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An Energy-focused Profile of the Video Gaming Marketplace

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Energy Technologies Area
June, 2017

An Energy-focused Profile of the Video Gaming Marketplace

Gaming Systems Market Utilization & Characterization Report

Project:
A Plug-loads Game Changer: Gaming System Energy Efficiency without Performance Compromise - CEC/LBNL Agreement # EPC-15-023 – Task 2

June 29, 2017

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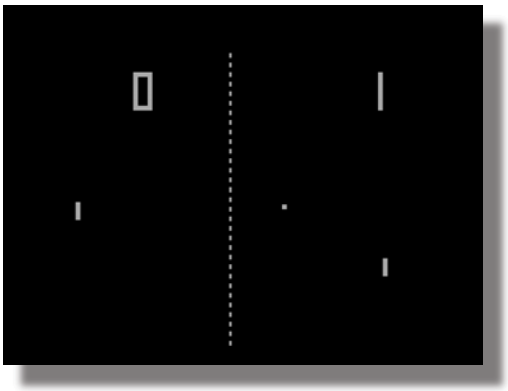

2017

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Executive Summary

Gaming is a major social and technological phenomenon, engaged in by a third to a half of humanity. The associated energy use has been understudied, and passed over in most energy policy and planning initiatives. This report reviews available energy-relevant information on the non-battery-powered video gaming market, including associated technology trends and gaps in the consumer information environment. We develop a profile of the California marketplace for the purposes of performing energy analysis. The resulting analytical platform is based on best-available data and industry expert opinions. Constituent data include an array of 25 individual gaming systems, operated by four user types across multi-step duty cycles, and running a representative assortment of game titles. This 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. We find that there are currently more than 15 million video-gaming devices in use in California. While the absolute number is projected to decline somewhat in response to the increasing popularity of mobile gaming, the mix of platforms and their applications will shift towards increasingly energy-intensive configurations. This analysis also sheds light on significant energy efficiency improvements occurring in the marketplace and other drivers of energy demand. In subsequent phases of this project, the specified gaming systems will be bench-tested and the results used to generate aggregate baseline energy demand assessments for California and scenarios for the future.

1 The Social and Technological Phenomenon of Video Gaming

Video gaming[1] traces its roots to an exhibit created for the World's Fair in 1940.[2] Today, three-quarters of a century later, and between a third and a half of humanity engages in the pastime,[3] through a myriad of types of electronic devices, including even smart watches.[4] In the U.S., two in three people over the age of 13 engage in gaming (Nielsen 2017).

In terms of economic activity, video games generate approximately $100 billion per year in sales globally (NewZoo 2016a). U.S. consumer expenditures on gaming software reached $24.5 billion in 2016, with an additional $6 billion on hardware and accessories.

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[1] Here, we adopt the term to "video gaming" to describe gaming on computers, video game consoles, or other TV-based gaming devices. The terminology is inconsistently used in this industry. In some documents, "computer" gaming refers only to gaming PCs, while "video" gaming refers only to gaming on consoles, but in many cases the terms are used interchangeably. We add specific references to PCs or Consoles where a distinction is being made by the data or discussion.

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

[3] An industry executive quoted in *Popular Science* magazine (2016) states that there are as many as 2-3 billion gamers in the world.

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

(ESA 2017). The top title as of mid-2014—*League of Legends*—boasted 67 million users each month, with 27 million users in a given day.[5] An estimated 66,000 people are employed in the gaming software industry in the US alone (ESA 2017).

Video gaming is sweeping the world (Figure 1). More than half of the population in industrialized countries self-identifies as gamers, spending 11-12% of their overall leisure time in the activity (Nielsen 2016b). Game designer Jane McGonigal (2011a) states that humanity (globally) spends 3 billion person-hours *a week* gaming, and goes on to say that:

> "[T]he average young person racks up 10,000 hours of gaming by the age of 21. That's almost exactly as much time as they spend in a classroom during all of middle school and high school if they have perfect attendance. Most astonishingly, 5 million gamers in the U.S are spending more than 40 hours a week playing games — the same as a full time job!"

The underlying technology is advancing at lightning speed, with increasing performance and steadily evolving user experiences. With this has come rising energy use—although few studies have looked at this in any detail—particularly as concerns the use of personal computers as the gaming platform (Mills and Mills 2015).

