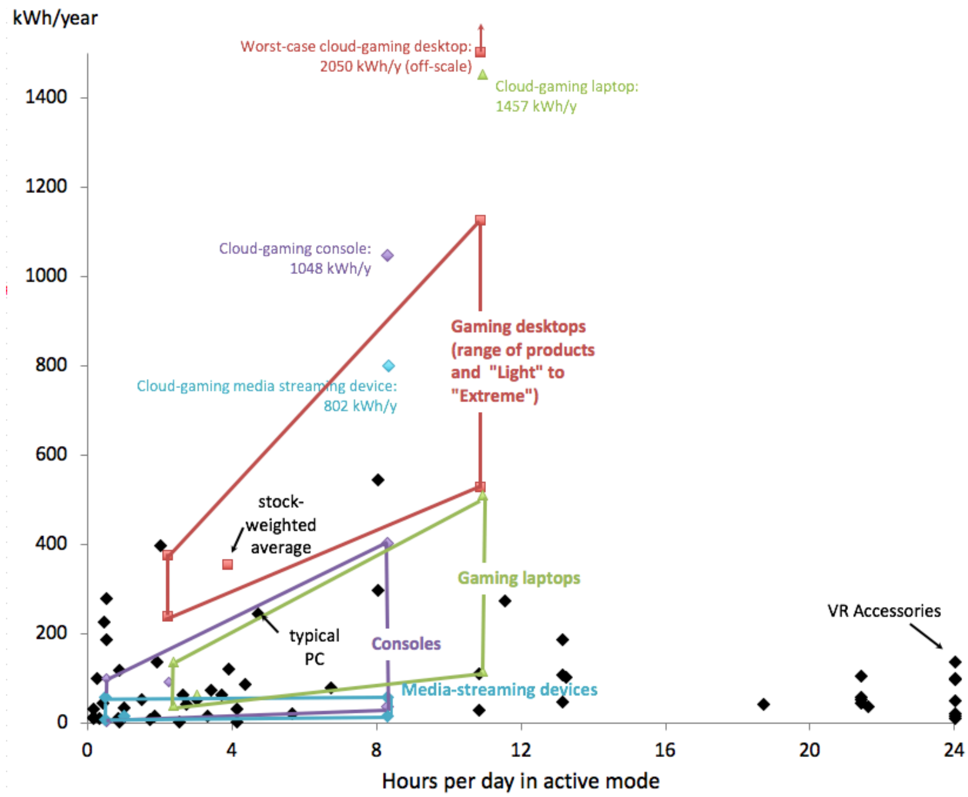




Upper panel (a) is absolute energy; lower panel (b) shows apportionment by system.

This information can be put into context by comparisons with other residential plug loads (Figure 39). 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 active 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 39.
Gaming is one of the highest energy-using plug loads



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 reflecting conditions prevailing in 2016. 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.[32]

This analysis expands significantly upon the original scoping work by Mills and Mills (2015). That work centered on High-end, high-use desktop PCs purpose-built for gaming representative of technologies in use during the 2014 timeframe. Measured system power of the base system during gameplay (~350 watts) was in the upper region of the range of 50-400 watts measured across the far-wider performance range of the vintage-2016 desktop systems described in this study (excluding displays in both cases). Moreover, multi-GPU systems factored into the 2014 estimates (SLI) are far less common today. Meanwhile, the earlier study focused on the market segment falling between the "Intensive" and "Extreme" user types defined in this study (4.4 hours/day in gameplay per Short (2013). In estimating aggregate energy use, those values were applied to a correspondingly smaller installed base than that used in this study, which represents a blend of users gaming between one hour per week and more than five hours per day

[32] See http://hes-documentation.lbl.gov/calculation-methodology/calculation-of-energy-consumption/major-appliances/miscellaneous-equipment-energy-consumption/default-energy-consumption-of-mels

(average 1.4 hours/day). The combination of these factors yields an expected reduction in unit energy consumption for the average system in today's stock, but of course occurring over a far larger variety and number of computers with larger aggregate energy demand.

Computer Gaming Energy Use on the Internet and in Data Centers

As noted above, there are three primary modes of gaming that result in energy use in the Internet: on-line gaming, digital distribution of games, and cloud-based gaming. Cloud-based gaming also results in energy use in data centers.

Common to each of these is the use of networks to transmit data. With the rapid improvements in Internet data-transfer efficiency, energy use for those tasks has declined rapidly (Aslan *et al.,* 2018), halving every two or so years, although it remains significant. A meta-analysis of the energy use associated with data transfer across the Internet—from the point at which the data leaves the data center to where it reaches the user—estimated this energy use at 0.027 kWh/GB (Aslan *et al.,* 2017). The corresponding values were 0.145 kWh/GB in 2011, and, if the trend continues, will the rate will fall to 0.005 kWh/GB by 2021. The Shield, for example, streams at an average rate of 15 Mbps, or 6.75 GB transmitted hourly. Per the intensities identified by Aslan *et al.,* (2018), this corresponds to 182 watts during gameplay for 2016 conditions.[33]

For traditional on-line gaming, the energy burden is small, given the very minor amounts of meta-data transmitted among gamers who are running the game on their local devices. For digital distribution, energy use is a function of game size, frequency of downloads (or game updates), and Internet electricity intensity as well as that of local networking equipment in the home. The large number of unknowns, including extent of game downloads versus disk purchases (by platform), have prohibited us from applying this approach to the current analysis.

Cloud-based gaming requires energy-intensive server equipment located in off-site data centers to execute the game logic and render game images, as well as the use of Internet data networks to continuously transmit large amounts of data from these servers to the client-side user devices during gameplay. No analysis has previously been published on the relative allocation of gaming energy use between the local client (gamer) and the network plus supporting core and edge data centers. There is limited non-proprietary data on the system-wide power requirements of those services.

Appendix E summarizes the energy calculations of streaming and network games on PC and console platforms. For the case of the Shield, we find that nearly 99% of the total energy during gameplay occurs in the cloud and 97% in the case of cloud-based console gaming. While energy use can be higher when cloud-based, the centralization of servers

[33] The network energy intensity estimate from Aslan *et al.,* (2017) represents an average for all access network technologies including the IP core. Actual network intensity depends on the specific combination network technologies used. Gaming systems may have an overrepresentation of fiber access networks owing to their large bandwidth requirements, which have lower energy intensity. However, in the absence of any specific network intensity data for gaming, this analysis applies a system-wide average.

handling the graphics workload provides unique opportunities for efficiency improvement as well as introducing carbon-free power sources.

We estimated cloud-based gaming energy requirements in networks and data centers based on the beta version of Nvidia GeForce NOW for the Mac, the Nvidia Shield TV system[34] and analogous systems for consoles. The majority of computation activity occurs in the data center, a building housing racks of servers with the infrastructure necessary to keep them cool and move data around. The GeForce NOW service for PC gaming currently uses rack servers each with eight Tesla P40 Nvidia GPUs. Average server electricity use, excluding GPUs, is assumed to be 257 watts per user,[35] based on typical hardware and operation characteristics found in large data centers (Shehabi *et al.,* 2016). Network power for switches and routers within the data centers is estimated as a 15% overhead on server electricity use, excluding GPUs (Masanet *et al.,* 2011). Each GPU increases server electricity demand by an additional 150 watts (Rated at 250 TDP by Nvidia) during gaming and 50 watts during idle periods.[36] (167 and 56 watts for gaming and idle, respectively, when accounting for PSU losses). Users of the Shield service are provided a dedicated GPU, indicating that up to eight users can access a server at any time. At capacity, the server electricity demand associated with each player would be 199W, however continuous full capacity is unlikely. Nvidia aims to achieve 80% capacity, though the actual capacity could differ, depending on how well the installation matches the demand for the service. Assuming a use capacity of 80%, each hour of game play must also account for an additional 15 minutes (i.e., for every 75 minutes of server time, 60 minutes are spent in play while the other 15 minutes is idle) of server use with an idle GPU, or 22 watts. Aside from direct IT workloads, data centers require a significant amount of power for cooling and electrical support of the IT-equipment. While this auxiliary power can range from 10% for best practices in large hyper data centers to many times the IT power, this analysis assumes 50%[37] to represent the mid- to large-size colocation facilities (Shehabi *et al.,* 2016) (i.e., space rented out by a third party), where gaming servers often reside to obtain wide geographic distribution and minimize latency.[38] When accounting for data center server and auxiliary power, as well as the data center power when gaming services are not being utilized, 340 watts is required per user at the data center while in cloud-based game.

Client-side user devices draw reduced amounts of power during cloud-based gaming since the majority of computational activity is occurring at the data center. We found the local-client's system power while engaged in cloud-gaming to be similar to that in

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

[35] Assumes a dual-processor volume server with an average processor utilization of 50%

[36] Phil Eilser, Nvidia email correspondence, Dec. 11, 2017

[37] This is typically expressed in terms of the Power Utilization Efficiency (PUE), which is the ratio of total facility power to the IT power, or 1.5 in the case where IT power is two-thirds of the total. This assumed value is probably more efficient than typical practice today (PUEs of 1.9 and 1.7 for Midt-ier and High-end data centers, respectively), and approaching what would be best practices in the U.S. by the year 2020 (Shehabi *et al.,* 2016).

[38] Phil Eilser, Nvidia phone correspondence, August 11, 2017

streaming mode. Devices dedicated for cloud-based gaming, such as the Shield, will require less than 15 watts on the client side, while a laptop or desktop computer will use more depending on the device (Eisler 2017). Total power for the network plus in data centers is 520 watts (182 watts + 340 watts), plus that of the local device

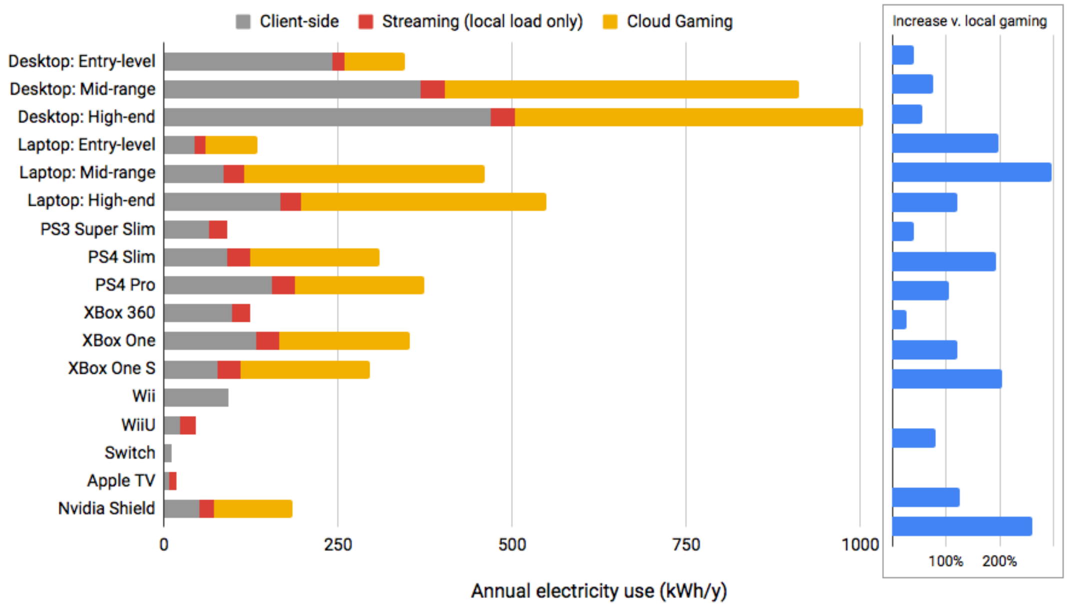
We conducted a parallel analysis for consoles, which are also beginning to have access to cloud-based gaming services such as Playstation NOW. In the absence of publicly available data, we developed a generic configuration. Network energy is identical to that in the PC example, at 182 watts, plus 120 watts in the data center during gameplay, for a total of just over 300 watts. The console's local power would then be added to this value to estimate total power requirements.

As a sensitivity to the highly advanced PUEs of ~1.1 available in the largest and most advanced hyper data centers, PC-gaming power would be 430 watts and console-gaming power 270 watts.

The energy estimates in this section are based on representative equipment and published data, but cloud-based gaming is an increasingly diverse and rapidly evolving gaming medium. The energy efficiency of data networks has drastically improved while the amount of data being transferred is constantly increasing. As cloud-based gaming grows and data centers become more tailored for gaming, these facilities have the potential to become much more efficient through both technological and operational improvements. However, gaming service providers co-locating their servers in facilities owned by others have limited, if any, influence towards the pursuit of infrastructure energy efficiency in those systems. 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 our 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.

Where users elect cloud-based gaming, 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 40 shows that for these systems 23 to 82% of total system energy use falls in networks and data centers. 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% to the otherwise total local annual electricity use for desktops, 120 to 300% for laptops, 30 to 200% for consoles, and 130 to 260% for media streaming devices.

Figure 40.
Network and cloud-gaming energy is significant; often more than half of total electricity use: 2016 conditions



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.

The balance of available information suggests that 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.

It is important to note that other use modes available for many client-side gaming devices also consume network energy. In particular, during video streaming, the client-side 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. This report estimates the data transfer of video streaming at 7.5 Mbps, based on a range of recent estimates for 1080p@60fps video streaming (the assumption in our testing protocols) (Gonzolaz 2017),[39,40] which corresponds to 91 watts during streaming. In online gaming, while the game logic and image rendering occur locally on the client-side device, information about each gamer is constantly exchanged and gamers communicate with each other through the Internet during game play. The data streaming to and from the client device during online gaming is assumed to be much lower, at 0.2

[39] See https://www.google.com/get/videoqualityreport/#methodology

[40] See https://help.hulu.com/s/article/requirements-for-hd?language=en_US

Mbps, which corresponds to about 3 watts during gameplay. We do not consider the energy use associated with ESports, although some degree of that can be assumed to occur in the streaming portion of the duty cycle.

Lifecycle Assessment and Embodied Energy Analysis

Extending the analysis boundary conditions further invites consideration of the direct and embodied energy associated with that of purchasing games on physical disks. Mayers *et al.,* (2014) performed an exhaustive analysis for certain console games under European conditions. Associated Internet energy includes download (and the efficiencies of supporting infrastructure, which are changing rapidly over time), size of game, and type of local networking equipment in the home. Energy associated with physical disks includes that embodied in raw materials production and transport, manufacturing, distribution, retail, consumer transport, and eventual disposal. When considering the tradeoffs between these two approaches, as game size increases, the relative energy use of the Internet increases compared to the fixed amount of energy embodied in the physical disk and its handling.

According to Mayers *et al.,* in both cases, gameplay itself (i.e., the underlying energy use) is the dominant source of greenhouse-gas emissions (~90 to 95%) for European conditions at the time of their study. About two-thirds of the impacts associated with game download occur on the consumer's premise (local networking equipment).

A thorough assessment should also include the energy embodied in the manufacture and sale of the gaming equipment itself. The large number of unknowns for U.S. conditions noted above have prohibited us from applying this approach to the current analysis.

Drivers of Demand

Variations in hardware and software/utilization choices clearly influence annual electricity consumption, in many cases quite substantially. The choice of core system is of course influential, exhibiting a 2.6-fold variation in average annual energy use across our three desktop PC technology tiers (Table 7). In parallel with hardware variations, usage-specific variables include duty cycle, firmware, in-game settings, and game choice. Another very key user variable is under/over-clocking of the CPU. These factors can have far greater impacts when they occur in combination.

As seen in Table 7, duty cycle is the most significant determinant of energy use for desktop PCs, exhibiting a 4.8-fold variation around the average by user type. In fact, the behavior-driven variation even within equipment tier (e.g., within Mid-range PCs) is greater than the technology range across all equipment tiers types. This translates into greater absolute energy use variability, i.e., 411 kWh/year between the average High-end and Entry-level equipment tiers versus 888 kWh/year across all user types and equipment tiers. For consoles, this contrast is even more pronounced. Duty cycle is also a key driver for console energy (as seen in Figure 37b).

Greater behaviorally-driven extremes are certainly possible. For example, this does not even account for enormous variations that arise from game choice.

What clearly emerges from these comparisons is that behavioral factors can have a more pronounced effect on energy use than hardware choices. This is ascribable to the much larger power requirements when in gaming mode than in other modes, as well as to the significant variability in the energy intensity of game-choice and in-game settings, among other factors.

Table 7. Relative influences of technology choice and user behavior for desktop PCs: 2016

			Behavioral effects	
Desktop PC technology tiers	**Intensity**	kWh/year	Variation within segment (kWh/year)	Ratio high/low
Entry-level	Light	236		
	Moderate	276		
	Intensive	363		
	Extreme	526		
	Weighted	248	290	2.2
Mid-range	Light	285		
	Moderate	374		
	Intensive	547		
	Extreme	917		
	Weighted	521	631	3.2
High-end	Light	373		
	Moderate	479		
	Intensive	681		
	Extreme	1,124		
	Weighted	648	751	3.0
Technology-choice effects				
Variation across weighted averages and segments (kWh/year)		411	888	4.8
Ratio high/low		2.6		

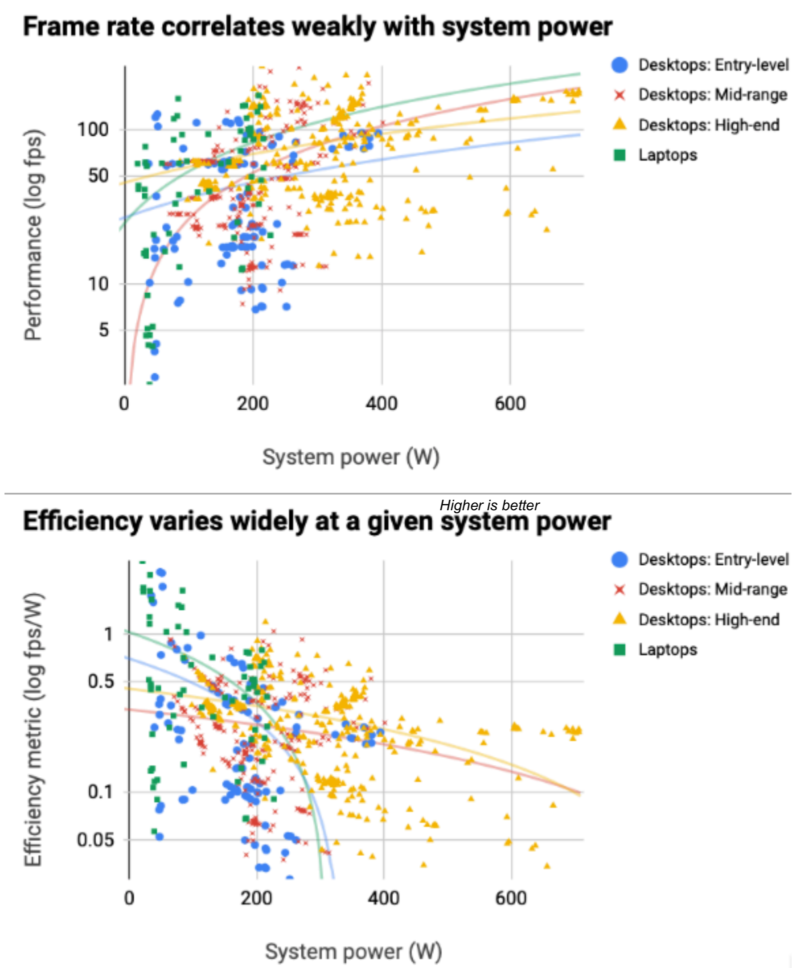
A hypothetical "worst-case" setup, involving the average of our two High-end PC systems, overclocking, three displays at 4k resolution, cloud-based gaming, and the "Extreme" user profile. This configuration would result in annual electricity use of 2,560 kWh/year, which is more than double the Baseline unit energy consumption for that equipment tier.