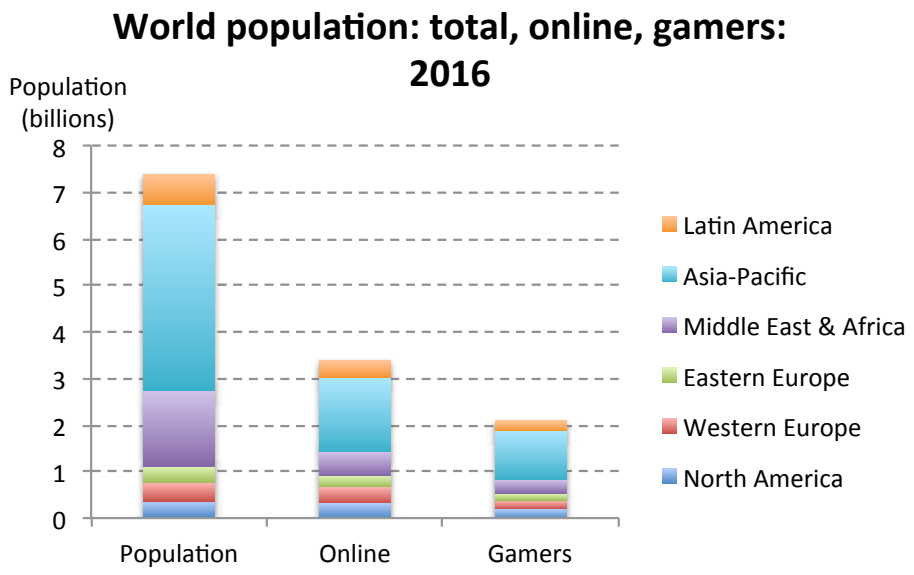

***Figure 1**. Source: NewZoo 2016a*

Gaming is a technologically diverse activity (Figure 2), employing many broad categories of equipment (consoles, PCs, dedicated handheld devices, and mobile devices), each with its own subcategories.

[5] http://www.riotgames.com/articles/20140711/1322/league-players-reach-new-heights-2014

The video gaming industry is credited with stimulating the development of improvements in technology that have trickled down to mainstream personal computing as well as other parts of the electronics industry. These include advances in CPUs, graphics cards, 3D graphics acceleration, and sound cards.[6] In 2006 Ralph Baer, inventor of the first gaming console, received the National Medal of Technology and Innovation from President George W. Bush.[7] A recent example of this dynamic involves using the computational power of NVIDIA graphics cards to improve the safety of Tesla self-driving cars (Eassa 2016).

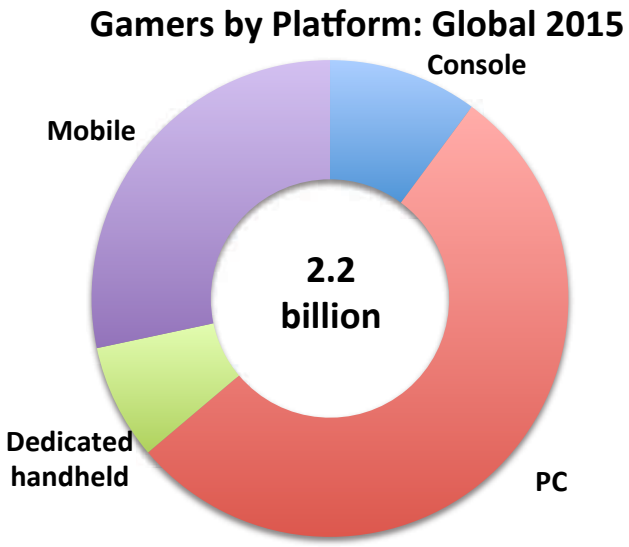

Figure 2. *Source: Open Gaming Alliance (2016)*

North America stands out as an important segment the global gaming market. All major demographics (gender, age, ethnicity, income, urban/rural, and level of education) are well represented in the gaming population (Statista 2016a). The Entertainment Software Association (ESA) reports that 65% of households play video games regularly (defined as 3 or more hours per week, with an average of 1.7 gamers per game-playing household) (ESA 2017). Nielsen estimates that 64% of U.S. citizens over the age of 13 gamed in 2016, corresponding to 207 million people. This is up from 58% just four years earlier. The average age of these gamers is 35 years, of which 58% are male and 41% female (ESA 2017). The Pew Research center (Duggan 2015) puts the male/female ratio at nearly equal. Notably, ESA finds that 26% of gamers are 50 or more years of age. In another perhaps surprising statistic, women age 18 or older represent a much larger proportion of the game-playing population (31%) than boys age 18 or under (18%) (ESA 2017). Women over 50 are more likely to game than men of the same age, i.e., 39% of women versus 29% of men, and people of all ethnicities play games in roughly similar

[6] https://en.wikipedia.org/wiki/Video_game_industry
[7] https://en.wikipedia.org/wiki/Ralph_H._Baer

proportions (Duggar 2015). Those gaming on PCs have an average age of 40 years, older than any other platform (Nielsen 2016a).

According to Nielsen surveys, American gamers spend more time gaming than in sports and wellness activities (Nielsen 2015). The emergence of ESports has garnered 200+ million regular watchers around the world, with up to 36 million viewers per event (100k in "attendees"). Among US men aged 21 to 35, ESports is as popular as baseball and hockey (22% watch regularly) (NewZoo 2016b).

The merits of gaming, and possibilities of adverse personal and social consequences are hotly debated by experts, and society itself is divided in its views – even within the gaming population (Duggan 2015). Some studies find that playing video games may have positive effects on children (Kovess-Masfety *et al.,* 2016), while others find that exposure to television and video games has adverse effects on attention for both children and adults (Swing *et al.,* 2010) and that even two hours per day of digital media interfere with studying and finishing homework (Walsh 2014 and American Academy of Pediatrics 2016). Pathological gaming is seen as causative of depression, anxiety, and social phobias (Gentile et al. 2016). Based on the existing body of research, in 2013 the fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* introduced a syndrome labeled Internet gaming disorder as an addictive disorder (American Psychiatric Association 2013). In contrast, gaming experts see games as teaching powerful problem-solving tools applicable to real-world issues (McGonigal 2011).

The purpose of this report is to assemble available market information of value in identifying and assessing drivers of energy use in video gaming, and to present an integrated map of the market to be used for estimating baseline energy use and projections for the future. A high-level view of the installed base indicates over 15 million gaming platforms in California as of 2016 (Table 1). While the overall number is projected to decline over the following five years, the composition of platforms will be shifting towards the more energy intensive product subcategories.

Table 1. Overview of gaming system installed base in California*

	2011	2016	2021
Desktop PCs	2,994,711	2,348,428	2,638,861
Laptops	1,132,449	782,185	817,055
Consoles	10,770,000	12,030,000	9,820,000
Other TV gaming	0	350,000	1,092,100
TOTAL	**14,897,160**	**15,510,613**	**14,368,016**

* Source: estimates developed within this report.

2 Market Data Requirements for Energy Analysis

Video gaming conducted on computers, consoles, and a host of portable devices is clearly a major social phenomenon. As the gaming population has grown and game-playing technology has become more powerful, the associated energy use has risen (Mills and Mills 2015). While many entities gather gaming market data, their focus is predominantly on software choices and revenues. Some analysts follow trends in certain components (graphics cards, displays, CPUs). Far less attention is paid to energy relevant factors such the mix of system types in the installed base, time spent using gaming devices for various purposes, and choices of in-game settings. Product-specific energy usage measurements combined with a wide range of market data are needed in order to understand the magnitude and drivers of aggregate energy demand and to assess the potential for improved energy efficiency.

Gaming energy demand is the product of a combination of exceptionally diverse physical and behavioral factors. These include a wide array of types and numbers of gaming devices and software, together with a host of user-determined parameters such as mix of devices used by a given consumer, types of games played, and time spent in various operating modes, including active gaming, web browsing, standby, sleep, and off. The market is further characterized by user choices among various system-level and in-game settings (e.g., fidelity levels and component overclocking), and choice of display technology (monitor versus virtual reality). The mix of offline versus online gaming also has increasingly important energy ramifications. A broad variety of market data is thus essential to understanding the patterns of energy use in gaming. There is a large but highly fragmented literature,[8] with no comprehensive synthesis providing a profile of the market that is usable for estimating aggregate energy demand. This report provides such a synthesis for the purposes of energy analysis.

One practical step in this process is to characterize the marketplace by specifying a representative range of specific gaming platforms. These must include “pre-built” equipment sold under brands such as Sony, Microsoft, or Digital Storm as well as custom do-it-yourself (DIY) gaming computers, assembled from individual components. This spectrum of platforms can then be instrumented in order to quantify their energy consumption under various combinations of usage assumptions and settings. Those results can, in turn, be applied to the installed base of gaming equipment for the purpose of estimating energy use at the macro level.

The DIY movement for is strong among PC gamers, and enables the consumer to make energy-relevant decisions on each and every component. Some pre-built computers are subsequently upgraded as well. No comprehensive data are available on the DIY marketplace, but as an indication, as of Q3 2016 Raspberry Pi had sold 10 million DIY units (Powell 2016). Many retail outlets offer individual components for sale, and a

[8] See bibliography here: https://sites.google.com/a/lbl.gov/greengaming/market-data/market-studies

variety of websites such as PCPartpicker.com are dedicated to individuals building their own computers.

Given the dynamic nature of gaming culture and technology, all of these variables are in a state of flux. Thus, we provide several scenarios of plausible trends for the future. These can be combined with unit energy consumption of the baseline platforms and behavioral profiles to estimate potential corresponding trends in energy demand at the macro level.

From an energy standpoint, games and the platforms they run on have evolved from highly simple, pixelated games such as the iconic single-person, two-dimensional, black-and-white "Pong"[9] released in 1972 and running on the earliest rudimentary gaming devices to high-fidelity, multiplayer, three-dimensional and computationally intensive games (Figure 3). The corresponding power requirements of these platforms during gameplay have increased from approximately ten watts to several hundred watts.[10]

1972 2017

Figure 3. Screen captures of Pong (circa 1972) and Assassins Creed 3 (circa 2016) exemplify the evolution of games from two-dimensional monochrome presentations to high-fidelity and immersive three-dimensional, 360-degree experiences.

With this technological intensification has come increased energy use. A number of key dynamics will continue shape energy demand going forward. These include:

- Total time in gaming as well as non-gaming modes.
- The changing size and mix of gaming technologies in the installed base.
- Rising performance expectations of gaming software.
- Game hosting choices: local versus cloud (the latter creating new energy loads within data centers and networks).

[9] https://en.wikipedia.org/wiki/Pong
[10] http://www.magnavox-odyssey.com/AC%20adappter.htm

- Integration of consoles with cable services fundamentally changing the use of televisions and thus the energy profile of this previously well-characterized energy end use.
- Emerging technologies. Virtual reality may prove to be the most important emerging technology. From an energy perspective, new power requirements will be created by VR equipment. Perhaps more importantly, it will place extra computing demands and performance expectations on the gaming PC's graphics processor. On the other hand, the use of eye-tracking may enable these systems to limit high-fidelity rendering to only a small field of view.

The mainstreaming of gaming has enlarged the user base, while the per-person amount of time spent gaming in the U.S. has been projected to increase by 60% between 2008 and 2018 (Statista 2016b). A counterbalancing factor is the strong ongoing modal shift towards mobile gaming, which will serve to moderate energy demand growth that might otherwise occur. For example, one source projected the number of mobile phone gamers to increase from 81 million to 213 million between 2011 and 2020, with tablet gamers growing from 20 million to 140 million over the same period (Statista 2016a). As of 2015, two-thirds of mobile-phone owners used their devices to game (Statista 2016d).