The Energy-vs-Frame-rate Nexus

Whether for cars or gaming systems, popular mythology holds that boosting performance requires more energy input. As discussed at length above, most aspects of performance are highly subjective and difficult or impossible to measure. We have been able to measure the most accessible performance 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 41a, high frame rates can be achieved at almost any power level. Conversely, at a given power level, frame rates achieved vary widely. Variations are similarly large when outcomes are viewed in terms of efficiencies (frames per second per watt) (Figure 41b). A high level of efficiency does not correlate to lower absolute power requirements. As discussed below, most efficiency improvements we implemented resulted in improved efficiency metrics (fps/watt). 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. Moreover, it is not clear that human gamers can actually perceive increasingly high frame rates, although gamers relish the "bragging rights" they confer.

Figure 41a-b.
Frame rate does not correlate with PC power: Laptop and desktops



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 for consoles.

While gamers will differ about the quality of experience on various console platforms, portability is a big advantage for some (Kuchera 2017). The drive for miniaturization has also yielded the lowest-energy-using and extremely popular console in the marketplace in the form of the Switch. Sony followed in 2018 with the small and portable PlayStation Classic (power measurements not yet available).

5. ENERGY EFFICIENCY OPPORTUNITIES

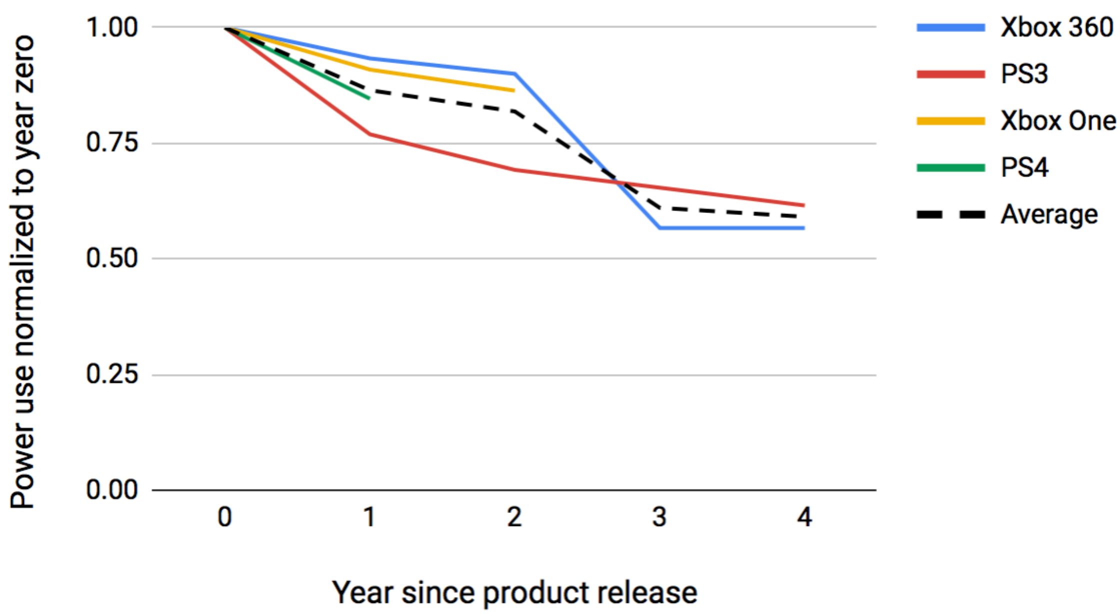
The gaming industry (and makers of components used in gaming systems) has made material efforts at improved energy efficiencies, in some cases in tandem with policy efforts and in other cases on their own. Component efficiencies have improved steadily, along with efforts to achieve power management through software and BIOS avenues.

Console manufacturers have made the greatest strides.[41] What can be observed is that each in-generation release of consoles has historically achieved gaming-mode power reductions compared to the prior version, and that the cross-generation trend is generally downwards, albeit with spikes at the initial launch. Using data from Urban *et al.,* (2017) (reproduced in Figure 9 in this report) we estimate that the historical pattern of improvement seen in the 7th-generation console gaming power reached 41% by four years after initial release (see Figure 42). 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% 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 shown in detail above, there remain large variations in energy use during gameplay across the representative systems we evaluated that nonetheless give similar measurable user experiences, as well as variations in the ability for systems to use less power in non-gaming modes. Moreover, for PCs, a steady stream of PC-relevant innovations is entering the market that often depends on users to implement.

[41] In one of many examples, per Urban *et al.* (2017), most consoles offer a "semi-off" mode called connected standby (or "networked standby") enabling users to resume gaming more quickly and enable online updates while the system is not in use results in substantially more energy use than "energy saver" modes. The most recent Xbox One model draws 10W in this mode and offers an "Energy Saver" mode that reduces the draw go 0.4W; versus 18W and 0.5W for the prior model (the authors estimate that 70% of users select the higher setting). The Wii achieves "connected standby" with only 1 watt.

Figure 42.
Reductions in console power in active gameplay after initial generation release



Estimated from Urban et al., (2017)

Hardware Strategies

The most energy-intensive component within most PCs used for gaming is the GPU, followed by the CPU and its coupled motherboard.

Graphics processing units

Graphics processing units (GPUs), also referred to as "graphics cards" or "video cards", provide computing power associated with visual display of information, including 2D and 3D rendering and animations, and is usually the single-largest node of energy use in the gaming platform. According to the latest Consumer Electronics Association survey, 37% of desktop computers and 16% of laptop computers today have discrete GPUs (Urban *et al.,* 2017). There is no consistent consumer information on actual power requirements for graphics cards in the marketplace.

Direct GPU energy measurement is quite difficult, and they are rated by manufacturers in terms of Thermal Design Power (TDP). Like CPUs, TDPs seem to underestimate actual power.[42] Laptop GPUs have historically had both lower computing performance and lower TDPs, a reflection of space constraints as well as need to the duration of use on a battery charge.

One metric of performance is the ratio of peak power requirement to corresponding floating-point operations per second (FLOPS). TDP varies between 60 and 500 watts across a sampling of gaming-specific devices found in the market between 2014 and

[42] See https://linustechtips.com/main/topic/453630-graphics-card-tdp-and-power-consumption-explained/

2016, and varies by almost a factor of two for a given performance level (Mills *et al.,* 2017). GPUs can be overclocked to frequencies above stock settings. Performance per TDP has been advancing in recent years (Figure 10).

Steady progress has been made in the energy-efficiency of the GPU architecture. This is driven by an imperative to control heat production, and in some cases to save energy *per se*. A comparison performed by AMD found 40% savings at the system level in gaming mode between its Radeon™ R9 390 GPU and Radeon™ RX 480 GPU products (AMD 2016).

GPUs vary significantly in the degree to which power use is managed during non-gaming parts of the duty cycle. Power measurements of 10 GPUs found idle power ranging from 7 to 16 watts (GTX 670 not included) and gaming power ranging from 150 to 367 watts under the Furmark frame-rate benchmark.[43] The ratio of idle to gaming power ranged from 11 to 25 watts, indicating the wide variation in and importance of careful system integration. We measured six GPUs as part of our component testing and found generally similar results: gaming power ranged from 85 to 230 watts while idle power ranged from 8 to 17 watts. The ratio of gaming to idle ranged from 10 to 18 watts.

As an illustration of these improved GPU opportunities, our upgrade of a High-end DIY system (H1) achieved substantial energy savings by changing from two AMD R9 Fury X GPUs (our base system) to one RX Vega 64 Liquid GPU. Power reductions for actual games ranged from 4 to 44% (for Witcher 3 and Skyrim).

Similarly, the retrofit of a Mid-level DIY system (M4), also achieved substantial energy savings by upgrading the base Nvidia GTX 970 to its next generation GTX 1070. On average across all tests, the GTX 1070 reduced power draw by 17%. Frame rates also reduced slightly from 141 fps to 137 (-2%), which translated into an overall 20% improvement of fps/W performance. Power reductions for actual games ranged from 3 to 33% (for Overwatch and SIMS 4, respectively). Frame rates improved 19% in Call of Duty: Black Ops, producing an efficiency (fps/W) improvement of 28% for that title when combined with its 8% power reduction.

While dual-GPU systems have fallen out of vogue, they were popular in the recent past and so still exist as an element of the installed base. Their original popularity arose from desire for improved performance.

A look at the published hardware and performance specifications of the Fury X versus Vega 64 GPUs shows some impressive improvements with the Vega generation, but not enough to explain the full power savings we measured compared to baseline the Dual Fury X configuration.[44] It is with the improved rendering process of "Draw String Binning Rasterizer" (DSBR) that the single Vega 64 appears to have achieved a much

[43] See http://www.tomshardware.com/reviews/amd-radeon-rx-480-polaris-10,4616-9.htm

[44] Radeon's next-generation Vega architecture, AMD Radeon Technologies Group, https://radeon.com/_downloads/vega-whitepaper-11.6.17.pdf

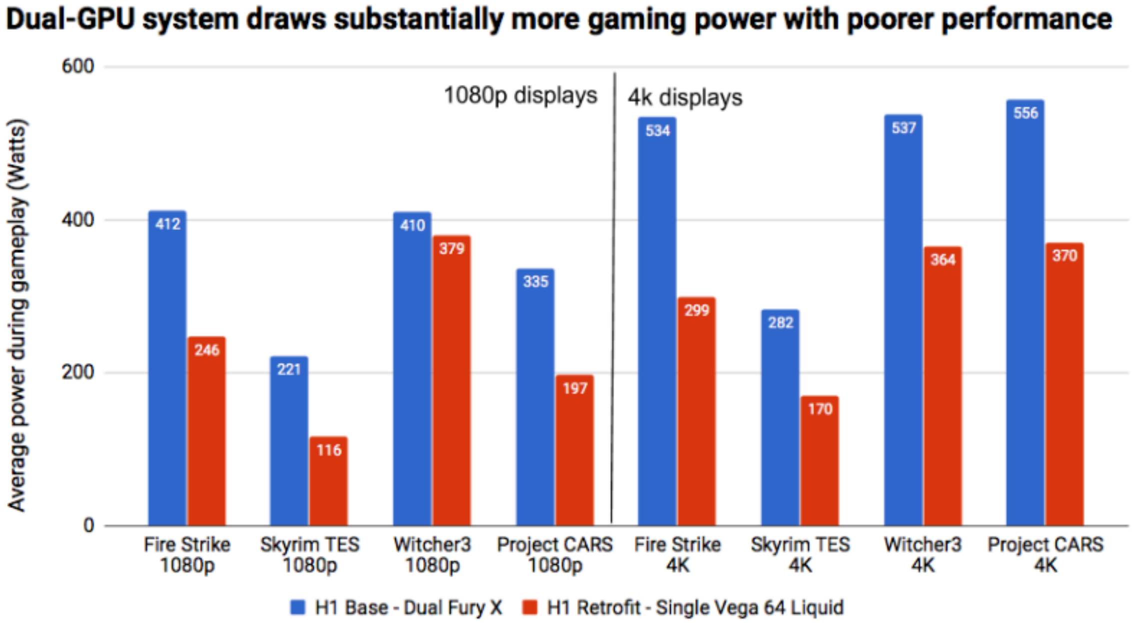
lower power draw profile across all games tested as well as the Fire Strike frame-rate benchmark. After the geometry engine performs its (already reduced amount of) work, the DSBR uses a “deferred pixel shading” process which identifies overlapping pixels and renders only the top layer pixels allowing the GPU to discard the non-visible pixels rather than wasting energy rendering them.

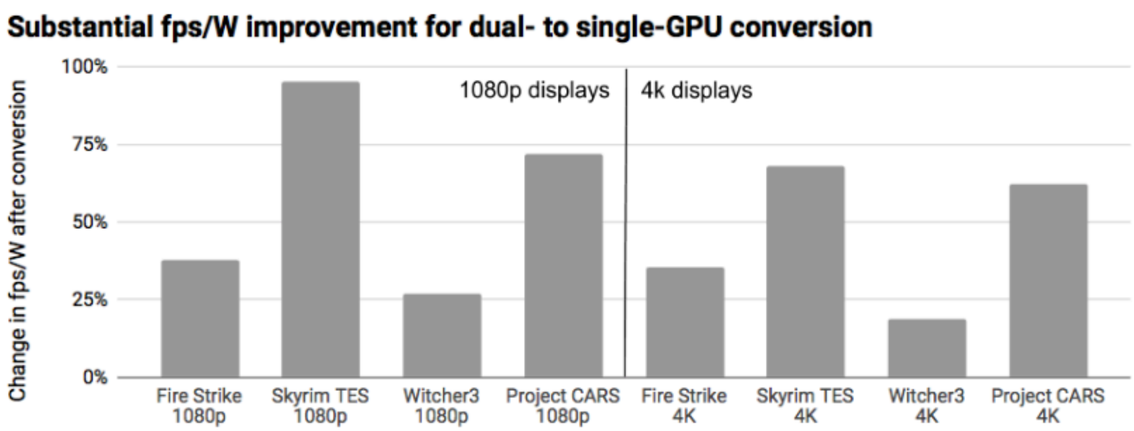
Our array of tests also enabled us to quantify impacts on power requirements for PC systems driving 1080p displays versus 4K displays. As can be seen from Figure 43a, significant increases in power requirements occurred. In three of the four cases, these increases ranged from 28 to 66%. In the remaining case, a reduction of 4% was observed, presumably corresponding to the lower frame rates achieved. Others have documented analogous increases in console power when connected to 4K displays (Microsoft, Nintendo, and Sony Interactive Entertainment 2017).

Looking at the frame rate, we found that the Vega achieved as good or better performance in all games with the exception of Witcher 3 on the 4K display, where rates drop from 49 to 39 fps. The Vega offers superior metrics of user experience and image quality including substantially greater shader throughput, texture filtering, memory bandwidth and memory capacity.

In terms of a combined performance metric of fps/W (Figure 43b), we observed impressive improvements across all the real-world games and the Fire Strike frame-rate benchmark. These improvements ranged from 19 to 95%, demonstrating that improved efficiency can be achieved in tandem with improved performance by this measure.

Figure 43a-b.
Power and fps/W in gameplay for alternate configurations: System H1.





Of note, we observed significantly improved power management within the efficient GPUs we evaluated. For the GPU applied to system E3 exhibited, the ratio of gaming to idle power improved from 10.3 to 18.2 for the improved componentry. For system H1, the improvement was from 13.3 to 17.3.

Central processing units and motherboards

The central processing unit (CPU) conducts the primary computing tasks, and is one of the most important energy-using components in the gaming system. Steady progress has been made in the energy-efficiency of CPU architecture.

Thermal design power (a loose proxy for electric power requirements, which generally under-predicts actual power) varies between 37 and 220 watts across a sampling of CPUs found in the market between 2014 and 2016 (Mills *et al.,* 2017). One metric of efficiency is the ratio of peak power requirement to corresponding processor speed; this metric varies by a factor of two among CPUs used for gaming (Mills *et al.,* 2017). The measurable service levels provided by these devices vary as well, as reflected in their differing clock speeds (measured in GHz). CPUs can be "overclocked" to above the rated performance levels indicated here, increasing power consumption.

CPU power varies considerably depending on whether they are under load or idle, as does the ratio of these two performance points which ranged from about 1.5 to 3.5 for 27 processors.[45] This wide range of outcomes indicates the importance of how system integration impacts power use and the potential energy savings of optimized power management.

The CPU and most other components are mounted on and orchestrated by the motherboard, the main circuit board in the computer. The motherboard also holds the chipset that manages data flows among internal and external components. Motherboard energy losses occur via voltage-regulation modules (VRMs) as well as via natural resistive losses depending on the thickness of traces used. Increased voltage must be supplied via the motherboard as CPU and RAM clock speeds rise. Nameplate power consumption varies between 30 and 150 watts across a sampling of devices found in the market between 2014 and 2016 (Mills *et al.,* 2017).

Some pre-built systems have an "Eco Mode" switch on the exterior of the case, the function of which is not clear but presumably its effect is conducted via the motherboard. We tested one on the system H1 and measured 4% savings when activated.

Memory and storage

Random access memory (RAM) holds data until called by the CPU. The underlying technology is solid state. Each "stick" (DIMM) of memory experiences losses, and there are often multiple sticks per machine. Efficiencies have improved dramatically over time, with power use per stick dropping from 5.5 watts in 2000 (2.5-volt DDR) to the current 1.3 watts (1.2 volt DDR4). Few significant efficiency opportunities remain compared to those available in other components.

There are two general categories of storage devices, mechanical (rotating) and solid state. The more poorly performing mechanical hard drives draw on the order of 10 watts (1 TB) while solid-state drives of the same capacity and interface draw as little as 2.6 watts. Operational savings occur depending on whether or not a sleep mode is employed. Storage devices use far less power than other componentry in the gaming system.

[45] See http://www.hardwarecanucks.com/forum/hardware-canucks-reviews/67240-intel-haswell-e-i7-5960x-review-14.html

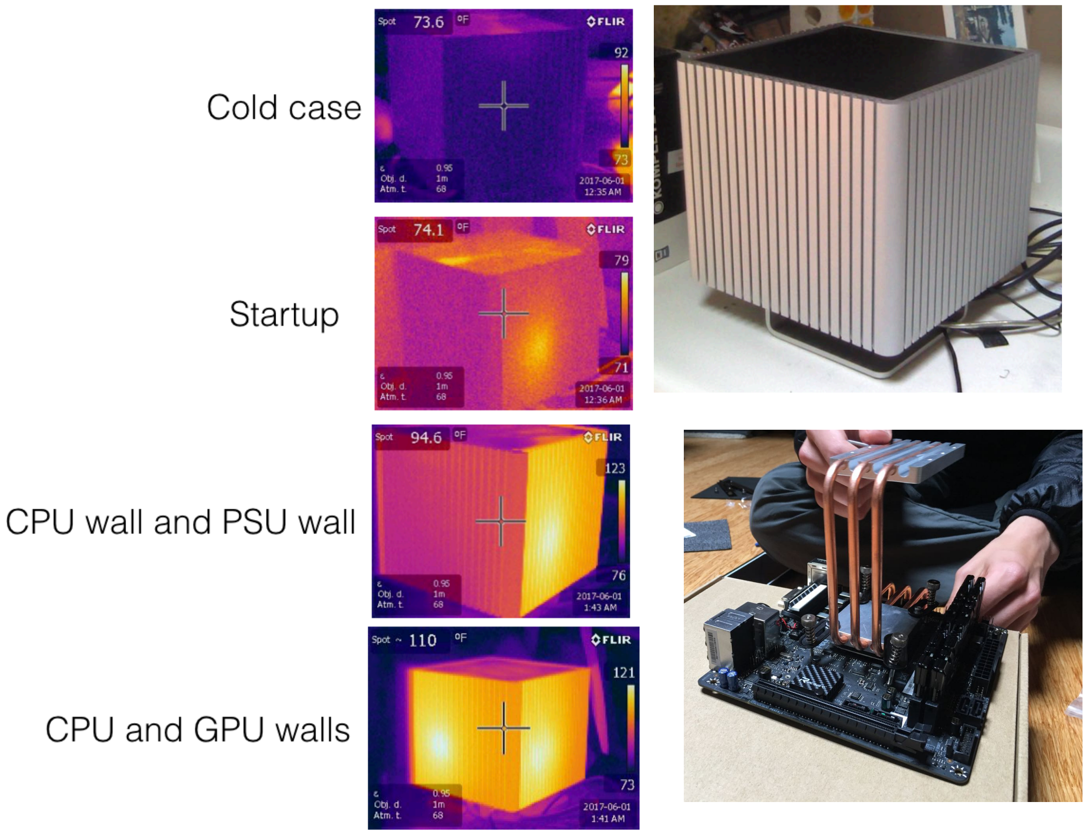
Cooling

Gaming computers require dedicated cooling systems in order to avoid overheating, even at idle. A high-end gaming PC can easily have six fans. While a relatively minor source of load in the gaming system, cooling componentry runs long hours and is subject to inefficiencies.