3 Existing Literature and Databases

There is extensive high-level documentation of gaming markets and user behavior. However, by academic standards, most existing market-research publications—at least those in the public domain—are nonchalant and proprietary in the presentation of data. Moreover, the documentation needed to understand the *energy implications* of gaming is often scant or non-existent. The industry lacks standardization on how to categorize hardware and users, with definitions and naming systems varying widely. Language such as "Extreme Gamer," "Avid Gamer", or "Casual Gamer" is often used without any sort of definition and freely conflates technological and behavioral variables. For example, the typology offered in a study by USC segments the market into a mix of hardware, user types, and game genres in ambiguous ways (Short 2013). The vintage of market data is also important as technologies together with user preferences evolving extremely rapidly.

Industry-based market researchers focus primarily on the user and their spending on gaming software, whereas for the purposes of energy analysis the device and how it is just as important, e.g., one platform may be used by multiple users thereby increasing aggregate on-time. The amount of time spent gaming, and how that is allocated across varying technologies is poorly understood. To the extent that industry statistics focus on hardware, the attention is almost exclusively on the name-brand manufacturers of consoles (Sony, Microsoft, and Nintendo), with scant effort to segment desktop and laptop PC manufacturers as well as do-it-yourself PC builders.

Meanwhile, energy analysts and forecasters have often equated "gaming" with video game consoles, for which substantial analysis have been performed (Kwatra *et al.,* 2013; USEIA 2013; Urban 2014). Desktop- or laptop-based gaming, however, has been almost universally ignored. Furthermore, no prior publicly available energy-focused assessments have provided data at the state level, which necessitates approximation when geographic specificity is desired.

3.1 The installed base of gaming equipment

Unambiguous estimates of the installed base of gaming PCs are lacking. As there is often more than one gamer per device, the number of individuals gaming exceeds the installed base of equipment. Consoles are the preferred device among 47% of the US population, followed by PCs (27%), and mobile devices (26%) (Nielsen 2017).

The market research firm EEDAR places the number of PC gamers at 33.7 million in the U.S. in 2014 (EEDAR 2015). EEDAR defines PC gamers as any gamer playing "client-based" titles, excluding social-based titles such as FarmVille. Per their analysis, 19.5 M of these gamers are over 18 years of age, 46% of which use a gaming desktop, 29% a general desktop, 21% a gaming laptop, and 58% a general laptop. A 2016 survey by Nielsen found that 42% of gamers play on one platform, 40% play on two, and 18% play on 3 (Nielsen 2017).

PCs are more widely used among the group Nielsen (2016a) defines as "hardcore gamers" (8 or more hours per week in active gameplay), i.e., 51% versus 37% for "casual gamers" (1-3 hours per week). Short (2013) provides values for multiple types of gamers and gaming devices, but category definitions are blurred insofar as PCs and consoles are mixed in some cases. VGchartz.com reports console sales by make and model (global, US, and other regions), with weekly data from 2006 forward. A steady downward trend in sales can be observed over this timeframe.

According to Deloitte (2016), 56% of U.S. consumers owned a gaming console as of 2015, ranging widely among age groups from 80% for the 14-18 bracket to 11% for people 69 years or older. Urban et al. (2014) estimated the U.S. installed base of video game consoles at 128 million as of July 2013 (updated in the report's appendix to 138 million by March 2014) (Table 2). Estimates of the installed base for other TV-linked gaming devices (e.g., Apple TV and NVIDIA Shield) are not readily found in the literature.

Table 2. Installed base and power requirements by mode of console game systems.
Urban et al. (2014)

	Years	Installed Base [millions]	Installed Base [%]	Power [W] Gaming	Power [W] Video Streaming	Power [W] Video Playback	Power [W] Navigation	Power [W] Standby
Nintendo								
Wii U	2012-2013	1.6	1.2%	33	31	-	32	0.4
Wii	2006-2013	42	33%	16	16	-	14	5.8 *
Microsoft								
Xbox 360 S/E	2010-2013	21	17%	86	67	67	67	0.4
Xbox 360	2007-2009	12	9%	121	97	96	97	1.8
ALL Xbox 360/Wt. Avg.	***2007-2013***	***33***	***26%***	***99***	***78***	***77***	***77***	***0.9***
Xbox	2001-2008	6.1	5%	64	-	-	60	1.7
Sony								
PS3 Super Slim	2012-2013	4.3	3%	82	62	74	68	0.2
PS3 Slim	2009-2011	12	9%	102	77	94	91	0.7
PS3	2008	4.4	3%	137	112	126	115	1.3
PS3	2007	2.3	2%	190	160	178	165	1.4
PS3	2006	0.6	0.5%	220	166	209	188	1.5
ALL PS3/Wt. Avg.	***2006-2008***	***23***	***18%***	***117***	***92***	***108***	***101***	***0.8***
PS2	2000-2013	22	17%	24	24 **	24	24	1.7
Total/Wt. Avg.	**-**	**128**	**100%**	**60**	**49**	**72**	**51**	**2.6**

* Calculated as the weighted average based on the portion of different vintages of the Nintendo Wii gaming consoles by year (1.7, 1.7 and 0.7 watts if connect24 disabled, 10, 7 and 5watts if enabled for Wii gaming consoles released since 2006, 2009 and 2010, respectively (Boxleitner 2014)) and assuming that 30% of users have the Wii connect24 disabled (FhCSE 2011). Wiiconnect24 is not available on the newer Wii U console.

** We used power draws for video streaming and playback the same as for active mode and navigation because we did not find power draw values for these modes.

The mix of gaming devices is evolving rapidly. Among console owners, the share also gaming on mobile/tablet devices rose from 26% in 2010 to 66% in 2015 (Nielsen 2016a). Product cycles are particularly rapid in this industry leading to important granular changes in the composition of the installed base, as illustrated for consoles in Figure 4.

Owners of multiple generations of the same technology transition only gradually to the newer systems. Nielsen (2017) found strong usage of multiple console-gaming platform generations. Importantly for energy analysis, as gaming activity shifts from 7th- to 8th-generation consoles among households that own both devices, the earlier-generation devices often remain in use as general multimedia devices (Nielsen 2016a).

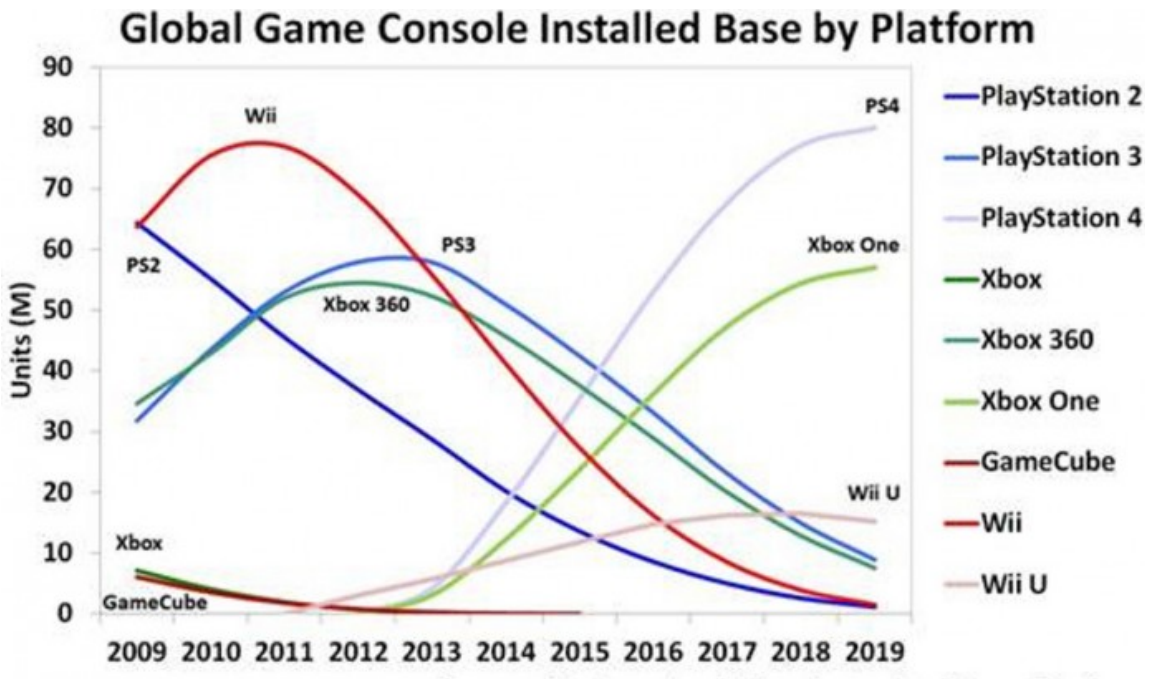

Figure 4. Rapidly evolving product cycles for gaming consoles.
Source: Mercer (2015)

Further complicating matters, gamers often utilize multiple platforms, and thus estimates of energy use for a gamer (or gamer household) must consider a mix of technologies, their respective energy use intensities, and the time allocated to each. According to NewZoo, only 13% of gamers play on a single device, with preferences spread approximately equally up to six devices (NewZoo 2012). About 87% of all console gamers also game on a PC (NewZoo 2016a). Usage patterns are complex even within categories. For example, Nielsen (2016a) found that gamers owning both the 7th and 8th generation consoles divided their time equally between them in 2013, with strong usage of both platforms persisting through 2016 (Nielsen 2017). Household gaming energy will be the sum of gaming on multiple devices. There are also multiple gamers in most households.

3.2 Gaming PC Component-level data

Gaming computers contain the same generic components as conventional computers. However, the performance requirements of these machines entail far higher energy intensities, and in many cases multiple components (e.g., multiple graphics processing units (GPUs), hard drives, fans, displays) are used. In conventional PCs, graphics are sometimes handled by the CPU and otherwise by a discrete GPU.

Proprietary market research provides highly granular data on component sales volumes. The Steam Hardware & Software Survey is a publicly accessible, continuously updated log of equipment and componentry used by 125 million gamers on the Steam

platform.[11] Aggregate data distinguish user share components by manufacturer, with drill-down tables indicating use at the model level. As an illustration, as of November 2016, NVIDIA's market share among graphics cards stood at 59%, AMD 24%, and Intel 17%. Among CPUs, Intel's market share stood at 78% and AMD's at 22%. Other indicators such as system RAM, display resolution, VR equipment in use, and hard drive space are also available. The Steam survey results can be filtered by operating system.