Active cooling is typically provided to each PSU, CPU, GPU and motherboard as well as to the general environment within the computer chassis. Larger power supplies often have dedicated built-in fans, as do GPUs. Some cooling systems are load-responsive, i.e., operating only when temperature set points are exceeded. In a CPU air cooler, there are typically one to three fans driving hot exhaust air across a heat sink. With liquid cooling, a heat exchanger mounts to a particular component (CPU, GPU, motherboard, or memory) and directs the coolant over a heat-exchange plate that is in direct contact with the component. Liquid cooling is often preferred because it allows the processor to achieve higher over-clocks (enhancing computational performance at lower temperatures). Even if power use is unchanged, efficiency metrics may improve with liquid cooling if the performance metric increases while energy holds constant.

Passive cooling strategies have been explored with some success. Fanless power supply units are available. We experimented with a new generation of fanless cases, which employ heat pipes to transfer heat produced by the CPU, GPU, and even the power supply to the case walls. The associated case is crafted from highly-conductive aluminum with a sculpted surface achieving 5x nominal surface area to maximize cooling to the room air (Figure 44). Key componentry chosen included an AMD Ryzen 7-1700 CPU, GTX 750 GPU, 32Gb DDR4 memory, and a high-efficiency fanless PSU. The case chosen is rated as having a capacity to dissipate 200 watts of thermal power. Surface temperatures did not exceed 50C, which is only warm to the touch. While this particular system would not likely be effective with a higher-wattage GPU, the efficacy for mid-level gaming systems is apparent and fanless cases hold great promise for a wider variety of systems if and as GPUs become more energy efficient.

Figure 44.
Fanless PC case test



Manufactured by Streacom (Netherlands)

Power supply units

Power supplies units (PSUs) play a critical role in energy use, as their inefficiencies are multiplicatively applied to every downstream component within the gaming platform. Thanks to the voluntary 80 Plus rating program (promoting efficiencies at 80% or higher), PSU efficiencies in desktop systems have increased in recent years, although they continue to drop off at part-load conditions. Power supplies used in gaming laptops are covered under the International Efficiency Marking Protocol for External Power Supplies, rather than 80 Plus, and tend to fall at the higher (more efficient) end of the spectrum, i.e., “Level VI”.[46]

While highly successful, adoption of 80 Plus efficiency levels is far from universal. Of 323 manufacturers (5,949 products) listed as of June 2017, 58% made Entry-level models (just barely achieving 80% efficiency), 77% Bronze, 34% Silver, 48% Gold, 23%

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[46] See https://www.energystar.gov/ia/partners/prod_development/revisions/downloads/International_Efficiency_Marking_Protocol.pdf

Platinum, and 6% Titanium.[47] Only in 2016 did the highest-rated Titanium models become available in wattage ranges appropriate for even the highest-end PCs used for gaming (previously they were limited to the 1500-watt size range). When we reviewed the market as of late 2016 (Mills et al., 2017), Amazon best-sellers tend to be 80+ or 80+ Bronze (the lower end of the scale. Some PSUs found on the shelves of retailers catering to PC do-it-yourself community are misleadingly packaged to imply 80 Plus compliance.

Peak PSU efficiencies are attained in the vicinity of 50% of rated load. Even among units rated 80 Plus, there is a steep drop-off in efficiency when the PSU is underutilized (running at lower part loads). PSU oversizing appears to be an issue in the industry, stemming perhaps in part to gamers' "bragging rights" of having a PSU with a "big" wattage number. Even where this is known to exceed the need, conventional wisdom is that "overbuying" provides headroom for growth. However, in the actual marketplace, more advanced components tend to use less rather than more power than prior generations.

The savings potential compared to units shipped with the minimum passing 80 Plus level and right-sized is on the order of 10 to 15% (Figure 45). Averaged across the duty cycle for our three tiers of PC systems and four user types, we estimate an average savings potential of 13% as illustrated in Figure 46 for our Mid-range systems.

We examined the peak one-second power requirements across all base systems and games tested. For our middle-of-the-road M4 system, we found that the as-shipped GPU averaged 11 to 46% of rated power during gameplay, and of course much less in non-gaming modes. Figure 47 shows that most of the PSUs shipped with our test systems were dramatically oversized, which, in turn, causes them to operate below their optimal efficiencies.

[47] See https://www.plugloadsolutions.com/80PlusPowerSupplies.aspx

Figure 45.
Varying efficiencies for gaming computer power supplies: 80 Plus thresholds and for specific systems

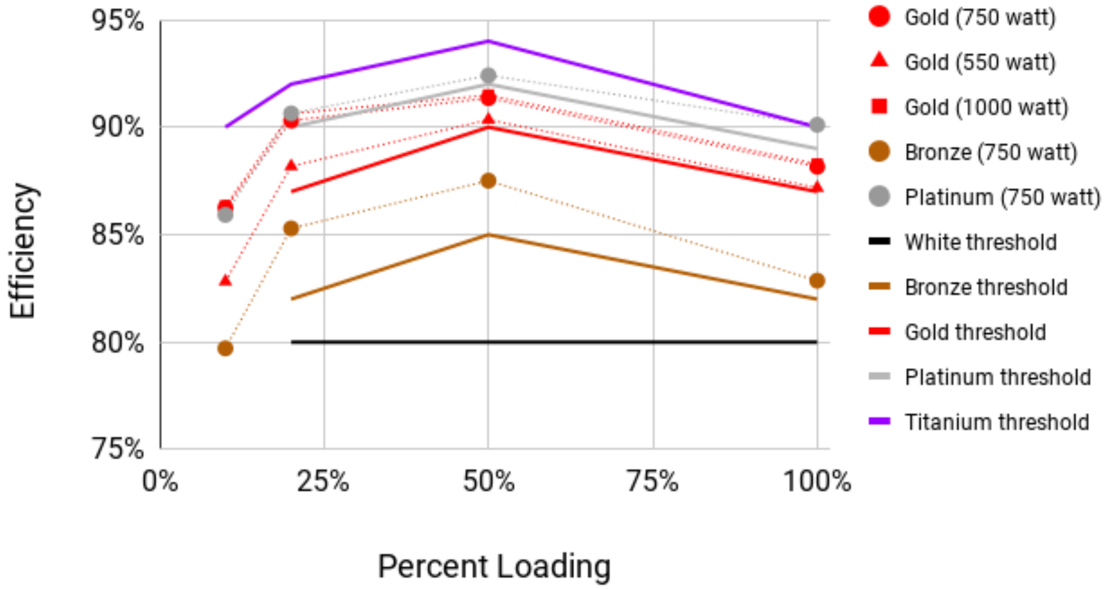
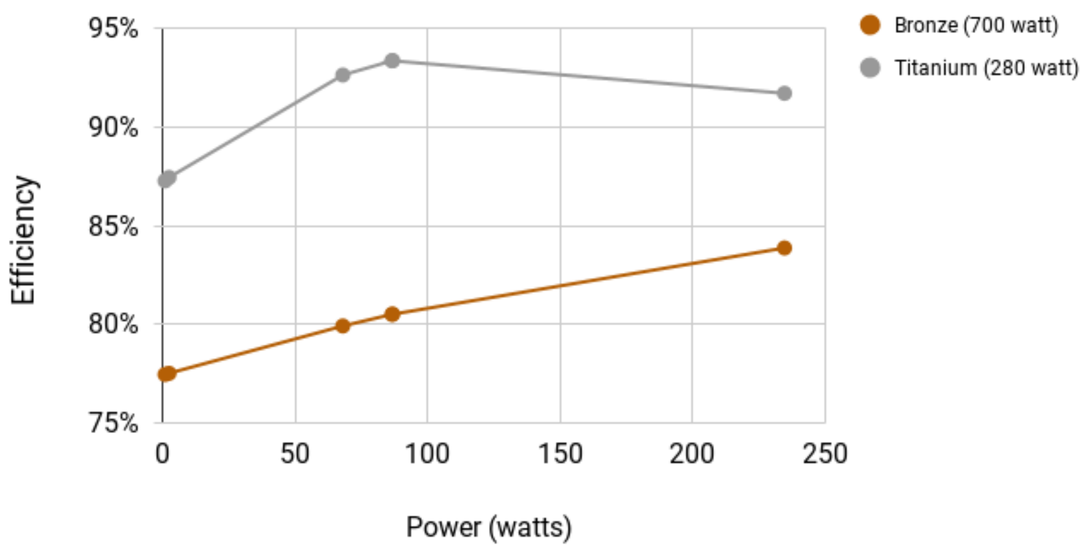
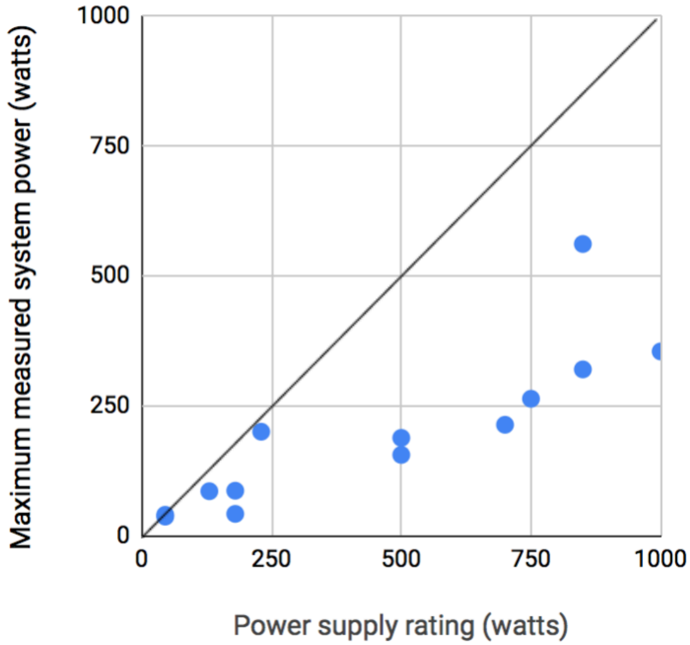


Figure 46.
PSU efficiency improvement potential across the duty cycle



Example of a Mid-range system. Note that the Bronze PSU's rated efficiency in Figure 45 is 85% at peak performance (50% load), but the system never reaches that level of power requirement. The operating efficiency for each PSU at each part of the duty cycle is shown along the curves. The 13% relative energy savings reflects the average efficiencies weighted by time in the various parts of the duty cycle.

Figure 47.
Oversizing of PSUs shipped with our test systems



All but three of our systems had significantly oversized PSUs. All desktops with the exception of E1 had internal PSU with average load factors of 37%, all laptops and E1 had external PSUs with average load factors of 74%

2D displays, virtual reality headsets, and televisions

The voluntary Energy Star V7 rating systems for displays and televisions were introduced into the market around the base-year of our assessment timeframe, lowering the voluntary level of energy use for displays (see Table 6, above, for the history). For our efficiency scenario, we adopt a 24" display power level of 13.5 watts for HD (1080p) and 23 watts for 4k (2160p) units to represent V7 best-in-class efficiencies. For context, these values are 46% and 8% lower than the stock-average values estimated for 2016.

In the case of televisions used with consoles, our efficiency scenario assumes a 39" display at 29.5 watts for HD and 45 watts for 4k (Urban et al 2017). These values are 64% and 45% lower than the corresponding average display of the same size in 2016.

Software Strategies

Displays

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's undersized for the game it is trying to run. However, this can cause unacceptable delays in screen refreshes which users must trade off against lower-quality frames. In our testing, VSync achieved 14% and 39% power reductions for the M2 and H2 systems, respectively. In an example of how various measures of user experience often run counter to one another, the smoother visual experience attained with VSync comes at the cost of reduced frame rates.

Recent technologies such as G-Sync (Nvidia) and FreeSync (AMD) allow more effective communication between the GPU and the monitor. When these run during gameplay, the GPU tells the monitor when to refresh, resulting in little to no stuttering and no tearing. If the frame rate in the game is low, these approaches will synchronize the GPU output with the game's capacity to render. This has been said to enable energy savings since, even at around 30 to 50 fps, the gaming experience becomes smoother to the gamer's eye, allowing the gamer to specify a GPU with lower nominal performance (and power requirements). With these technologies, manufacturers claim that gaming will be as smooth as with a higher-power GPU. Both variable-refresh technologies rely on a combination of hardware and software. G-Sync supplies a custom monitor control module based on a field-programmable gate array (FPGA) chip to monitor makers. That chip also handles things like scaling images and user interfaces and menus. For FreeSync, vendors of monitor-control chips produce custom ASICs that support FreeSync along with their other functions.

While our testing was conducted primarily on 24" 1080p displays, for the purpose of savings potentials it is appropriate to consider the wide range of display size and technology in use. Lacking survey data on the distribution of display types and sizes among gamers, we take as our baseline the average across Energy Star-labeled products under Version 6, which was in place until mid-2016. The average of Version 5 was used for the 2011 baseline reference point.

As noted earlier in the VR display section, we found significant energy use increases in some cases within gaming systems when virtual reality (VR) headsets are used in lieu of external displays. A simple energy saving measure is powering down the external sensors when the system is not in use. More sophisticated software solutions for managing VR energy are noted below.

Dynamic voltage frequency scaling (DVFS)

Software solutions offer a significant potential to reduce energy consumption while maintaining or even improving the gaming experience. Dynamic Voltage Frequency Scaling (DVFS)[48] involves changing power states in real time to better match the resources actually required by the computing process (e.g., graphics rendering in the case of gaming systems). The practice is widespread for CPUs, but has only recently been applied to GPUs. A review found energy savings as high as 54% depending on the nature of the workload, with central values in the 20% range (Mei *et al.,* 2016).

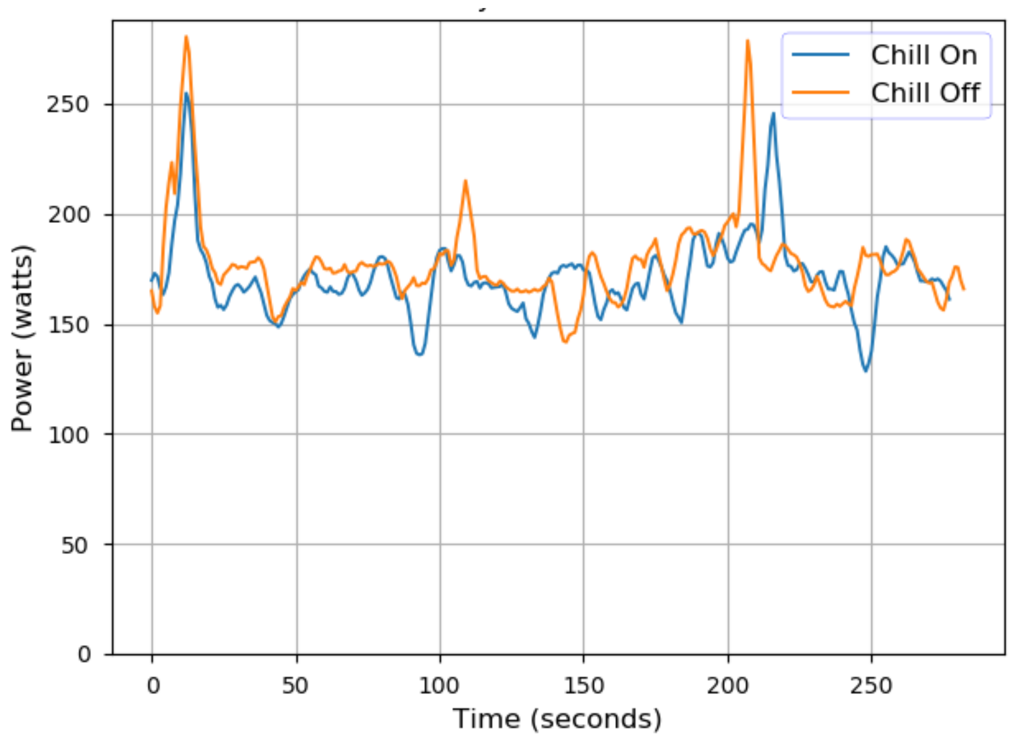
Major GPU manufacturers have launched DVFS-based power-management methods to take advantage of the fact that frame rates can be varied depending on the level of action

[48] See http://whatis.techtarget.com/definition/dynamic-voltage-and-frequency-scaling-DVFS

in the scene. One set of trials using one of AMD's tools (Radeon Chill[49]) found 31% power savings (108 to 75W) when applied to World of Warcraft, as well as significant temperature reductions (88 to 77C; 190 to 171F), plus quieter operation. More interestingly, responsiveness was actually improved, probably because there is less congestion (aka "backpressure") in the pipeline of cached frames (average frame rates fell from 125 fps to 62 fps, without compromising image quality). They note that the level of savings varies by game title. A third-party account measured a power reduction from 260 to 160 Watts (about 37%) with Chill activated.[50]

The benefits of DVFS appear to vary widely depending on the application (and type of activity happening within a gaming session). Games defaulted to use exceptionally high frame rates, such as World of Warcraft are the best candidates. We tested AMD's Radeon Chill, since it allowed for active control of the feature for two game titles in our testing line-up. The results for *The Elder Scrolls V: Skyrim* and *The Witcher 3: Wild Hunt* demonstrate negligible power savings (Figure 48), which is likely due to the active movement of character activities during our standardized gameplay testing sessions.

Figure 48. System H1 power running Skyrim with and without Chill activated.



Note drops in power at 90 and 250 seconds. Games with more quiet periods are expected to exhibit far greater benefit from Chill.

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[49] See https://www.youtube.com/watch?v=_RKJB47PoRg&list=PLx15eYqzJifcAtaYxVK2YpCL-nUKq6uqs&index=2

[50] See http://techreport.com/review/31077/radeon-software-crimson-relive-edition-an-overview

As distinct from automating framerate control, Nvidia's GeForce Experience[51] allows for user-varied frame rates. Nvidia's PowerMizer[52] is described as focusing on extending battery life in notebooks by managing GPU power levels to match the needs presented by the task (gaming and non-gaming).

Foveated rendering for virtual reality

Manufacturers of virtual reality equipment have several reasons to be interested in reducing the computing power requirements for VR, most notably that the path to cordless headsets requires less data transfer. An emerging strategy for accomplishing this is to gradually reduce the precision of rendering along a gradient from the center of view to the periphery of view, as the eye's Fovea is most sensitive in the central area. Some games are beginning to implement this strategy, which we have measured in the case of Batman Arkham VR, on our Digital Storm Velox system. This game refers to the two modes as "Full Resolution" and "Fixed-Foveated", the latter referring to a rendering gradient where resolution drops off towards the periphery.

We identified 36% reductions in average power across the "Fixed-Foveated" gaming session for the Oculus and 30% for the Vive (Figure 49). We conducted blinded back-to-back "A|B" tests with three gamers, only one of which eventually noticed the reduction of fidelity at the periphery of their vision. Batman's implementation allows users to vary the size of the high-resolution central area, as well as pixel density and pixel quality in the down-rendered outer region. While these results are promising, future enhancements to user experience could "take back" these savings in the form of increased power requirements.

These first-generation VR optimization strategies cannot, however, detect whether the gamer is looking sidelong at the periphery of the scene they are facing. More advanced applications of this method such as foveated rendering will incorporate eye-tracking, much improving user experience and allowing even deeper energy savings by adjusting the rendered scene with greater precision.[53] An important caveat for the future is that gaming equipment manufacturers or software developers could offset these savings in the form of increased performance and associated computing power.

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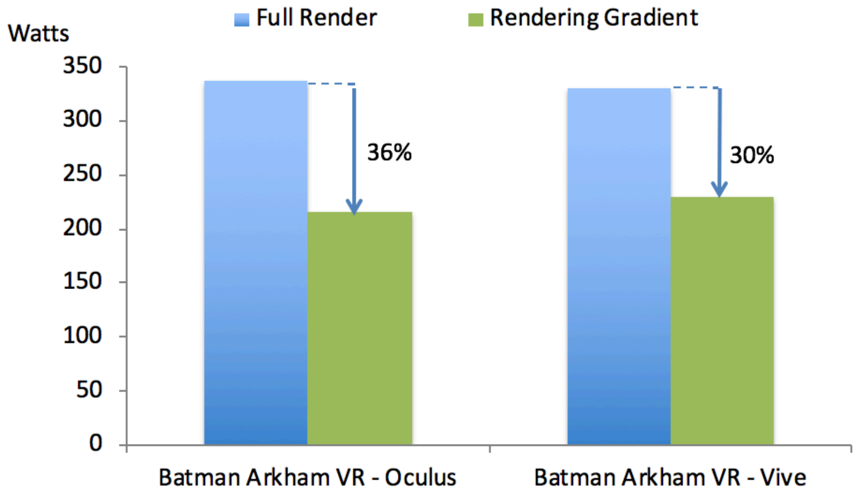
[51] See http://www.geforce.com/geforce-experience

[52] See http://www.nvidia.com/object/feature_powermizer.html

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

Figure 49.
Virtual reality foveated rendering gradient lowers gaming power >30%

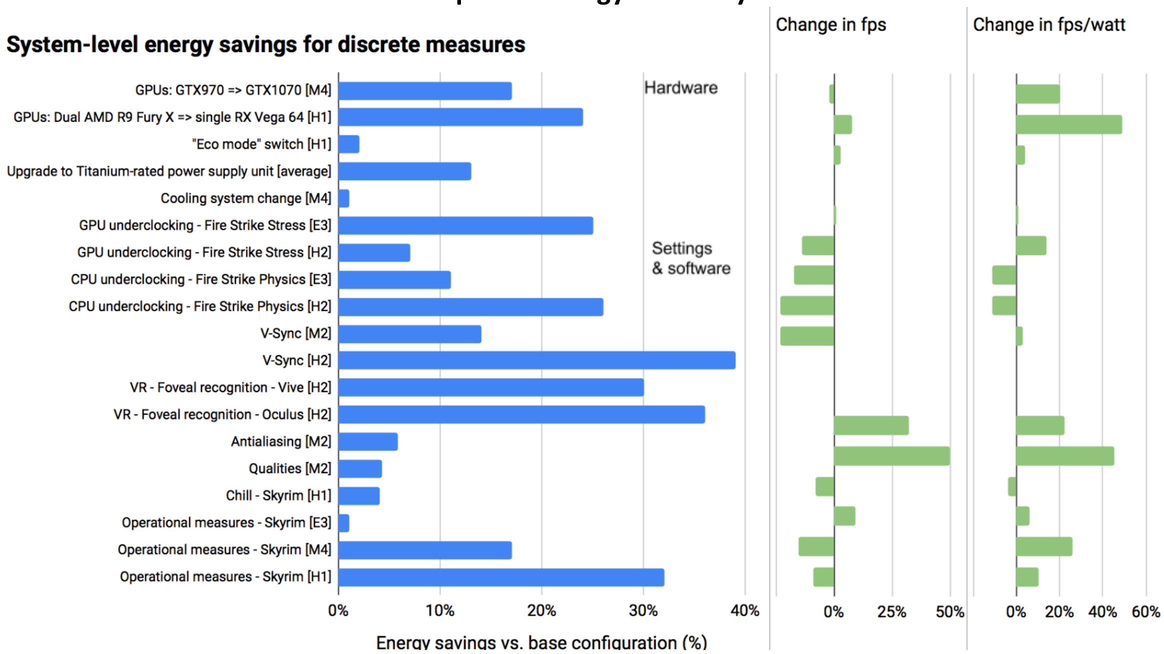


Results for system H2. Excludes power of secondary 2D display commonly used in conjunction with VR.

Savings from Energy Efficiency Packages for PCs

The preceding discussion provides a sense of the wide array of efficiency measures available to gaming system designers and owners. A cross-section of results from our testing is provided in Figure 50. Note that percentage savings for given measures can vary depending on the system to which it is applied, paired display, *and* the game being played. In one of the more dramatic illustrations, the GPU changeout on system H1 reduced power during gameplay under Skyrim by 44% while the reduction was only 4% under Witcher 3.

Figure 50.
Test results for specific energy efficiency measures



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 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.

The following hardware, BIOS, and system-settings measures were considered for each of the three PC systems (one from each market tier), which were tested under efficiency measure retrofit scenarios. These measures were assembled after the execution of the regular testing categories, which conducted targeted parametric adjustments to individual components such as GPU, CPU, motherboard, cooling heatsinks and BIOS settings. These tests provide the information needed to assign quantitative energy savings amounts to each change, which was then used in the exploration of effective energy efficiency packages for the E3, M4 and H1 PCs. An additional package of software measures was tested on the H2 system. Detailed breakdowns of the measure packages are provided in Appendix F.

Laptops are sealed systems, and represent a very small segment of gaming energy use. We did not attempt to estimate efficiency potential for these devices. As video game consoles are also sealed, proprietary systems, we did not attempt any direct efficiency improvements. Rather, we used the historical rate of reduction in gameplay power levels estimated previously (see the beginning of this Section) and applied this improvement only to new additions of the latest-generation Xbox One and PS4 systems to the 2021 stock, as these are the models that replace older consoles in our stock projections. We did not make explicit assumptions about the introduction of 9th-generation consoles, although that could occur within the timeframe of our scenarios.

Given the large number of potential component combinations, and limitations on the number of tests we were able to conduct, we speculate that deeper energy savings could very well be identified. This applies particularly in the case of CPUs and motherboards, as well as to BIOS-level software and in-game settings. We also did not include VSync, which can clearly achieve large savings in higher-performance systems. Based on lab-bench testing of the PCs, we identified ("packages") of applicable measures and evaluated their impact on desktop systems from each of our performance tiers. Among the hardware measures, our primary focus was on the GPUs, as they are the key driver of energy use in these systems. The efficiency packages for PCs varied by system (full details in Appendix F), but broadly included:

Hardware Changes

1. GPU Upgrade
2. CPU & Motherboard Upgrade
3. Storage Drive(s) Adjustments
4. Cooling Fan Adjustments
5. PSU Upgrade (impact calculated arithmetically)
6. Efficiency improvements in standard displays

System Software, Firmware (BIOS) & Operational settings

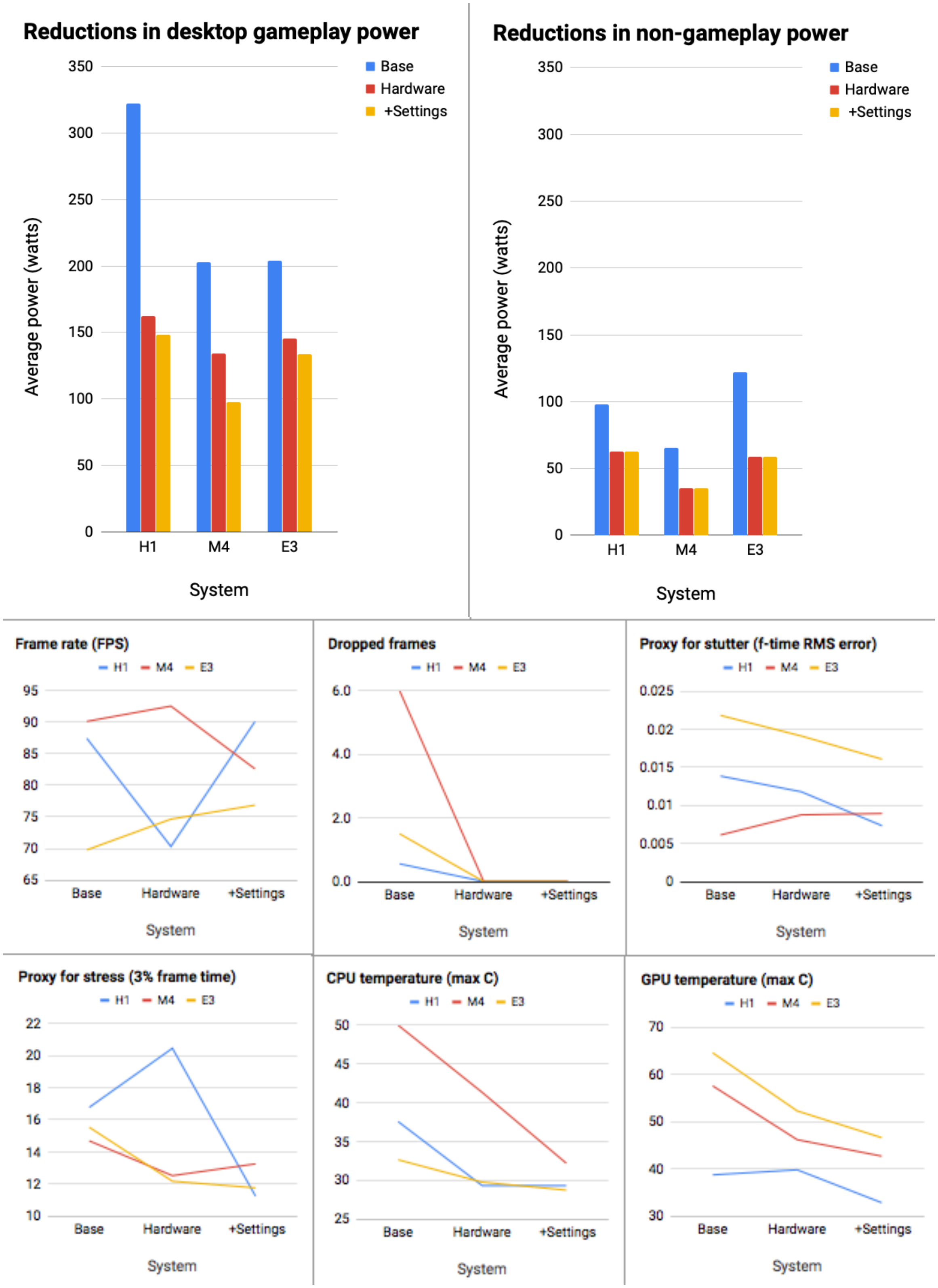
1. CPU BIOS
    - CPU underclocking
    - CPU undervolting (Including input voltage, offset voltage, Vcore voltage, CPU Cache voltage)
    - Enable power-saving CPU states (C1E, C3, C6, C7 [lowers idle power])
    - Enable Enhanced Intel Speedstep Technology
2. Other BIOS
    - Serial (COM) Port 0 = Disabled
    - EuP 2013 = Enabled
    - AMD Cool'n'Quiet feature = Enabled
    - Hot plugging = Disabled
    - SATA Aggressive Link Power Management = Enabled
    - Set fans = silent mode
3. GPU
    - GPU Underclocking
    - GPU power target setting (This limits the amount of power the GPU uses)
4. Other
    - Adjust case fan speed controls
    - Windows OS power plan changed to "Balanced"
    - AMD Radeon™ Chill (Dynamic Voltage Frequency Scaling)
    - Optimized rendering in VR

For the desktop systems, we found overall average measured savings of 52% in gaming mode and 48% in idle mode. The resulting savings in gaming mode ranged from 29 to 54% and those in the idle mode ranged from 35 to 62%. A further breakdown for hardware and operational measures is outlined in Figure 51. Additional energy saving factors and strategies have not been included in this package 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 fanless 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 our 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.

A key observation from Figure 51 is that the energy use of the improved High-end PC system was in range of that of the base Entry-level system. 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.

Figure 51.
Efficiency improvements for three tiers of desktop system price and performance



Performance and temperature metrics are averages measured during gameplay.

The Importance of Systems Integration

Gaming involves complex systems, and complex patterns of utilization. The primary devices (PC, laptop, console, or media-streaming) contain many interacting components, and are in turn connected to peripheral devices (displays, VR headsets, audio equipment, local network equipment, external graphics card docks, etc.) that cause the core system's energy use to vary. Computer networks and data centers are also increasingly utilized. 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 final service produced by the system. In the case of PCs, gamers or other third-parties sometimes build their own systems as well, leading to further potential for sub-optimization. Consoles, on the contrary, employ a "system-on-a-chip" approach that has far greater potential for standardization and optimization. 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.

Integrated sizing influences energy use. Even with today's much-improved componentry, further gains can be made with right-sizing. The most familiar sub-optimization in this regard is the oversizing of power supplies, discussed above, which operate less efficiently at low part loads. Other more-subtle interactions occur when systems are "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. A typical case of the latter is a CPU more powerful than necessary to run the selected GPU, although the opposite mis-configuration is more common. Another example is the aforementioned case in which VSync achieves significant energy savings by slowing down screen refresh rates to match the chosen display.

Our measurements determined that display choice has a strong effect on energy use within the PC, particularly the graphics card. As shown above, when 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.

Two of our systems—Entry-level system E3 and High-end system H2—demonstrate the variability of systems integration. Not surprisingly, as seen in Table 8, system H2 exhibits far greater user experience, as measured in a limited fashion by frame rate. It is also a system that can easily support VR, while system E3 is not powerful enough to do so. While system H2 uses 30% more power in active gameplay (averaged across the games), it uses less in every non-gaming mode (virtually the same in "off"). As a result, system H2 demonstrates substantially better energy proportionality, as well as a wider spread of power depending on the game, suggesting that it adapts more flexibly to the demands of a given game. Remarkably, system H2 uses less electricity under all four of our user-type duty cycles (from "Light" to "Extreme" users). The comparison also illustrates that similar fps/W metrics for two system are not useful indicators of relative user experience or energy use.

Table 8. Indicators of differences in systems integration quality for two desktop PC systems

	E3	H2	H2/E3
User experience			
Frame rate - Fire Strike benchmark	16	77	*4.8*
Frame rate - actual games	81	124	*1.5*
Frame rate range	16-110	60-224	
Power by mode			
Average power in gameplay	183	239	*1.3*
Average streaming power	134	98	*0.7*
Average browser power	146	79	*0.5*
Average idle power	134	88	*0.7*
Average sleep power	2.4	2.0	*0.8*
Average power in off	1.2	1.5	*1.3*
Energy metric (fps/watt)	0.45	0.51	1.1
Scaling			
Variation in gaming power x game (min-max)	1.8	3.5	*1.9*
Energy proportionality (power in gaming/non-gaming modes)	1.4	2.7	*1.9*
Annual electricity use (kWh)			
Light user	488	325	*0.67*
Moderate user	549	407	*0.74*
Intensive user	692	565	*0.82*
Extreme user	946	913	*0.97*

6. AGGREGATE ENERGY DEMAND

In this stage of our analysis, additional second-order energy use is also estimated. This includes that of connected displays, local networking equipment (LNE) and audio peripherals (speakers)[54] as well as network energy associated with streaming video and cloud-based games. For cloud-based gaming, we also include energy used in data centers hosting gaming servers, per the method described above.

[54] Speakers were assumed to use 21 watts on, 4 watts idle, and 1.4 watts off and LNE was assumed to use 11 watts constant (Urban *et al.,* 2017). 80% of desktop systems were assumed to have external speakers (Ibid) and 27% of the LNE power (3 watts) was apportioned to gaming activity based on an average of 3.7 networked devices per home.

Present-day Energy Consumption

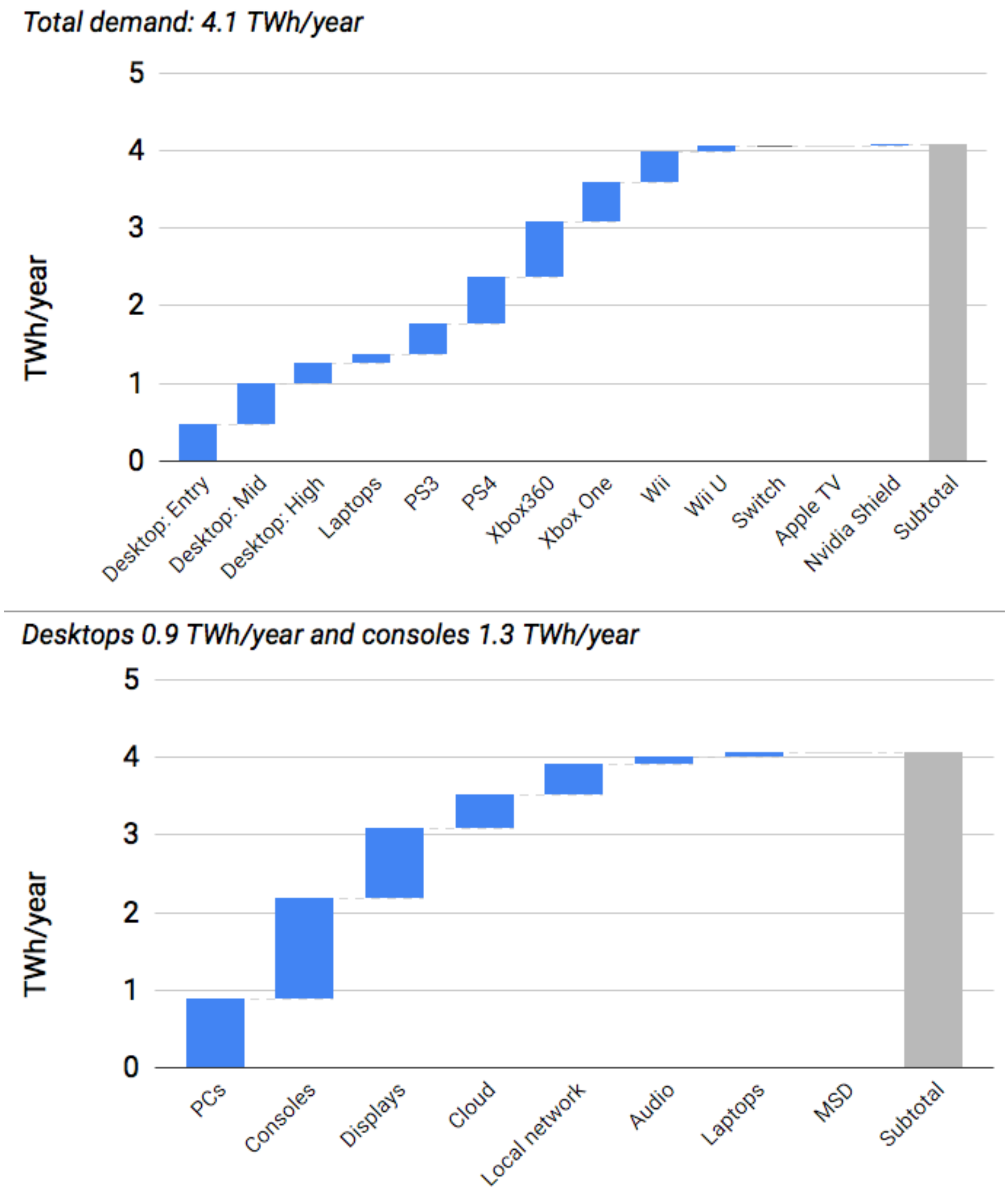
We estimate statewide gaming electricity use by applying our baseline unit energy consumption values for each system (weighted by the associated mix of user types and duty cycles) to the current installed base of equipment represented by that system (Figures 52a-b).

Per this approach, overall electricity use for gaming (local and cloud-based, across the duty cycle) in California was 4.1 TWh in 2016. Consoles are responsible for 66% of the total system-level energy use for computer gaming across the duty cycle, followed by 31% for desktops, 3% for laptops and less than 1% for media-streaming devices, with the shares shifting toward PCs by 2021 in the Baseline scenario. When considering only energy use at the core system level, PCs and consoles use almost the same amount of energy by 2021.