While many sorts of component-level data are available, energy-relevant data are elusive. Power ratings are offered through third-party sources (e.g., motherboard wattage from PCPartpicker.com) but are not labeled on the part itself or its packaging, and without details as to the assumed operating conditions (e.g., low load or high load). In other cases the information is not available aside from approximate proxies such as TDP in the case of graphics cards. Similar to nameplate power, TDP is at times inappropriately equated with power requirement because it is in fact the "Thermal Design Power" or "Thermal Design Point", representing thermal energy that the cooling system has to dissipate. TDP is an unreliable proxy for actual power consumption.

Some product reviewers spend considerable effort measuring system-level power requirements (i.e., for entire PCs) but there are no standards, rendering cross comparisons among reviews non-definitive. Underlying assumptions such as OS or power management settings are not often documented. Reviews also use an array of benchmarks (some synthetic and some actual games), further complicating cross-comparisons.

A variety of metrics may be defined for a given component. Useful metrics either provide a direct efficiency measure, or an analogous ratio of energy or power required per unit of performance. Frame rates (frames per second, FPS) are almost universally used as proxies for performance. This metric is highly limited, as there are at least 11 measures of performance and user experience (Koomey et al., 2017). Moreover, even the basic frame rate metric has nuances that are not typically considered, i.e., the quality and completeness of frame delivery varies.

Benchmarking the computational performance of gaming computers involves running a preset gaming process and collecting metrics. Some benchmarks focus on central processor performance (e.g., Cinebench); others focus on the graphics (e.g., Unigine).[12] Component product literature, however, emphasizes nameplate estimates of power requirements (or proxies of power requirements), rather than actual performance or power needs under a given mode of operation. Accurate energy use calculations cannot be made with nameplate data (Mills and Mills 2015). However, no standardized test

[11] See http://store.steampowered.com/hwsurvey; https://www.vg247.com/2015/02/24/steam-has-over-125-million-active-users-8-9m-concurrent-peak/; https://steamdb.info/graph/

[12] See http://www.maxon.net/products/cinebench/overview.html and https://unigine.com/products/heaven/.

procedures exist for evaluating gaming actual computer energy use, which results in conflicting estimates and perpetuates market reliance on over-estimated nameplate data.

The limitations of nameplate data notwithstanding, a review of the wide range of nameplate power requirements for components of analogous performance already on the market suggests that dramatic opportunities exist for improved energy efficiencies in each component category, through hardware as well as control improvements (Mills and Mills 2015).

3.2.1 Energy Efficiency Opportunities

Component efficiencies (approximated as the ratio of power per unit of performance) vary widely in the existing marketplace. Only two components of gaming systems have been formally targeted with energy efficiency ratings and policies. These include power supplies (addressed by the 80Plus rating system) and displays (addressed by Energy Star ratings). That said, the industry has voluntarily pursued efficiency on many fronts. Progress is particularly apparent in the case of GPUs and memory.

There is ample evidence of an extremely dynamic and rapidly changing market environment, where capabilities, performance, energy use, and efficiency metrics are undergoing significant evolutionary change. Figure 5 illustrates this with information on six generations of graphics cards, each evaluated on an otherwise identical system although with varying benchmarks. An important observation *for this particular comparison* is that absolute energy use has not changed much over time, while efficiency has increased in terms of frame rates obtained per watt of power input. In essence, power-reduction gains have been "reinvested" in increased performance. The opposite trends in power use for the latest two generations of cards are also notable. That said, these benchmarking results are highly dependent on the choices of which equipment is compared, other componentry in the machine (CPU, motherboard, power supply, etc.), settings chosen for the system as well as in-game options, and choice of benchmarking method. For example, in a different comparison of two boards by AMD, the system with the R9 380 was found to use 32% less energy than the R9 480 (AMD 2016).

Countervailing trends include the move towards increasingly powerful componentry and technology changes such as virtual reality, which may increase computing requirements, together with some indicators that gaming activity is increasing.

In parallel with hardware improvements, efforts have been invested on the software side, both in terms of OS-level power management controls as well as component-specific controls and drivers. Software solutions offer a similarly significant potential to reduce energy consumption while maintaining or even improving the gaming experience. Some win-win opportunities exist in that there is no cash investment

required in order to get these savings. Dynamic Voltage Frequency Scaling (DVFS)[13] is an important element of this approach, which involves dynamically changing power states to better match the resources actually required by the computing process (e.g., graphics rendering).

Major GPU manufacturers have launched power-management methods to take advantage of the fact that frame rates can be varied depending on the level of action in the scene. One set of trials using one of AMD's tools (Radeon Chill,[14] a subtab of WattMan)[15] found 31% power savings (108 to 75 W) when applied to World of Warcraft, as well as significant temperature reductions (88 to 77C; 190 to 171 F), 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). They note that the level of savings varies by game title. A third-party account published in *The Tech Report*[16] measured a power reduction from 250-260 Watts to 160 Watts with Chill activated.

Figure 6 shows an example for a Chill session of Witcher 3, in which power reductions were as high as 22% during periods when little or no screen activity was occurring. Conversely, for only a handful of moments was the full defaulted frame rate actually needed in order to achieve the desired user experience.

Gaming equipment manufacturers are giving attention to efficiency. NVIDIA publishes annual environmental reports, although these focus primarily on manufacturing and corporate operations versus their products.[17] Sony states that its strategic goal is "Road to Zero", a reference to reduced carbon footprint in manufacturing.[18] Many display manufacturers have adopted technologies to earn ENERGY STAR ratings, and many have improved power supply efficiencies to meet 80Plus levels.