Considering only the core systems, energy use for PCs is 0.9 and for consoles is 1.3 TWh/year in 2016. Gaming mode is responsible for 40% of total energy use on the client-side for consoles and 31% for desktop PCs, 29% for laptops, and 7% for media streaming devices. In all cases, idle and sleep (PCs) or connected standby (consoles) remains a source of energy use as well, 40% in the case of consoles and 45% in the case of PCs (Figure 53)

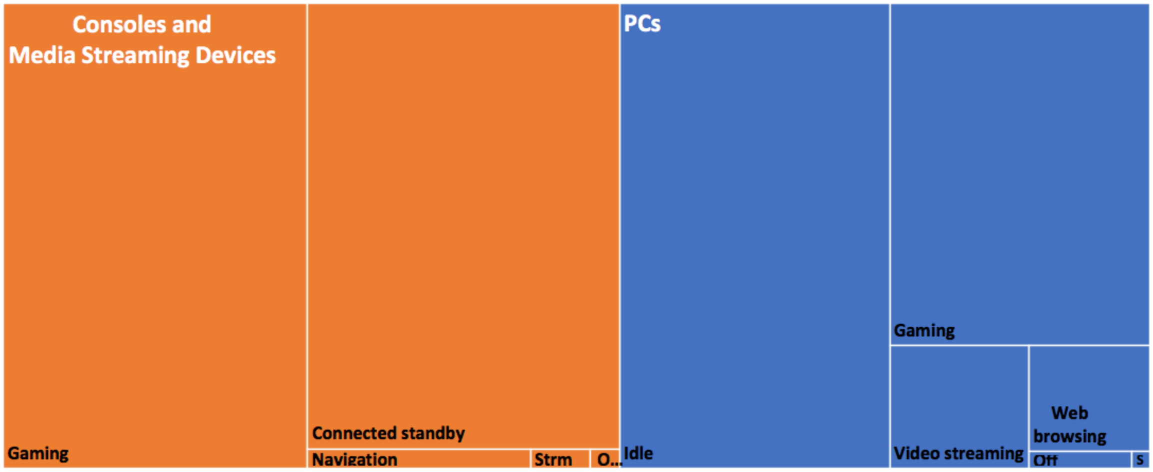
This is placed into a broader context in Figure 54, which compares gaming energy to that of other plug loads, and Figure 55 which does so strictly for consumer electronics. We find that computer gaming—including the primary systems together with associated peripheral devices—is responsible for nearly a fifth (19%) of all energy consumed within the residential miscellaneous end-use in California. Computer gaming emerges as the second largest broad category of consumer-electronics plug loads in California, second only to television and other media viewing, consuming about 25% of that total.

Figure 52a-b.
Structure of California gaming energy use in 2016



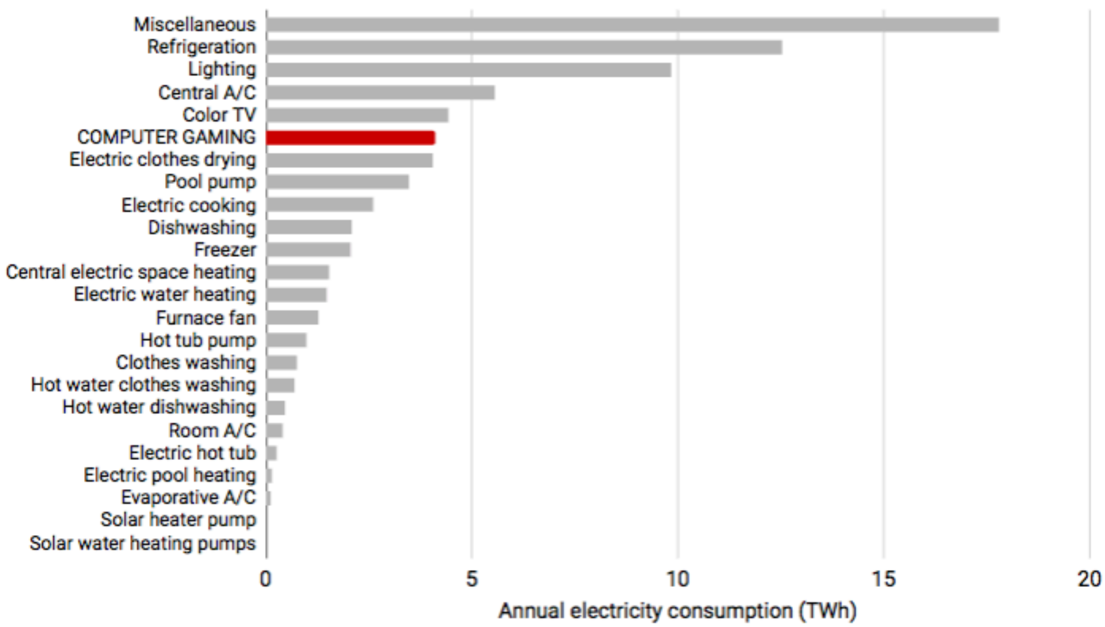
In the upper panel, the energy use of each system includes associated displays and peripherals (audio, local networking equipment) as well as upstream network and cloud-based computing workloads. Media streaming devices were just emerging in 2016 and their energy use was nominal at that time.

Figure 53.
Aggregate client-side Baseline energy use by platform and duty cycle: gaming and standby/idle are dominant modes: California 2016



Excludes display and network energy.

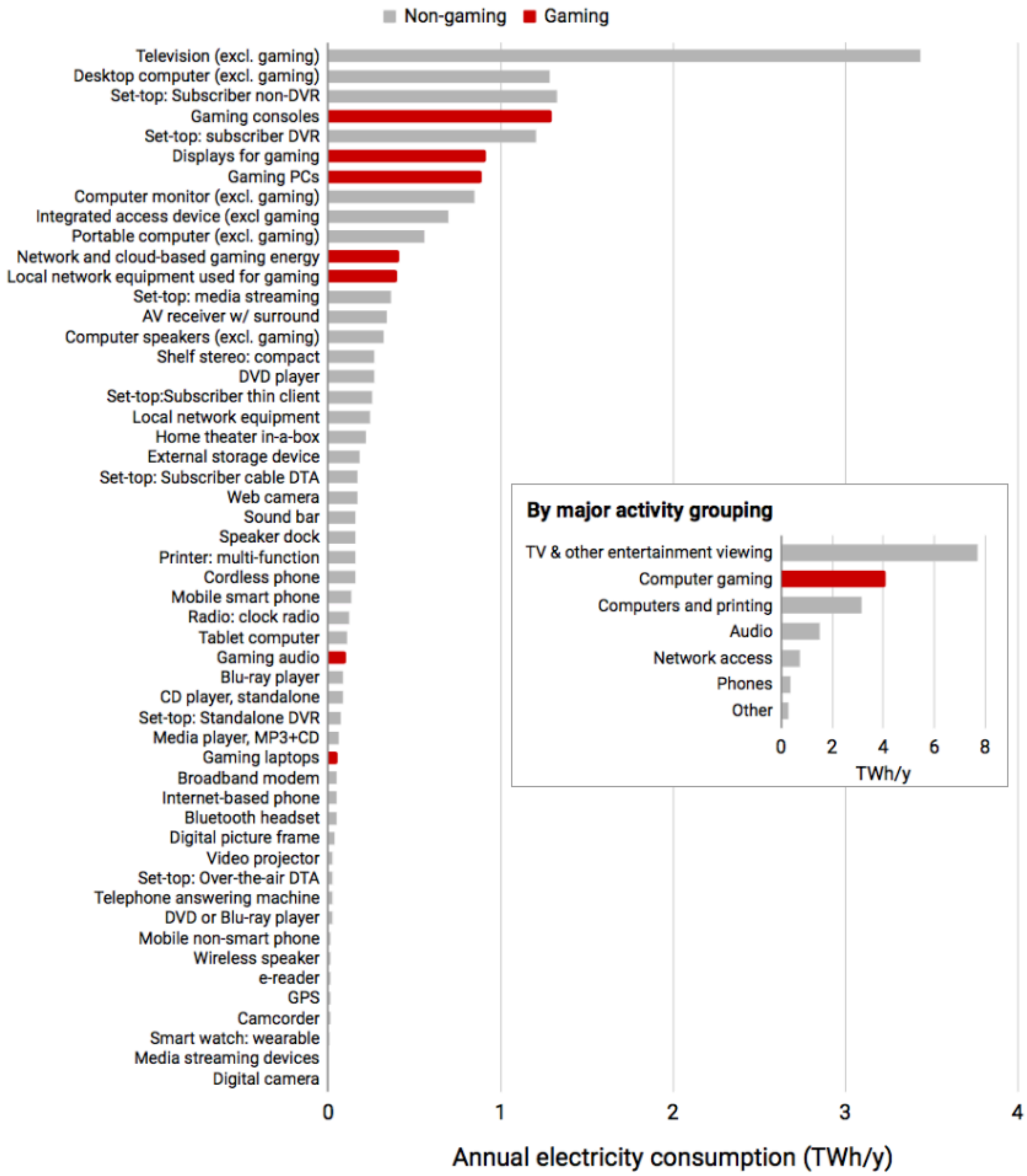
Figure 54.
Computer gaming consumes more electricity in California than many familiar residential uses



For the purposes of this chart, unlike the other end uses, "Computer Gaming" includes multiple device types: desktop and laptop computers, consoles, and media streaming devices and associated displays, local network equipment, and speakers, and associated network and data-center energy. Values shown for Color TV are net of our estimates for their use while operating gaming devices, and the Miscellaneous total is net of Computer Gaming. Gaming estimate for 2016; other end uses are estimates for 2015.[55]

[55] See http://www.energy.ca.gov/contracts/GFO-15-310/12-Attachment-12-Energy-Efficiency-Data_2015-11-10.xlsx The CEC does not further disaggregate miscellaneous.

Figure 55.
California gaming consumes one-quarter of California's consumer-electronics electricity



Values for end-uses other than computer gaming platforms are derived by multiplying national values from Urban et al., (2017) by the ratio of U.S.-to-California population. Chart includes network and data-center energy for reference although these are not formally loads occurring inside the household. Gaming estimate for 2016; other end uses are estimates for 2017.

Recent Trends and Future Scenarios

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. 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.

We define a primary Baseline scenario for how the installed base might evolve to the year 2021.[56] We hold the year-2016 unit energy consumption for each system constant in the Baseline scenario for 2021. For comparison, we then apply a scenario with improved energy efficiency. This enables an examination of the distinct roles of efficiency and structural change in the installed base.

Providing context for alternate broader structural market developments, we create three alternative Baseline scenarios reflecting alternate structural and market trends that could drive energy use either upward or downward. We cast each such 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 potentials thus defined are to be regarded as full-saturation technical opportunities for the particular set of measures considered (Appendix F), 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, as seen in Figure 10, it is equally possible that improved efficiencies will be offset by increased workloads (e.g., for streamed VR gaming).

Cloud-based gaming takes on varying importance in our scenarios. While on the one hand power requirements of GPUs and other componentry in cloud-gaming servers may decline over time, our 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. Meanwhile, the broader PUEs 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 our scenarios. Thus, we do not alter server characteristics or the assumed PUE (1.5) across scenarios. This is an area that merits future investigation.

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[56] The Nintendo Switch was just being introduced to the market as of our initial assessment, at which time projections were not possible (Mills *et al.,* 2017). As an indication of its popularity, 10 million units were sold in the ensuing nine months and it is expected to exceed all-time sales of the Wii U within its first year on the market. We thus add the Switch to our scenarios, offsetting all attrition in other Nintendo units to the year 2021.

Games are also downloaded from the Internet, which results in additional energy use associated with Internet data transmission. Insufficient data are available on the dimensions 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 that is beyond the scope of the present assessment and insufficient data are available to model it thoroughly in any case.

A key assumption for both cloud-based gaming and game downloads is the rapidly evolving network electricity intensity (kWh/GB of data transmitted). Per Aslan *et al.,* (2018) we assume a rate of 0.15 kWh/GB in 2011, 0.027 kWh/GB in 2016, and 0.005 kWh/GB in 2021. This strongly attenuates the amount of energy that would otherwise be used in association with streaming and cloud-based gaming. We 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.

Current energy estimates and baseline projection to 2021

Historically (2011 to 2016), the rapidly changing nature of the installed base is evident. 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 (Appendix A). Gaming laptops saw a decline in each tier, while consoles saw an approximately 20% 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 our use model.

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. We estimate California gaming electricity demand at 4.9 TWh for the year 2011.

Looking forward, market shares of Entry-level, Mid-range, and High-end systems will shift towards the more energy-intensive end of the spectrum by 2021. Aside from the core systems, active power for connected displays are assumed to be at the average of the Energy Star V5 specifications for 2011, an average of V6 and V7 for 2016 (in effect October 2009), and V7 for 2021 (in effect July 2016). Active power for TVs were calculated using the efficiency curves from Urban *et al.,* (2017): an average of the 2007 and 2010 curves for 2011, an average of the 2010, 2013, and 2015 curves for 2016, and the Energy Star V8 level for 2021.

In the Baseline 2021 scenario, user behavior and annual energy use per gaming system are assumed to remain unchanged from base-year (2016) conditions, although the long-standing trend towards improved efficiency in Internet infrastructure is assumed to continue. Ongoing structural change in the mix of systems in the installed base continues to the year 2021, with consequent implications for energy use. We assume that the 5% rate of overclocking in 2016 remains unchanged as well.

Projections developed in by Mills *et al.,* (2017) suggest that the California installed base of desktops and laptops will rebound during the scenario period from 3.1 to 3.5 million units (10%), while that of consoles rises from 11.9 to 13.4 million (12%). Some of this expansion is absorbed by the emerging media streaming devices for gaming, which increase in number from 150,000 to 690,000 (361%).

Drivers of the rebound in desktop and laptop gaming reflect multiple factors, including that some Entry-level PCs have now eclipsed console-gaming capabilities, high-resolution (1080p) desktop displays priced just over $100, rising popularity of e-sports watched on computers, and a degree of fatigue with mobile gameplay. New PC users will likely seek higher-end gaming equipment and cloud-based on-demand services, the latter of which are now also becoming available to some consoles. The installed base of the most energy intensive High-end desktops grows from about approximately 150,000 to nearly 400,000 units by the year 2021 while the emergence of energy-intensive media streaming devices (when counting network and data-center energy) is very substantial.

We assume that 4k displays achieve a 15% market penetration by 2021 for PCs and 4k televisions upon which console gaming occurs achieve a 20% market penetration. We also project that 20% of gaming is cloud-based by 2021. Alternate scenarios (described below) test the effect of differences in these baseline assumptions.

Baseline energy efficiency opportunities

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 3.2 TWh/year (17%). This reduction represents the diverse bundled impacts of systems, displays, peripherals, etc. The underlying per-unit savings for constituent core PC systems as shown previously in Figure 51 (e.g., 52% gaming mode and 48% non-gaming for PCs and 41% for consoles) are diluted by the consumption of other components, some of which are unchanged, such as data centers hosting cloud-based gaming servers.

As described above, key trends in system-level energy efficiency for gaming mode involve graphics processing, the streaming of those graphics, and the rendering of the ultimate imagery. GPUs can continue to become more efficient. The trend towards eye-tracking foveated reconstruction as the standard operating mode for all head-mounted "virtual reality" displays will go a long way towards managing future energy demand associated with virtual reality growth. For other modes, power management and

CPU/motherboard efficiencies are quite important, and power-supply efficiency benefits every part of the duty cycle.

Improvements in each of these areas can however be offset—and even overwhelmed—by parallel trends and desires in user experience that can increase the computational workload. These include faster processing, larger and/or higher resolution displays as well as intensified user experience offered by the games themselves which may be more energy intensive.

For the Baseline scenario, two-thirds of the 650 GWh/year savings in 2021 are attributable to PCs, with the balance from consoles.

Following are several alternate scenarios. They are not predictions, but, rather alternate paths along which the market could evolve.

Alternate Baseline Scenario 1 – Surge in High-fidelity Desktop Gaming & Virtual Reality

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 our 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,[57] 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-range and High-end PC installed base. The trend towards increased time spent gaming continues, with 25% more time spent in gameplay and 20% of gamers implementing CPU overclocking.

Alternate Baseline Scenario 2 – Strong Uptake of Cloud-based Gaming

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

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

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% 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 equivalent to those while streaming. As noted above, we assume a Power Utilization Efficiency (PUE)[58] of 1.5 to represent the types of data centers most likely to host cloud-gaming servers (Shehabi *et al.,* 2016). 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 – Shift to Consoles

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.

[58] Ratio of total data center load to the IT load.

Gaming energy futures for California

Table 9 and Figure 56 summarize the scenarios and their outcomes.

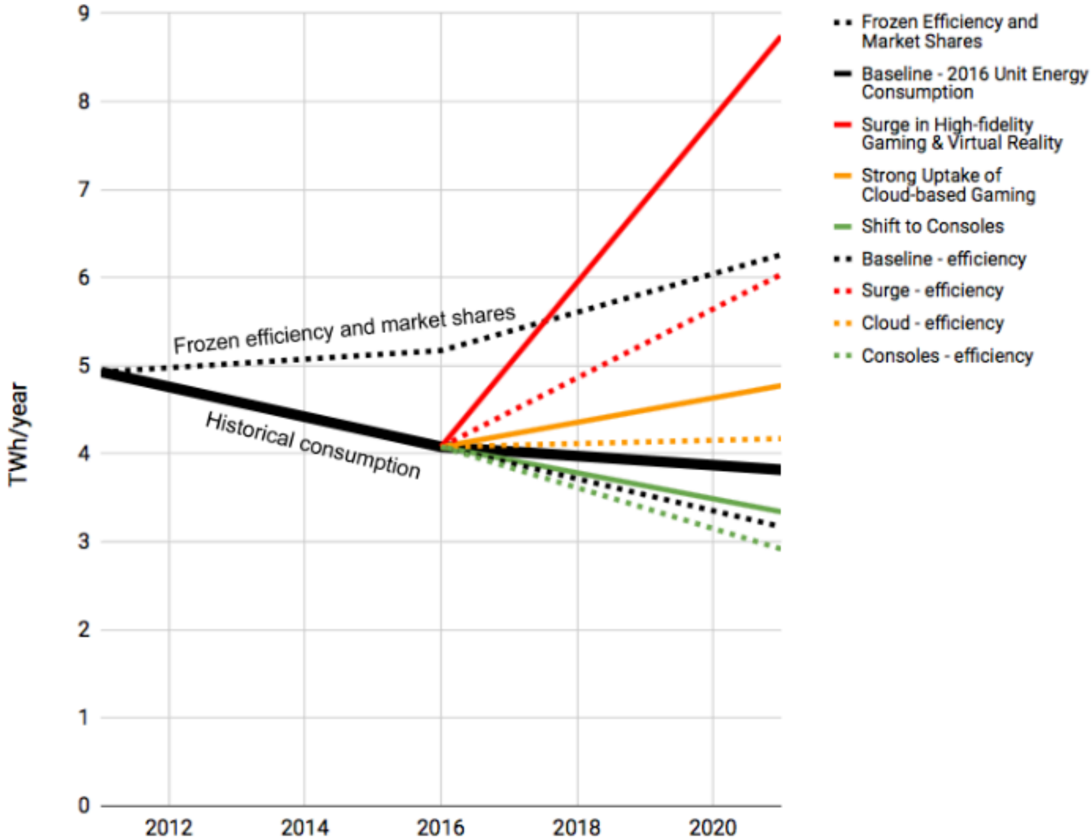
Table 9. Alternate California gaming future scenarios for the year 2021

	2016 conditions	2021 Baseline Conditions - 2016 Unit Energy Consumption	2021 Scenario 1: Surge in High-fidelity Gaming & Virtual Reality	2021 Scenario 2: Strong Uptake of Cloud-based Gaming	2021 Scenario 3: Shift to Consoles
Installed Base/Behavioral changes		No change from baseline	Doubled Mid-range and High-end gaming desktop installed base (users shift from the existing Entry-level gamer population) 40% of console users convert to PCs capable of VR	10% increase in overall number of gamers -- across all platform types (all are media streaming device users)	Aggregate installed base is unchanged, but 50% of gaming laptops and 50% of PCs used for gaming convert to consoles
2D displays: 4k **Televisions: 4k**	All displays 1080p	15% of stock 20% of stock	30% of stock 50% of stock	No change from baseline	No change from baseline
Virtual Reality	Negligible	Negligible	20% of Mid-range and High-end desktop and laptop systems utilize virtual reality.	No change from baseline	No change from baseline
Cloud-based gaming	5% of gaming hours	20% of gaming hours	No change from baseline	75% of gaming hours	No change from baseline
CPU Overclocking	5% of gamers	No change from baseline	20% of gamers	No change from baseline	No change from baseline
Duty cycle		No change from baseline	25% increased time in gameplay across all gamers	25% increased time in gameplay across all gamers	No change from baseline

Additional key baseline assumptions: Weighted average of 1.1 displays for desktop systems. Laptops utilize external displays half the time. A secondary 2D display is paired with each system using VR. 80% of desktop systems use external speakers. By 2021, 60% of consoles have 8th-generation levels of energy efficiency. Average television connected to consoles increases from 43" to 46" by 2021.

Efficiency variants to each Baseline scenario assume: 25% of the installed base present in 2016 is still in the stock in 2021 (and has not been altered in any for improved energy efficiency). PC "package" savings for new units 52% in gaming mode and 48% for non-gaming mode. Consoles that are 8th-generation and added to installed base after base year use 41% less energy across the duty cycle compared to pre-existing units. For display and connected television sizes, see Table 6.

Figure 56.
Enormous potential variations in California computer gaming energy demand driven by market structure, user behavior, and energy efficiency: 2011-2021

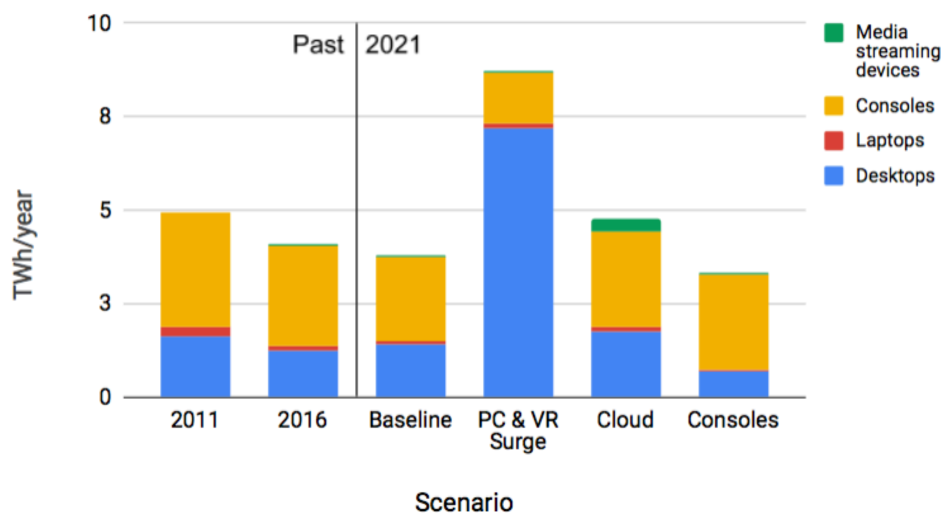


Solid lines are baseline projections, while dotted lines of the same color represent near-term efficiency improvements for the indicated scenario (same proportionate savings assumptions as Baseline scenario described in the text). The "Frozen efficiency and market shares" case (dotted black lines) reflects 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 timeframes of these scenarios, savings do not fully reflect stock turnover of core systems and displays.

The heavy dotted black curve in Figure 56 entitled "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% lower than this "Frozen efficiency and market shares" level, and the 2021 consumption is 39% 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% 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, etc. Figure 57 disaggregates demand by gaming system type, while Figures 58a-c segregate those results by sub-system type.

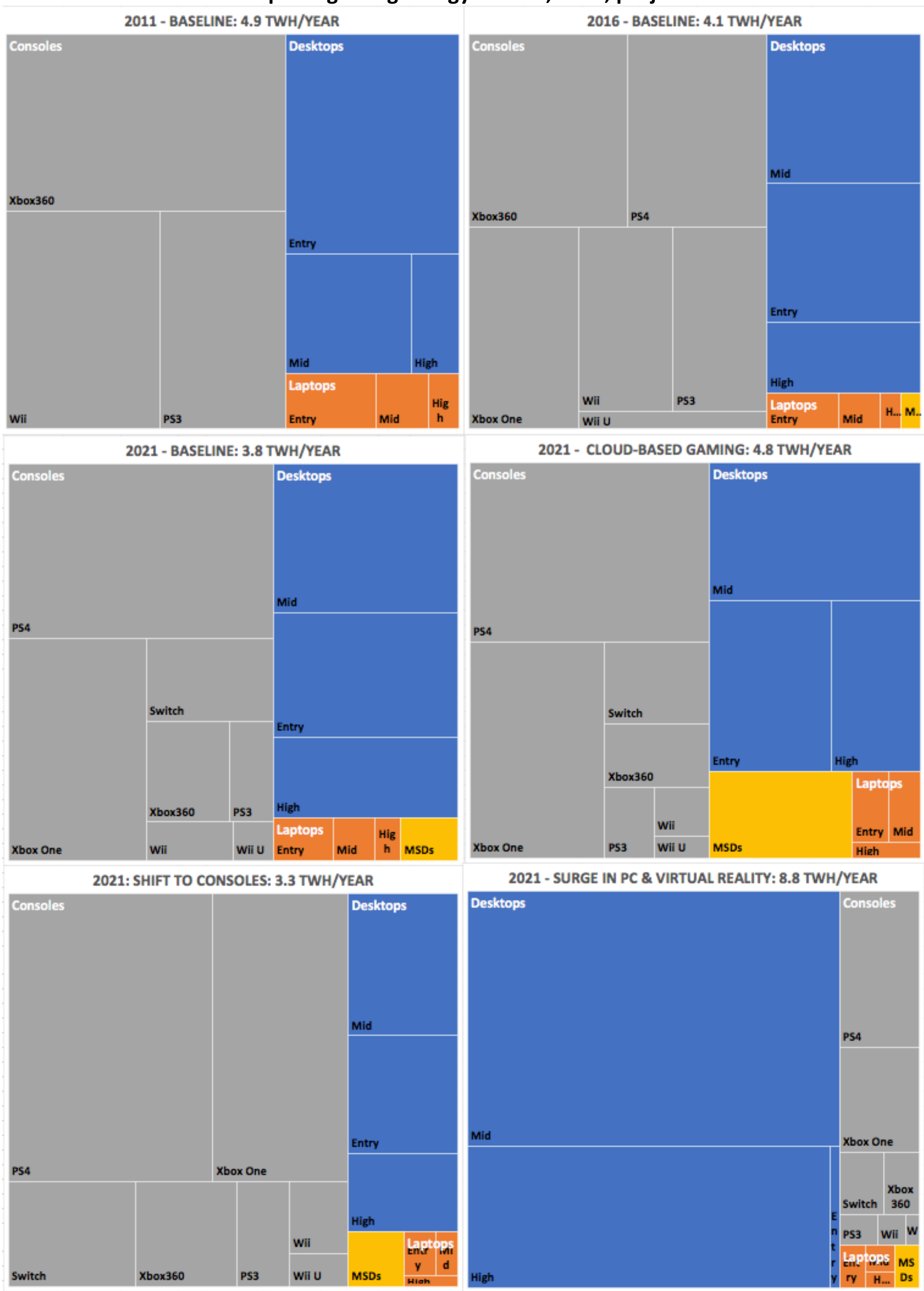
Figure 57. Consoles or PCs dominate energy demand, depending on scenario



Includes energy associated with displays and peripherals, as well as network and cloud-based workloads.

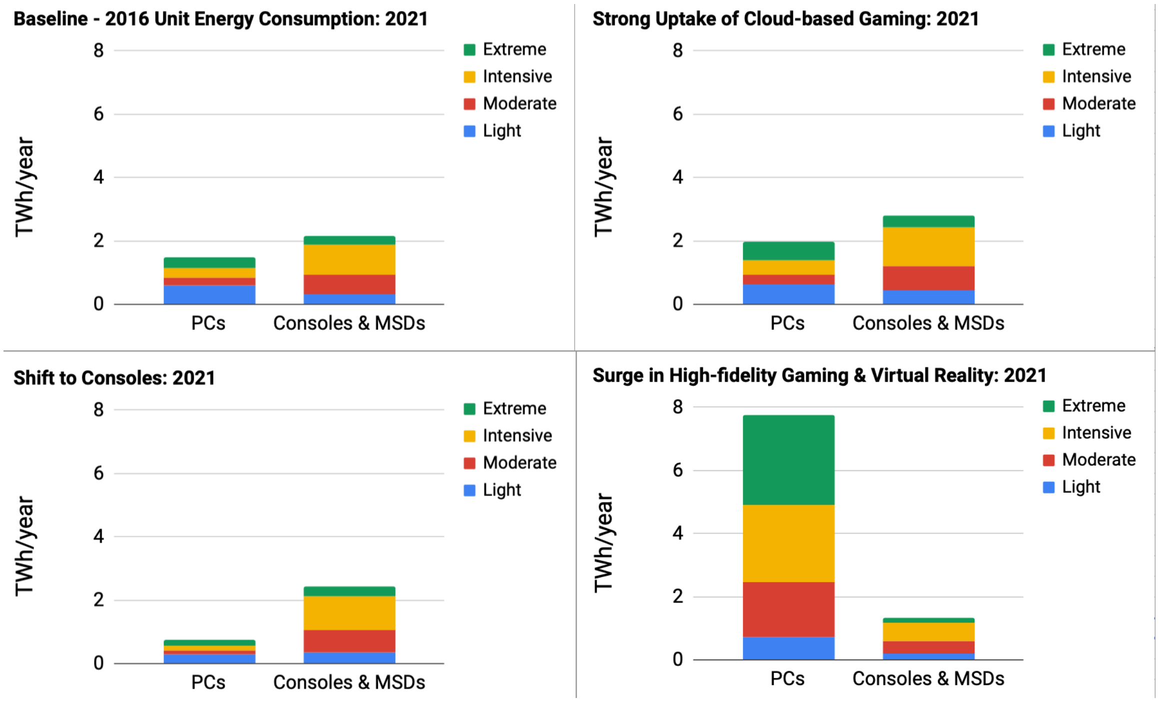
Figure 59a-d further segregates the results by user type. Intensive gamers tend to be the user group associated with the largest segment of energy use across all platforms. Consoles and PCs alternate in dominating energy demand, depending on scenario.

Figure 58a-e.
California computer gaming energy in 2011, 2016; projection to 2021



Includes display and network energy.

Figure 59.
The "Intensive" user type is dominant in most cases and scenarios



Includes energy associated with displays and other peripherals, as well as network and cloud-based workloads.

Figures 60a-h break down the total electricity use of the primary Baseline and alternate scenarios by system type (left column) and by locus of electricity use, e.g., 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**: Although energy efficiency does not change in this case, and despite an increase in total installed base, total electricity consumption decreases by 6% from 2016 levels. This is due to structural shifts in the installed base towards less energy-intensive gaming systems, i.e., 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% reduction in aggregate demand.

- **Surge in High-fidelity PC Gaming and Virtual Reality**: The greatest demand growth from 2016 levels (114%) 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%

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

- **Shift to Consoles**: Electricity demand declines by 18% 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%.

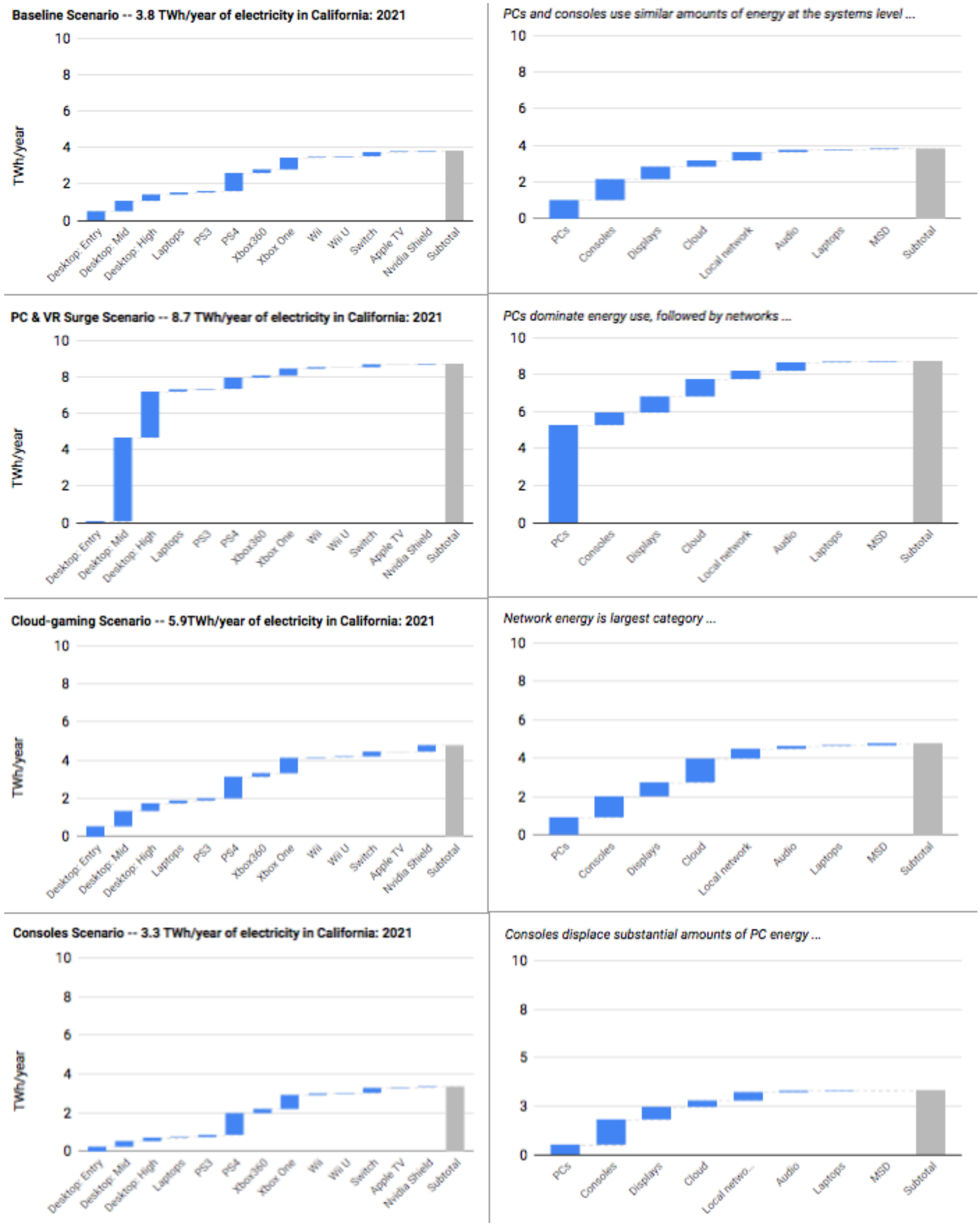
- **Other possible outcomes**: A combination of increased cloud-based gaming and the transition to more PC gaming, could yield a far higher electricity demand trajectory – around 11 TWh/year.

Examples of factors that could give rise to higher energy consumption than captured in these scenarios include introduction of new energy-consumptive peripherals (e.g., 8k displays, now entering the market), more energy-intensive user experiences requiring more computationally intensive software (e.g., 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. We have 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.

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% of total gaming energy demand. Conversely, in the Consoles scenario, demand declines in absolute terms (offset by the introduction of lower-intensity devices such as the Nintendo Switch), but represents about 76% of total baseline gaming energy demand in 2021. Media streaming devices are responsible for 7% 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 Appendix G.

Figure 60a-h.
California computer gaming scenarios by system (left) and category (right)



Uncertainties

Uncertainty is an unavoidable factor in analyses such as this. We have made a concerted effort to identify and manage these uncertainties, while carrying out numerous parametric tests to gauge the sensitivities of key assumptions.

Sources of uncertainty in user behavior include duty cycle, apportionment of gamer population to the four user types, system and in-game settings, power management, game choice, and variance in duty cycle and gameplay energy among real-world gamers. Stipulation of user types was based on industry expert judgement rather than survey data (which does not exist). Our duty-cycle definitions are based on best-available data. Energy-relevant gamer behavior is certainly an understudied topic. We examined a range of user-specified system and in-game settings, discussed above and in Mills *et al.,* (2017). Most of these have small (single-digit) percentage effects on energy use during active gameplay, and far less so in other parts of the duty cycle. Game choice is a very difficult uncertainty to manage insofar as there are thousands of games and user preferences vary by platform, demographics, etc. Moreover, the games are constantly being updated. We measured energy use across a large number of popular games, and, as described above, have identified enormous variation in energy use for a given game and platform effect they have on energy use. Analyses here under gameplay are the simple averages of outcomes for all games tested, i.e., no effort was made to weight those outcomes by the market share of each game. The type and mix of games is constantly changing.

Sources of uncertainty in the characterization of the market include the specification of the 26 systems chosen to represent the market for bench testing and characterization of the installed base. We reviewed extensive literature and commissioned experts in the gaming marketplace to create an energy-relevant characterization of the installed base and user behavior (Mills *et al.,* 2017). Our selected baseline systems represent a very granular look at the market, covering the full range of cost and performance sought by gamers. All major consoles in the installed base were tested. The combined weight of each system and user-type in the installed base is one source of uncertainty in our characterization of the market.

Sources of uncertainty in the bench-testing of individual systems include power and performance measurement accuracy, the repeatability of our test procedures, and representativeness of the bench testing performed by project staff of the behavior of gamers "in the wild". Our measurement accuracy is high. System power is measured within +/- 0.1% accuracy. We conducted comparative trials to evaluate the repeatability of the human tests and simulated frame-rate benchmarks. Among multiple trials by two in-house testers, average measured power varied by 2.4% or 1.4 watts for Skyrim (3 tests) and 2.2% or 2.5 watts for Call of Duty Black Ops (4 tests). Average frame rates varied by 0.4% and 6%, respectively. The combined efficiency metric varied by 2.8% and 11.7%. We deem these variations well within the necessary precision and acceptable uncertainty band for our broader analyses. Surprisingly, we saw variations in power and frame times among the Fire Strike trials as well, which is unexpected from a programmatic simulated frame-rate benchmark (no human role in gameplay choices). Overall Fire Strike scores were very similar (less than 1% variance), however.

Sources of uncertainty in the estimates of present and future statewide energy use center on projections of structural change in the market—which ultimately represent gamers' choices of equipment and services such as cloud-based gaming discussed previously—and the level of energy efficiency that can be achieved in data centers and networks. The alternate scenarios are normative by design, and represent the boundaries of how the market could evolve differently than the Baseline scenario. Our energy efficiency packages address many opportunities but are certainly not all-inclusive and do not attempt to capture innovations that have yet to be brought to market. All hinge on user awareness and implementation, and thus the degree to which the technical potential defined here is captured in practice is a matter for consumer temperament, education, and policy-making. The factors underlying these projections are constantly in flux in the actual market, suggesting that such scenarios be updated often to maintain their relevance for energy planning.

7. NON-ENERGY DRIVERS OF ENERGY EFFICIENCY

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.

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 some gamers on high-power systems will 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, i.e., miniaturization and efficiency pursued to achieve portability and long battery life.

There are indications that certain energy efficiency strategies may improve game performance. Following examples we encountered in our 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% energy savings (battery life improvements) and reduced GPU temperature, while decongesting the graphics pipeline with unneeded frames thereby improving user experience (37% decrease in frame time).[59] This benefit is highly game-specific and we found it to be 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 our 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 we did not test this hypothesis in our research.

- A new frontier is VR is Foveated *Reconstruction*, which uses eye tracking to render only the area at which the user's eye is actually looking (rather than a fixed zone in the geometric center of view irrespective of where the gamer's eyes are focused). Foveated reconstruction stands to save additional energy while enabling a better user experience and opening up new opportunities for in-game functionality. According to Nvidia,[60] resolution can be boosted well above normal in the central area of vision even while saving energy overall by relaxing resolution in the periphery—and even shifting to black-and-white—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 evaluating our efficiency packages, we 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 51).

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

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

8. ENERGY COSTS AND GREENHOUSE-GAS EMISSIONS

Total Cost of Ownership

Gaming involves considerable investment on the part of individual consumers, more than most other plug loads. The desktop systems we evaluated ranged from several hundred to several thousand dollars, while consoles are in the $250 to $500 range. The VR equipment ranged from $200 to $500. Displays and televisions can cost even more than the gaming equipment itself.