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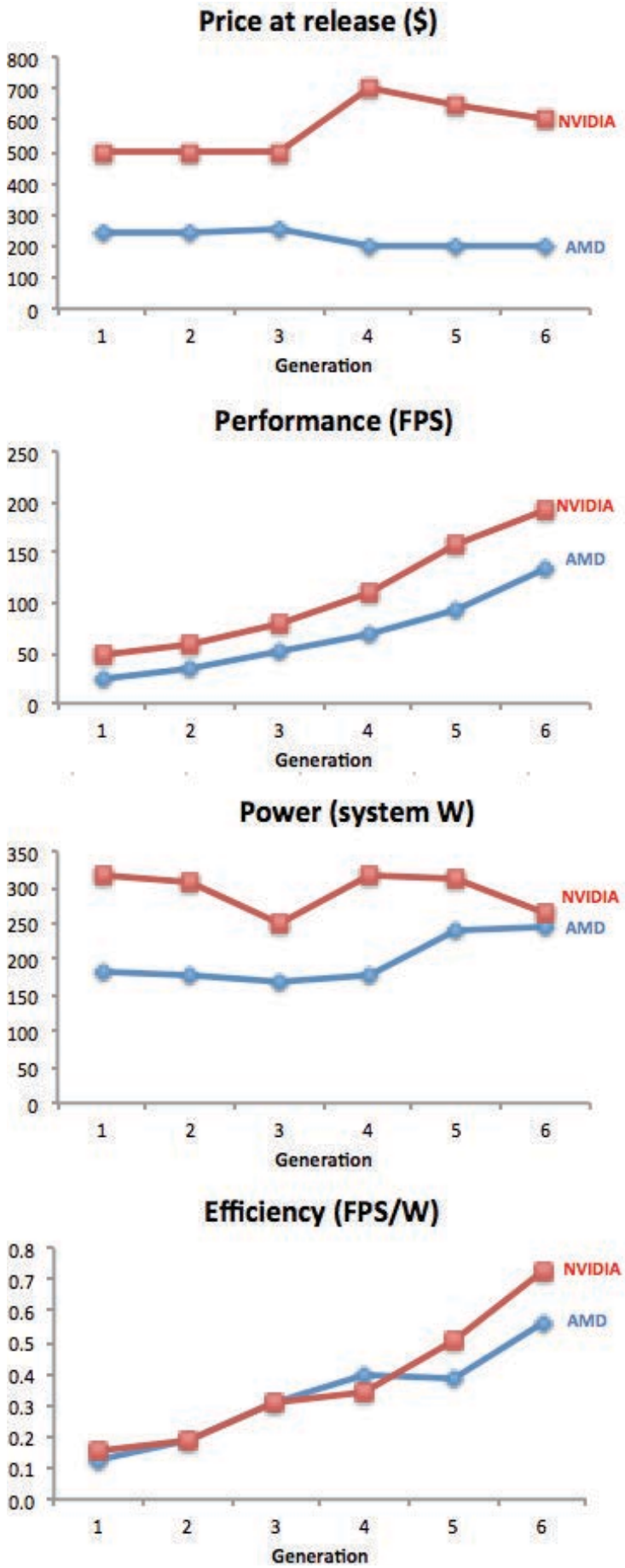
[13] http://whatis.techtarget.com/definition/dynamic-voltage-and-frequency-scaling-DVFS
[14] https://www.youtube.com/watch?v=_RKJB47PoRg&list=PLx15eYqzJifcAtaYxVK2YpCL-nUKq6uqs&index=2
[15] http://www.amd.com/en-us/innovations/software-technologies/technologies-gaming/radeon-wattman
[16] http://techreport.com/review/31077/radeon-software-crimson-relive-edition-an-overview
[17] See http://www.nvidia.com/object/fy15-responsibility-report.html
[18] http://www.sony.net/SonyInfo/csr/SonyEnvironment/products/ps4.html?s_tc=eco000077_top1



GPU generations

	AMD	NVIDIA
1	HD 5830	GTX 480
2	HD 6870	GTX 580
3	HD 7850	GTX 680
4	R9 270X	GTX 780 Ti
5	R9 380	GTX 980 Ti
6	RX 480	GTX 1080

Figure 5. Trends for six generations of GPUs (two distinct tiers) by the two leading manufacturers. Games used for benchmarking and power measurements vary. AMD tests noted as done with "medium quality" setting; no corresponding notation provided for NVIDIA. NVIDIA performance benchmark made using a 1366x768 display; display not specified for AMD. NVIDIA power measurements made using different benchmarks than FPS measurements. Anti aliasing noted as off for NVIDIA case. These are two specific families of cards and the results are not necessarily indicative of the broader trends in the marketplace.