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 $3 to $1700 on energy over a 5-year product life (Table 10). In some cases, these values approach or even exceed the equipment purchase price. Costs can range far higher than those shown here, depending on actual equipment choice, peripherals, time in gameplay, games played, and energy prices.

Table 10. Lifecycle costs (fixed + operational) of individual computer gaming systems

Gamer and system type			5-year energy cost at given electricity price				
			Electricity price ($/kWh)				
Light Gamer	kWh/y	Purchase cost	**$0.10**	**$0.15**	**$0.20**	**$0.25**	**$0.30**
Entry-level PC	236	$550	$118	$177	$236	$295	$354
Mid-range PC	285	$1,500	$143	$214	$285	$356	$428
High-end PC	373	$2,500	$187	$280	$373	$466	$560
PS4 Pro	99	$400	$50	$74	$99	$124	$149
Xbox One	101	$500	$51	$76	$101	$126	$152
Switch	5	$300	$3	$4	$5	$6	$8
Extreme Gamer							
Entry-level PC	521	$550	$261	$391	$521	$651	$782
Mid-range PC	897	$1,500	$449	$673	$897	$1,121	$1,346
High-end PC	1101	$2,500	$551	$826	$1,101	$1,376	$1,652
PS4 Pro	398	$400	$199	$299	$398	$498	$597
Xbox One	318	$500	$159	$239	$318	$398	$477
Switch	37	$300	$19	$28	$37	$46	$56

Notes: Lifecycle cost is purchase cost plus 5-year energy cost. Marginal electricity prices can be substantially higher than those shown above.

Statewide Energy Expenditures

From an aggregate perspective, the 4.1 TWh/year that computer gaming systems use today in California translates to approximately $700 million/year[61] in energy expenditures, hypothetically rising to $1.1 billion/year as the stock grows but without efficiency improvements or structural changes that can influence energy demand. Under our most energy-intensive ("Surge") scenario, costs rise to $1.5 billion per year, while they fall to $500 million/year in our least energy-intensive ("Consoles" plus efficiency) scenario.

Perspectives on Cost-benefit Analysis

Energy consumers and policymakers are typically eager to understand the cost-benefit tradeoffs of efforts to improve efficiency. As is the case with many energy end uses, non-energy factors such as those discussed in this report are also key sources of value but are rarely quantifiable. In addition, reduced heat gains in cooling-dominated climates of course translate to reduced air-conditioning costs, which we have not quantified here.

As indicated by our analysis, some of the energy savings potential comes at no cost, i.e., is based on software and user settings rather than hardware investments. Game choice, also not requiring investment *per se*, can also create savings although we have not stipulated any of this sort of user behavior in our scenarios.

Other categories of improvements do indeed entail a capital cost. These include improved CPUs/motherboards, GPUs, and power supplies. In some cases, proper system integration and "right sizing" of componentry to eliminate bottlenecks offers first cost *savings* in conjunction with operating cost savings. We encountered three variant illustrated cases of this in system H1, which was a dual-GPU system using Fury X GPUs, which retail at approximately $400. Removing one of these drives resulted in substantial energy savings while performance was improved.

Ultimately, gamers' decisions about implementing more energy-efficient systems hinge predominantly on non-energy benefits, limiting conventional cost-benefit analysis to an academic exercise.

Greenhouse-gas Emissions

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 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 (Table 11).

[61] Assuming the CEC default state-average residential electricity price of $0.1698/kWh. At the marginal prices where this actually occurs, the value would be two- to three-times higher.

Table 11. California computer gaming energy consumption, expenditures, and emissions

	Annual electricity use (TWh)	Annual electricity expenditures ($billion/year)*	Annual greenhouse-gas emissions (MT 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%

* Costs computed at average residential electricity prices. At the marginal prices where this actually occurs, the value would be approximately 50% higher.

9. POLICIES TO PROMOTE GAMING ENERGY MANAGEMENT

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, etc. In other cases, where the service may be changing gradually over time or across product categories (e.g., with larger and larger refrigerators), normalizations of efficiency metrics (e.g., 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 purpose-built gaming PCs. 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. We find that 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 utilize products. As driving conditions and habits changed over time (and roadways became more congested), the U.S. fuel-economy ratings eventually under-predicted actual energy use by over 30% 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, etc.), 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 energy-benchmark.

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, e.g., 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 (e.g., 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 (Figure 10). Console manufacturers have demonstrated a more decisive reduction in gaming power requirements in recent years (Figure 9). 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 our 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, total 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 our 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

In order 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 (e.g., 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.

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)[62], or address only one component in the system (e.g. power supplies[63]). 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, etc. Moreover, in some cases (e.g., 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

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

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

decisions and perhaps establish a set of best practices in this regard. Perhaps even more importantly, opportunities may exist to work with the creators of game-development engines – we have identified 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 (e.g., "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.

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 U.S. EPA once considered labeling for consoles, but they struggled with finding an appropriate energy-per-performance metric and protocol 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.[64] 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, 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).

Lack of attention to PCs and laptops used for gaming 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

[64] See http://www.efficientgaming.eu. Note that this activity has not historically addressed gaming-mode operations.

consoles while turning a blind eye to gaming on PCs. 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 absolute 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 for motherboards (even TDP) are not available to consumers.

As demonstrated in this report, power requirements vary considerably depending on the test procedure, which game is being played, etc. 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.[65] 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 PC idle mode (Figures 20a-b) suggest the need for real-world idle test cycles rather than idealized ones.

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

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

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[66] may provide models that an interested third-party could offer to the marketplace. Creating new energy-delimited game genres would be a complementary way to categorize games, as it is clear from Figures 28 and 30 that, perhaps counter-intuitively, energy use does not track genre among PCs or consoles.

Mandatory Standards and Ratings

The latest California standard for personal computers effectively excludes those purposely 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 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).

We have previously discussed the 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, e.g., regarding power management in CPUs, GPUs, or motherboards. The benefits of component-level standards would spill over into mainstream PCs as well.

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

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. Much more analysis is necessary to clearly characterize this source of gaming energy use and to identify downstream efficiency opportunities.

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).

10. CONCLUSIONS & FUTURE DIRECTIONS

We 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 energy demand growth that would be caused by an expanding installed base of gaming systems. Our scenarios defined an envelope in which energy use, cost, and emissions rise by 114% or drop by 28% from 2016 levels, depending on how 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.

Taken in aggregate, gaming energy use is greater than that of many more well-understood plug loads. High-performance gaming computers are among the very most energy-intensive plug loads in use, and are arguably the most difficult to characterize. Many avenues remain to be explored, with broad opportunities spanning technology, user behavior, and energy policy.

The evolution of gaming technology has shown that on the one hand improved efficiencies (performance per unit energy) can readily be captured, but also that the energy penalty for rising numbers of users together with demands 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 computer and console gaming trends insofar as the average absolute per-unit power for consoles is falling, while that of computer-based gaming systems is increasing due to structural shifts towards higher-end systems.

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.

Especially in light of the complex nature of gaming energy services, much must be done to define and promulgate better methodologies for testing and energy-per-performance metrics, e.g., establishing realistic standardized test procedures for gaming mode, considering the highly varying energy use across games, capturing the effect of individual and multiple displays, improving non-gameplay test procedures that reflect the way gamers use their systems and displays in practice (particularly in PC idle modes).

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.

System integration offers opportunities beyond component-level measures. Increased attention to power management is one such promising avenue for capturing energy savings. As suggested by our analysis showing the ratio of power requirements during gaming and non-gaming modes, the current efficacy of power management is uneven across all gaming products and their sub-components, even in idle mode. Best practices could be more widely promulgated, and emerging technologies more usefully deployed.

Virtual reality stands to become a dominant upward influence on energy use for all gaming platforms, perhaps more by virtue of the more highly-powered gaming systems selected to run it than the headsets themselves. 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 called "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. Importantly, VR technology is rapidly finding professional applications in science, medicine, and other fields. Moreover, new VR technologies may prove to be vastly more energy-intensive than those in today's marketplace, particularly if VR is streamed from data centers.[67]

A critical trend is online games and the use of cloud-based graphics servers to perform the graphics rendering services, which is shifting much of the energy demand from homes to data centers, and the networks connecting them to gamers. Among the important research questions are the efficiencies of servers and data center infrastructure hosting the servers, part-load conditions experienced by the 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.

We find that 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. 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. Where enabled, developers may consider "gamifying" this information. Gamers seek out goal-driving systems for scoring and garnering merit for doing so. Carbon could be introduced as another variable.[68]

For energy planners, 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, policies have to be developed quickly and be very adaptable, supported by routine market assessment and system testing in order to maintain awareness of changing marketplace and associated drivers of energy demand.

[67] For example, the Wide-Area Visualization Environment (WAVE) strategy being developed by the University of California is utilizing 20 high-power (GTX 1080) graphics cards driving approximately six 4K 3D televisions placed in a semi-circular configuration.

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

APPENDICES

Appendix A – California Installed Base by Year, System Type, and Scenario

Installed base (number of systems)								
		Baseline			Efficiency	Surge	Cloud	Consoles
System type	User type	2011	2016	2021	2021	2021	2021	2021
Desktops	Entry	2,367,830	1,331,621	1,404,168	1,404,168	169,475	1,404,168	702,084
	Mid	471,587	726,290	843,816	843,816	5,350,772	843,816	421,908
	High	155,294	290,517	390,877	390,877	2,478,614	390,877	195,439
	Total	2,994,711	2,348,428	2,638,861	2,638,861	7,998,861	2,638,861	1,319,431
Laptops	Entry	793,266	570,695	569,498	569,498	569,498	569,498	284,749
	Mid	241,892	160,236	179,521	179,521	179,521	179,521	89,761
	High	97,291	51,254	68,036	68,036	68,036	68,036	34,018
	Total	1,132,449	782,185	817,055	817,055	817,055	817,055	408,528
Consoles	PS3	2,100,000	2,130,000	700,000	700,000	420,000	700,000	785,833
	PS4	0	1,860,000	4,040,000	4,040,000	2,424,000	4,040,000	4,535,380
	Xbox 360	3,510,000	3,230,000	1,080,000	1,080,000	648,000	1,080,000	1,212,428
	Xbox One	0	1,650,000	3,120,000	3,120,000	1,872,000	3,120,000	3,502,571
	Wii	4,760,000	2,490,000	500,000	500,000	300,000	500,000	561,309
	Wii U	0	570,000	380,000	380,000	228,000	380,000	426,595
	Switch	0	0	3,580,000	3,580,000	2,148,000	3,580,000	4,018,976
	Total	10,370,000	11,930,000	13,400,000	13,400,000	8,040,000	13,400,000	15,043,093
Media streaming devices	Apple TV	0	120,000	540,000	540,000	540,000	540,000	606,214
	Nvidia Shield	0	30,000	152,100	152,100	152,100	1,837,692	170,750
	Total	0	150,000	692,100	692,100	692,100	2,377,692	776,965
TOTAL	All	14,497,160	15,210,613	17,548,016	17,548,016	17,548,016	19,233,608	17,548,016

See Table 8 for scenario definitions and assumptions.

8th-generation Consoles are modeled as follows: The PlayStation family products is modeled as PS4 (using a PS4 Pro measurements as a proxy) in 2016 and using a weighted mix of 25% PS4, PS4 Pro 15%, and PS4 Slim 60%. Xbox One is modeled as Xbox One in 2016 and as Xbox One S in 2021, and a weighted mix of 25% Xbox One and 75% Xbox One S in 2021. Nintendo has only a single model in each generation, so there is no need for special consideration in this regard.

Appendix B – Gaming User Types Weighting by System Type

User Intensity Weighting										
	Gaming Intensity	Entry	Mid	High	2011	2016	2021			
Desktop	Light	90%	15%	20%	75%	58%	56%			
	Moderate	5%	35%	30%	11%	17%	18%			
	Intensive	3%	30%	30%	9%	15%	16%			
	Extreme	2%	20%	20%	6%	10%	10%			
Laptop	Light	90%	34%	30%	73%	75%	73%			
	Moderate	5%	26%	30%	12%	11%	12%			
	Intensive	3%	25%	25%	10%	9%	10%			
	Extreme	2%	15%	15%	6%	6%	6%			
Console & media-streaming devices		PS3	PS4	Xbox360	Xbox One	Wii	Wii U	Switch	Apple TV	Nvidia Shield
	Light	30%	15%	30%	15%	65%	45%	55%	78%	55%
	Moderate	40%	40%	40%	40%	21%	30%	26%	20%	22%
	Intensive	25%	40%	25%	40%	12%	20%	16%	2%	20%
	Extreme	5%	5%	5%	5%	2%	5%	4%	0%	3%

Appendix C – Estimates of Duty Cycle by System and User Type: 2021

Hours per day

	User type	Gaming	Video streaming	Web browsing	Idle	Sleep	Off	Display
Desktop	Light	0.20	0.40	1.46	7.53	7.81	6.6	3.26
	Moderate	1.19	0.60	1.55	7.14	7.22	6.3	4.48
	Intensive	2.80	1.20	2.80	5.93	5.88	5.4	7.75
	Extreme	7.00	2.00	3.00	4.44	3.36	4.2	12.71
Laptop		Gaming	Video streaming	Web browsing	Idle	Sleep	Off	Display
	Light	0.17	0.40	1.46	6.44	6.74	8.8	2.80
	Moderate	1.02	0.60	1.55	6.09	6.34	8.4	3.90
	Intensive	2.40	1.20	2.80	5.03	5.38	7.2	7.00
	Extreme	6.00	2.00	3.00	3.74	3.66	5.6	11.45
Console & media-streaming devices		Gaming	Video streaming	Navigation	Connected Standby*	Off**	Display	
	Light	0.28	0.18	0.03	23.03	0.47	0.49	
	Moderate	1.02	0.65	0.06	21.82	0.45	1.73	
	Intensive	2.36	1.50	0.09	19.64	0.41	3.95	
	Extreme	6.24	1.91	0.14	15.39	0.32	8.29	

* When the console is not being used users most commonly select (or enter through APD) what we refer to as "Connected Standby" mode. This mode can allow the console to quickly resume use and has many functions, including battery charging, suspend to RAM, and network connectivity (which keeps the system connected to the Internet to automatically perform software updates). Each console has different manufacturer default standby settings (which we adopted, unchanged, in our testing) and names ("Energy saving", "Rest", etc.). This mode is also referred to by others as "Sleep", "Networked standby", and "Low power mode".

** "Off" is the lowest power mode available in which the console is performing no other functions and can only be restarted by the power button or controller. This mode is labeled differently on various consoles, e.g., "Full shutdown", or "Turn off". During initial setup, the user can decide what mode the system enters by default when shut off, and this can be changed in the settings. This mode is also referred to by others as "Off/Standby" and "Non-connected standby", but in our view this is not a "Standby" mode as it is not actively listening or sensing.

Appendix D – A Review of Market Surveys of Time in Gameplay

Gaming Category*	Active gaming mode (hrs/d-person)**	Geography	Population (Million)	Platform	Year	Applicable population (sample size)	Source
AGGREGATE							
All gamers - all platforms	1.9	US		All	2010	All gamers (18,872 consumer panel members aged 2 and older)	NPD (2010)
BY PLATFORM							
All gamers - desktops	1.20	US	all us gamers	Desktops	2017	Representative sample of entire US	Urban et al., (2017)
All gamers - desktops with discrete graphics	1.56	US	all us gamers	Desktops	2017	Representative sample of entire US	Urban et al., (2017)
All gamers - consoles	0.82	US	105	Consoles	2017	Console players (range 0.04 for Wii to 1.60 for PS4, depending on model)	Urban et al. (2017)
All gamers - consoles	1.03	US		Consoles	2016	Aged 13+	Nielsen (2017)
All gamers - consoles	0.98	US	42.5	Consoles	2015	Probably derived from NPD 2010	Short, J.E. (2013)
All gamers - PCs	0.91	US	268	PCs	2014	PC gamers 9 years or older (6225 individuals, of which 2,312 are PC gamers; minors' responses were provided by parents)	NPD (2014b)
All gamers - PCs	1.16	US		PCs	2016	Aged 13+	Nielsen (2017)
CLASSES OF GAMERS							
Core gamers, 5+h/wk - all platforms	0.7	US	33.7	All	2014	Gaming 5+ hours/week (7927 surveyed, ages 9+ For children, parents provided the response)	NPD (2014a)
Core gamers, 10+h/week - PCs	1.3	US	13.8	PCs		Gaming 10+ hours/week (7927 surveyed, ages 9+ For children, parents provided the response)	NPD (2014a)
Core gamers, 10+h/week - consoles	1.6	US	13.3	Consoles		Gaming 10+ hours/week (7927 surveyed, ages 9+ For children, parents provided the response)	NPD (2014a)
Core gamers, 10+h/week - all platforms	3.2	US	27.6	All		Gaming 10+ hours/week (7927 surveyed, ages 9+ For children, parents provided the response)	NPD (2014a)
Avid gamers - PCs	3.65	US	30.9	PC	2015	Probably derived from NPD 2010	Short, J.E. (2013)
Online gamers - PCs	1.87	US	31.9	PC	2015	Probably derived from NPD 2010	Short, J.E. (2013)
Online gamers - all platforms	0.90	US		All	2016	Annual consumer survey fielded in December 2016. Survey reached 4003 households, with 2608 of those households containing individuals who play video games at least three hours a week. Nationally representative sample of the U.S. population. Value is for the most frequent gamer in the household (vs total hours for all gamers).	ESA, private communication, Michael Warnecke (February 24, 2017)
Offline gamers - PCs	1.20	US	23.8	PC	2015	Probably derived from NPD 2010	Short, J.E. (2013)
Offline gamers with others in person - all platforms	0.67	US		All	2016	Annual consumer survey fielded in December 2016. Survey reached 4003 households, with 2608 of those households containing individuals who play video games at least three hours a week. Nationally representative sample of the U.S. population.	ESA, private communication, Michael Warnecke (February 24, 2017)
Hard-core gamers - PCs	1.14	US		PC	2016	unspecified	Nielsen (2016)
Extreme gamers - unspecified	5.7	US	5	unspecified	2011		McGonigal (2011b)
Extreme gamers - unspecified	6.9	US		unspecified	2010	4% of total gamer population (online survey of 18872 - all gamer types, with answers for up to age 13 provided by parents)	NPD (2010)
Extreme gamers - unspecified	7.50	US	8	unspecified	2015		Short, J.E. (2013)
DEMOGRAPHIC GROUPS							
Unemployed men; no college degree - unspecified	6.00	US		unspecified	2015	Men aged 18-30	Thompson (2016)
Millenials - consoles	1.25	US		Consoles	2015		Nielsen (sited in Statista 2016a)
Generation X - consoles	0.57	US		Consoles	2015		Nielsen (sited in Statista 2016a)
Baby Boomers - consoles	0.40	US		Consoles	2015		Nielsen (sited in Statista 2016a)
Children ages 8-18 years - unspecified	1.60	US		unspecified	2008	All gamers (randomized sample of 975 children who game)	Harris Poll for D. Gentile
Teens and tweens - PCs	2.23	US		PC	2015		Rideout (2015)
Teens and tweens - consoles	2.15	US		Console	2015		Rideout (2015)
SPECIFIC GAMES							
Multiplayer and online games - unspecified - US	1.59	US		unspecified	2015	All such gamers	ESA (2016)
World of Warcraft - PCs - Global	3.1	Global		PC	2005-7	7043 players (quintiles: 0.5, 1.6, 3.1, 5.1, 8.8h)	Tarng et al. (2008)
Destiny - consoles - Global	3	Global		unspecified	2014	Entire user base (16 M users)	Taormina (2014)
Cataclysm - PCs - Global	2.86	Global		unspecified	2010	Entire user base	Blizzard Entertainment (2015)
Call of Duty - all platforms - Global	0.47	Global		Console and PC	2011	Entire user base	Gatson (2011)
*Note: Identifying language in the first column is verbatim from the source document.							
** Estimates are per user, not per device. There are typically multiple users per device.							

Appendix E – Estimation of Network and Data Center Energy for Cloud-based Gaming

Energy calculation for online and cloud-based games: PCs (values are per user): 2016

Data Network			
Cloud-Based Gaming	15	Mbps	
	6.750	GB/hour	Conversion from bits per second to gigabytes per hour
Online Gaming	0.22	Mbps	Average streaming rate
	0.10	GB/hour	Conversion from bits per second to gigabytes per hour
Video Streaming	7.5	Mbps	Average streaming rate
	3.375	GB/hour	Conversion from bits per second to gigabytes per hour
Network Energy	0.027	kWh/GB	As of 2017, includes core and access networks
Cloud-Based Gaming	182	W	Network power during gameplay
Online Gaming	3	W	Network power during gameplay
Video Streaming	91	W	Network power while viewing
Data Center (Nvidia cloud-based gaming)			
Server (except GPU)	32	W	Based on dual-processor server operating at Average 50% utilization, divided among 8 players per server
GPU	150	W	Active
GPU	50	W	Idle
PSU efficiency	90%		Assumes 80 Plus Platinum PSU
Assumed use	80%		GPU is sitting idle 20% of the time
GPU contribution	181	W	During gameplay and idle
CPU contribution	40	W	During gameplay and idle
Total server Contribution	221	W	During gameplay and idle
Network ports	6	W	Assumes 15% overhead (server power excluding GPU) for data center network equipment
Data center Power Usage Effectiveness (PUE)	1.5		Assumes servers in colocation with only slightly better than average PUE
Total data center	340	W	During gameplay and idle
Client-side user device			
Cloud based gaming device	8.5	W	Assumes SHIELD TV during play
TOTAL power associated	**531**	**W**	Cloud-based gaming

Energy calculation for online and cloud-based games: Consoles (values per user): 2016

Data Network			
Cloud-Based Gaming	15	Mbps	Average streaming
	6.750	GB/hour	Conversion from bits to bytes
Online Gaming	0.22	Mbps	Average streaming
	0.1	GB/hour	Conversion from bits to bytes
Video Streaming	7.5	Mbps	Average streaming
	3.375	GB/hour	Conversion from bits to bytes
Network Energy	0.027	kWh/GB	In 2017, includes core and access networks
Cloud-Based Gaming	182	W	Network power during play
Online Gaming	3	W	Network power during play
Video Streaming	91	W	Network power while viewing
Data Center (Cloud-based Gaming)			
Server (except GPU)	7	W	Assumes server comprised of eight PS4pro GPU on a single PS4pro motherboard, divided among 8 players. Non-GPU power assumed to equal measured [Psnavigation] power of one PS4pro
GPU	66.9	W	GPU active power assumed to equal measured [PSactive-PSnavigation] power
GPU	9.5	W	GPU idle power assumed to equal measured [PSstandby] power
PSU efficiency	100%	W	Assumes PSU losses included in PS4 measurements
Total server power draw	595	W	Reality check
Assumed use	80%		i.e. 20% of the time a GPU is sitting idle
GPU contribution	69	W	During play and idle
CPU contribution	9.3	W	During play and idle
Total server Contribution	79	W	During play and idle
Network ports	1.4	W	Assumes 15% overhead (server power excluding GPU) for data center network equipment
PUE	1.5		Total/IT data center loads. Assumes servers in colocation with only slightly better than average PUE
Total data center	120	W	During play and idle
Client-side user devices	12.4	W	Assumes measured Switch during play
TOTAL power associated	**315**	**W**	

Appendix F – Efficiency Measures Evaluated and Applied to the Base Systems

Energy Efficiency Measure Categories

The following Hardware Change and System Settings categories were considered for each of the three PC systems (one from each market segment) that were retrofit and tested under standardized energy performance tests. For each PC, the base configuration energy performance testing results were compared against identical testing results of two retrofit package configurations of the same systems as follows:

1. Hardware Upgrades
2. Hardware Upgrades, System Setting Adjustments & CPU/GPU Underclocking

PSU efficiency improvements were applied arithmetically to the test-bench results.

Hardware Changes

7. GPU Upgrade
8. CPU & Motherboard Upgrade
9. Storage Drive(s) Adjustments
10. Cooling Fan Adjustments
11. PSU Upgrade (calculated analytically, vs measured on each system)

System Software, Firmware (BIOS) & Operational settings

5. CPU BIOS
    - CPU underclocking
    - CPU undervolting (Including input voltage, offset voltage, Vcore voltage, CPU Cache voltage)
    - Enable power-saving CPU states (C1E, C3, C6, C7 [lowers idle power])
    - Enable Enhanced Intel Speedstep Technology
6. Other BIOS
    - Serial (COM) Port 0 = Disabled
    - EuP 2013 = Enabled
    - AMD Cool'n'Quiet feature = Enabled
    - Hot plugging = Disabled
    - SATA Aggressive Link Power Management = Enabled
    - Set fans = silent mode
7. GPU
    - GPU Underclocking
    - GPU power target setting (This limits the amount of power the GPU uses)
8. Other
    - Adjust case fan speed controls
    - Windows OS power plan changed to "Balanced"

Display efficiency improvements

· HD monitor: 17W -> 14W
· 4K monitor: 29W -> 24W
· HD TV: 38W -> 30W
· 4K TV: 56W -> 46W

Systems EE Measures Summary

Entry-level PC #3 (E3)

The third PC in our representative Entry-level market segment was chosen as the lower priced system for retrofit measures testing. The baseline configuration has all the typical attributes of a highly budget conscious do-it-yourself consumer, with Entry-level AMD CPU, motherboard and GPU products. In particular, the configuration proved to have a somewhat bottlenecked CPU performance thereby providing a CPU upgrade ad optimized settings opportunity.

Base Configuration (E3a)

PC - Make & Model:	DIY Custom Build
CPU:	AMD FX-6300
Processor Family:	Piledriver
Cores:	6
Clock Rate:	3.5 GHz
Heatsink/Fan Model:	Cooler Master Hyper 212
Motherboard Make & Model:	MSI 970 Gaming
GPU Make & Model:	AMD Radeon R7 360
VRAM (GB):	2 GB
Storage 1 Type & Spec:	SSD Crucial MX300 275GB
Storage 2 Type & Spec:	None
System RAM Type & Spec:	DDR3 Kingston Hyper X Fury 8GB 1866MHz
Case Make & Spec:	Fractal Design Define S 6-fans
PSU Model & Spec:	EVGA 500 W1 550W, 80+ White
Combined MSRP:	$576

Retrofit Configurations

- E3n - Hardware Upgrades & System Setting Adjustments (*Used in final reporting results*)
- E3o - Hardware Upgrades, System Setting Adjustments & GPU Underclocking
- E3p - Hardware Upgrades, System Setting Adjustments & AMD Radeon Power Save Mode (*Used in final reporting results*)

Hardware Changes

1. GPU Upgrade *(E3n, E3o & E3p configurations)*
   - From an AMD Radeon R7 360 to AMD Radeon RX Vega 56
2. CPU & Motherboard Upgrade *(E3n, E3o & E3p configurations)*
   - From an AMD FX-6300 to AMD FX-8350, placed into the existing MSI 970 Gaming Motherboard
3. Storage Drive(s) Adjustments
   - No changes
4. Cooling Fan Adjustments *(E3n, E3o & E3p configurations)*
   - Quantity 3 excess case fans were disabled (assuming easy re-enabled by user if needed)

System Software, Firmware (BIOS) & Operational settings

1. CPU BIOS *(E3n, E3o & E3p configurations)*
    - CPU Underclocking
        - No changes
    - CPU Undervolting
        - CPU Voltage = -0.100000 V
        - CPU-NB Voltage = -0.100000 V
        - DRAM Voltage = 1.230 V
        - NB Voltage = 1.00000 V
        - SB Voltage = 1.00000 V
2. Other BIOS *(E3n, E3o & E3p configurations)*
    - C1E Support = Enabled
    - AMD Cool'n'Quiet = Enabled
    - Serial (COM) Port 0 = Disabled
    - EuP 2013 = Enabled
3. GPU
    - *E3o configuration only*
        - GPU Underclocking - Using MSI Afterburner software
            1. Core Clock = 1442 MHz (Base = 1590), -10%
            2. Memory Clock = 780 MHz (Base = 800), -10%
        - GPU power target setting (This limits the amount of power the GPU uses)
            1. Power Limit = -10% (Base = 0%)
    - *E3p configuration only*
        - AMD Radeon Software driver
            1. Global Wattman = Power Save
            2. Global Chill = On (only affects supported games)
4. Other *(E3n & E3o configurations)*
    - Windows OS power plan changed to “Balanced”

Mid-range PC #4 (M4)

The fourth PC in our representative Mid-range market segment was chosen as the middle market priced system for retrofit measures testing. The baseline configuration has components reflecting moderate to high performance ratings falling in a price range that arguably commands the bulk of do-it-yourself sales. The NVIDIA GTX 970 GPU has a very large installed base in the market due to its popularity.

Base Configuration (M4a)

PC - Make & Model:	DIY Custom Build
CPU:	Intel Core i7-4790K
Processor Family:	Haswell Devil's Canyon
Cores:	4
Clock Rate:	4 GHz
Heatsink/Fan Model:	Cooler Master MasterLiquid Pro 280 (CLC)
Motherboard Make & Model:	ASRock Fatal1ty Gaming Z97X Killer
GPU Make & Model:	NVIDIA ASUS GeForce GTX 970 STRIX-GTX970-DC2OC-4GD5
VRAM (GB):	4 GB
Storage 1 Type & Spec:	SSD Samsung 850 EVO 500GB
Storage 2 Type & Spec:	HDD Western Digital Black Series 7200 rpm 1TB
System RAM Type & Spec:	DDR3 G.Skill Sniper Series 16Gb 2400MHz
Case Make & Spec:	NZXT Phantom 410 Red ATX 5-fans
PSU Model & Spec:	CS Series Modular CS750M 750W, 80+ Gold
Combined MSRP:	$1,549

Retrofit Configurations

- M4w - Hardware Upgrades & System Setting Adjustments & CPU/GPU Underclocking (*Used in final reporting results*)
- M4x - Hardware Upgrades, System Setting Adjustments (*Used in final reporting results*)

Hardware Changes

1. GPU Upgrade *(M4w & M4x configurations)*
   - From NVIDIA GTX 970 to NVIDIA GTX 1070
2. CPU & Motherboard Upgrade
   - None
3. Storage Drive(s) Adjustments *(M4w & M4x configurations)*
   - Upgraded primary storage to m.2 storage
   - Replaced Storage 2 HDD with the Storage 1 SSD (SSD Samsung 850 EVO 500GB)
4. Cooling Fan Adjustments
   - None

System Software, Firmware (BIOS) & Operational settings

1. CPU BIOS *(M4w configuration)*
   - CPU Underclocking
     - CPU underclocked 20%
   - CPU Undervolting
     - Vcore Voltage = 0.900

        - CPU Cache Voltage = 0.900
        - CPU Input Voltage =1.350
    - Enabling power-saving CPU states
        - CPU C States Support = Enabled
        - Enhanced Half State (C1E) = Enabled
        - CPU C3 State Support = Enabled
        - CPU C6 State Support = Enabled
        - CPU C7 State Support = Enabled
2. CPU BIOS *(M4x configuration)*
    - CPU Underclocking
        - None
    - CPU Undervolting
        - Vcore Voltage = 1.100
        - CPU Cache Voltage = 1.000
        - CPU Input Voltage = 1.400
    - Enabling power-saving CPU states
        - CPU C States Support = Enabled
        - Enhanced Half State (C1E) = Enabled
        - CPU C3 State Support = Enabled
        - CPU C6 State Support = Enabled
        - CPU C7 State Support = Enabled
3. Other BIOS *(M4w & M4x configurations)*
    - SATA Aggressive Link Power Management = Enabled
    - CPU Fan 1 & 2 Setting = Silent Mode
    - Chassis Fan 1 Setting = Silent Mode
    - Chassis Fan 2 Setting = Silent Mode
    - Chassis Fan 3 Setting = Silent Mode
4. GPU *(M4w configuration)*
    - GPU underclocking (Using GPUTweak software application)
        - Core Clock = 1,585MHz (Base = 1,785), -22%
        - Memory Clock = 6,808MHz (Base = 8,008), -15%.
    - GPU power target setting
        - Power Target = 60% (Base = 100%)
5. Other *(M4w & M4x configurations)*
    - Lowered case fan speed slide control to minimum

High-end PC #1 (H1)

The first PC in our representative High-end market segment was chosen as our system for retrofit measures testing. This system reflects a do-it-yourself consumer that has a primary focus on system performance first then price. The dual AMD Radeon R9 Fury X GPUs reflects a consumer desire to have a system capable of processing very High-end graphics loads for HD, 4K and virtual reality featured games. Additionally, High-end Haswell Core i7 processor provides power for the most demanding simulation games. Retrofit configurations maintaining the dual GPU configuration and reducing to a single GPU were explored.

Base Configuration (H1a)

PC - Make & Model:	DIY Custom Build
CPU:	Intel Core i7 5820K
Processor Family:	Haswell-E
Cores:	6
Clock Rate:	3.3 GHz
Heatsink/Fan Model:	Corsair Hydro H110i GT 280mm
Motherboard Make & Model:	EVGA X99 Classified
GPU Make & Model:	Dual AMD Radeon R9 Fury X
VRAM (GB):	8 GB
Storage 1 Type & Spec:	SSD Samsung 850 EVO 500GB
Storage 2 Type & Spec:	SSD Kingston Hyper X Savage 480GB
System RAM Type & Spec:	DDR4 Kingston Savage Black 16GB 2400MHz
Case Make & Spec:	Corsair 600C 6-fans
PSU Model & Spec:	EVGA Supernova G2 850W, 80+ Gold
Combined MSRP:	$2,565

Retrofit Configurations

- H1l - Hardware Upgrades (2 GPU) & System Setting Adjustments & CPU/GPU Underclocking
- H1m - Hardware Upgrades (2 GPU), System Setting Adjustments
- H1o & H1q - Hardware Upgrades (1 GPU) & System Setting Adjustments & CPU/GPU Underclocking
- H1p - Hardware Upgrades (1 GPU, Vega Liquid), System Setting Adjustments (*Used in final reporting results*)
- H1r - Hardware Upgrades (1 GPU, Vega Air), System Setting Adjustments
- H1u - Hardware Upgrades (1 GPU, Vega Liquid), System Setting Adjustments & AMD Radeon Software settings
- H1v - Hardware Upgrades (1 GPU, Vega Air), System Setting Adjustments & AMD Radeon Software settings (*Used in final reporting results*)

Hardware Changes

1. Dual GPU Upgrades *(H1l & H1m configurations)*
   - From (2) AMD Radeon R9 Fury X to (2) AMD Radeon RX Vega 64 Air-Cooled
2. Revision to single GPU
   - From (2) AMD Radeon R9 Fury X to (1) AMD Radeon RX Vega 64 Liquid-Cooled *(H1o, H1p & H1v configurations)*

- From (2) AMD Radeon R9 Fury X to (1) AMD Radeon RX Vega 64 Air-Cooled *(H1q, H1r & H1u configurations)*

1. CPU & Motherboard Upgrade
    - None
2. Storage Drive(s) Adjustments
    - Primary storage upgrade: None
    - Secondary storage removal/replacement: Removed secondary SSD
3. Cooling Fan Adjustments *(H1l & H1m configurations)*
    - Two case fans added to increase air flow

System Software, Firmware (BIOS) & Operational settings

1. CPU BIOS *(H1l & H1o configurations)*
    - CPU underclocking
        - CPU Multiplier Setting (x1000 MHz) = 29 (Base = 36), -20%
        - Ring Ration = Auto
    - CPU undervolting
        - CPU Voltage Target = 0.850
        - CPU Offset Voltage = 0.000
        - RING Voltage Target = 0.950
        - VSA Voltage Offset = Auto
        - CPU VIN = 1.500
        - CPU VIN Droop = Auto
        - PCH 1.05V = Auto
        - PCH 1.5V = Auto
2. CPU BIOS *(H1m, H1p, H1u & H1v configurations)*
    - CPU underclocking
        - None
    - CPU undervolting
        - CPU Voltage Target = 0.950
        - CPU Offset Voltage = 0.000
        - RING Voltage Target = 0.950
        - VSA Voltage Offset = Auto
        - CPU VIN = 1.500
        - CPU VIN Droop = Auto
        - PCH 1.05V = Auto
        - PCH 1.5V = Auto
3. Other BIOS
    - All unused SATA ports (7 ports): Hot Plugging = Disabled
4. GPU
    - *H1l & H1o configurations*
        - GPU Underclocking (Using GPUTweak software application)
            1. GPU Clock = 1,401 MHZ (Base = 1,630), -14% (Max allowed)
    - *H1u & H1v configurations only*
        - AMD Radeon Software driver
            1. Global Wattman = Power Save
            2. Global Chill = On (only affects supported games)
5. Other
    - Windows OS power plan changed to “Balanced”

Appendix G – California Electricity Use (Aggregate and Per Unit) by Gaming Systems

Annual energy consumption (GWh)								
		Baseline			Efficiency	Surge	Cloud	Consoles
System type	**User type**	**2011**	**2016**	**2021**	**2021**	**2021**	**2021**	**2021**
Desktops	**Entry**	1,049	487	490	353	66	556	245
	Mid	415	526	593	424	4,623	783	296
	High	156	246	321	221	2,504	404	161
	Total	**1,619**	**1259**	**1,404**	**998**	**7,194**	**1,743**	**702**
Laptops	**Entry**	138	60	54	53	54	70	27
	Mid	81	34	38	37	38	59	19
	High	46	18	23	23	23	29	11
	Total	**265**	**112**	**114**	**113**	**115**	**159**	**57**
Consoles	**PS3**	752	394	93	90	56	93	105
	PS4	0	617	991	839	612	1,154	1,113
	Xbox360	1,370	701	179	173	107	179	201
	Xbox One	0	509	654	595	406	780	734
	Wii	922	396	71	69	42	71	79
	Wii U	0	74	33	31	20	33	37
	Switch	0	0	226	213	136	226	254
	Total	**3,043**	**2691**	**2,247**	**2,009**	**1,378**	**2,536**	**2,523**
Media streaming devices	**Apple TV**	0	8	27	26	27	27	30
	Nvidia Shield	0	8	25	25	25	307	29
	Total	**0**	**16**	**52**	**50**	**52**	**334**	**58**
TOTAL	**All**	**4,928**	**4078**	**3,818**	**3,171**	**8,739**	**4,772**	**3,340**

Includes energy use associated with displays, home networks, peripherals, and network energy associated with streaming. Cloud-based gaming is assumed at varying levels in the scenarios. See Table 8 for scenario definitions and assumptions.

Average unit energy consumption (kWh/year)									
		Baseline			Efficiency	Surge	Cloud	Consoles
System type	User type	2011	2016	2021	2021	2021	2021	2021
Desktops	Entry	443	366	349	251	392	396	349
	Mid	879	724	703	502	864	928	703
	High	1,003	847	822	567	1,010	1,034	822
	Total	541	536	532	378	899	660	532
Laptops	Entry	174	105	95	93	95	124	95
	Mid	336	214	210	207	212	330	210
	High	471	346	335	331	337	429	335
	Total	234	143	140	138	141	194	140
Consoles	PS3	358	185	134	128	134	134	134
	PS4		332	245	208	252	286	245
	Xbox360	390	217	166	161	166	166	166
	Xbox One		309	210	191	217	250	210
	Wii	194	159	141	138	141	141	141
	Wii U		130	86	81	86	86	86
	Switch			63	59	63	63	63
	Total	293	226	168	150	171	189	168
Media streaming devices	Apple TV		68	49	47	49	49	49
	Nvidia Shield		261	167	163	167	167	167
	Total		107	75	73	75	140	75
TOTAL	All	340	268	218	181	498	248	190

Includes energy use associated with displays, home networks, peripherals, and network energy associated with streaming. Cloud-based gaming is assumed at varying levels in the scenarios. See Table 8 for scenario definitions and assumptions.

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