Source: Walton 2016a,b

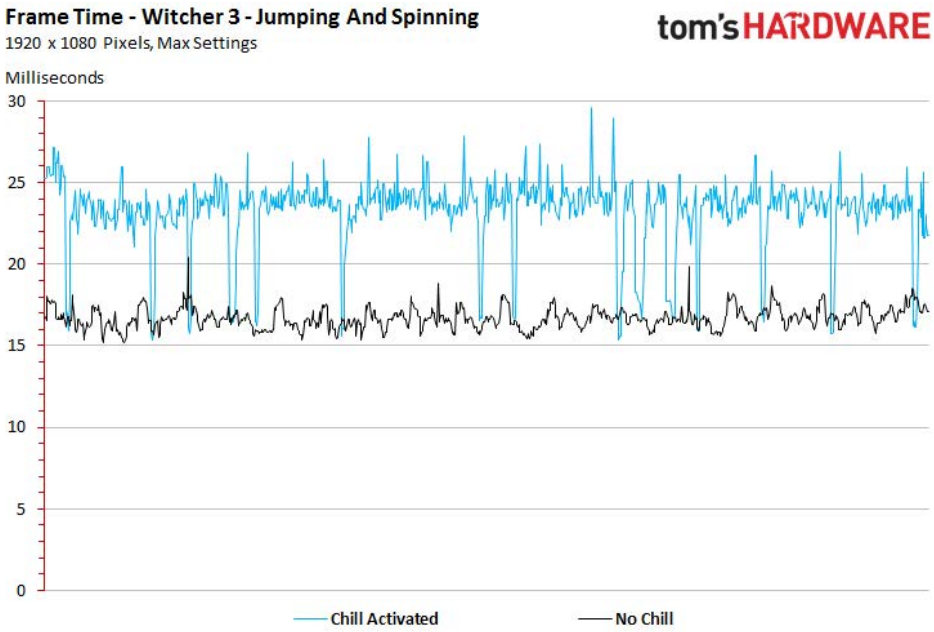


Figure 6. Frame time (1/FPS) with and without Chill in operation.

3.2.2 Central Processing Units

The central processing unit (CPU) conducts the primary computing tasks, and is one of the important nodes of energy use in the gaming system. Steady progress has been made in the energy-efficiency of CPU architecture. One metric of efficiency is the ratio of peak power requirement to corresponding processor speed. As seen in Figure 7, TDP varies between 37 and 220 W across a sampling of CPUs found in the market between 2014 and 2016. The 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.

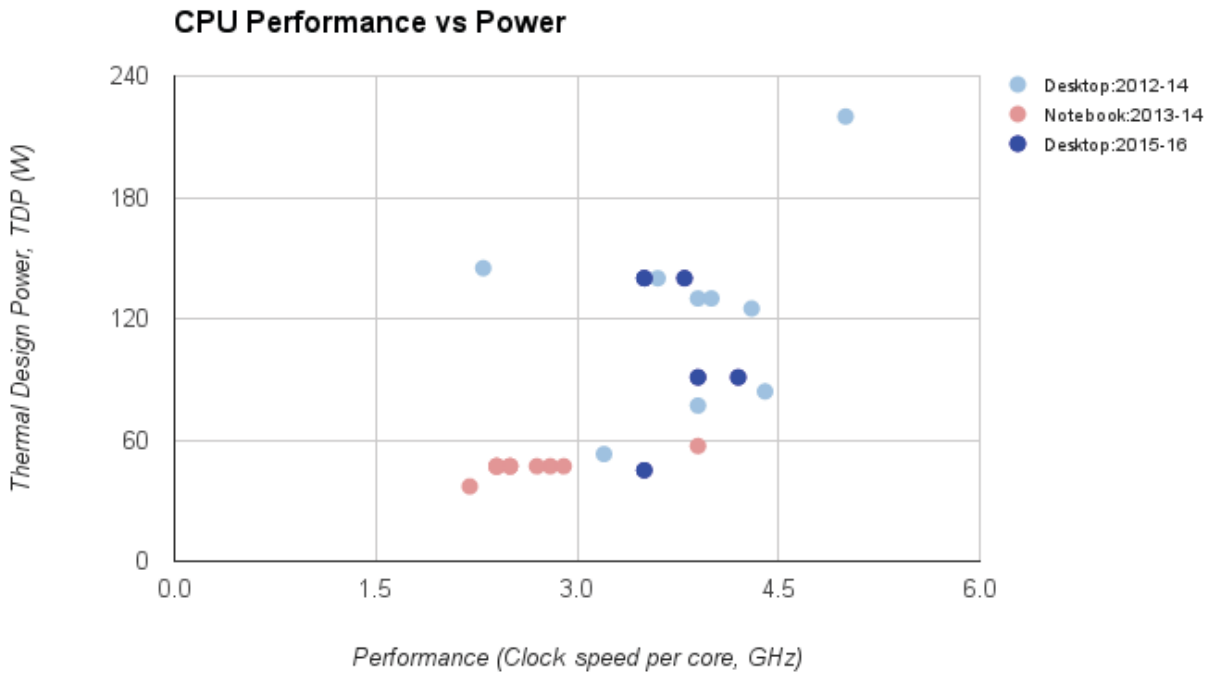


Figure 7. Examples of CPUs on the market between 2014 and 2016
Sampling of available models, using manufacturer data

As seen in Figure 8a, CPUs TDPs not surprisingly under-predict actual *system* power requirements in trials for an array of CPUs used in gaming PCs. This is partly due to associated loads created by the motherboard, paired PSUs, idle power of the associated GPU, etc. That said, actual power can vary by ~25% *for a given TDP*. Moreover, CPU power varies considerably depending on whether they are under load or idle, as does the ratio of these two performance points (Figure 8b). This wide range of outcomes indicates the importance of how system integration impacts power use.

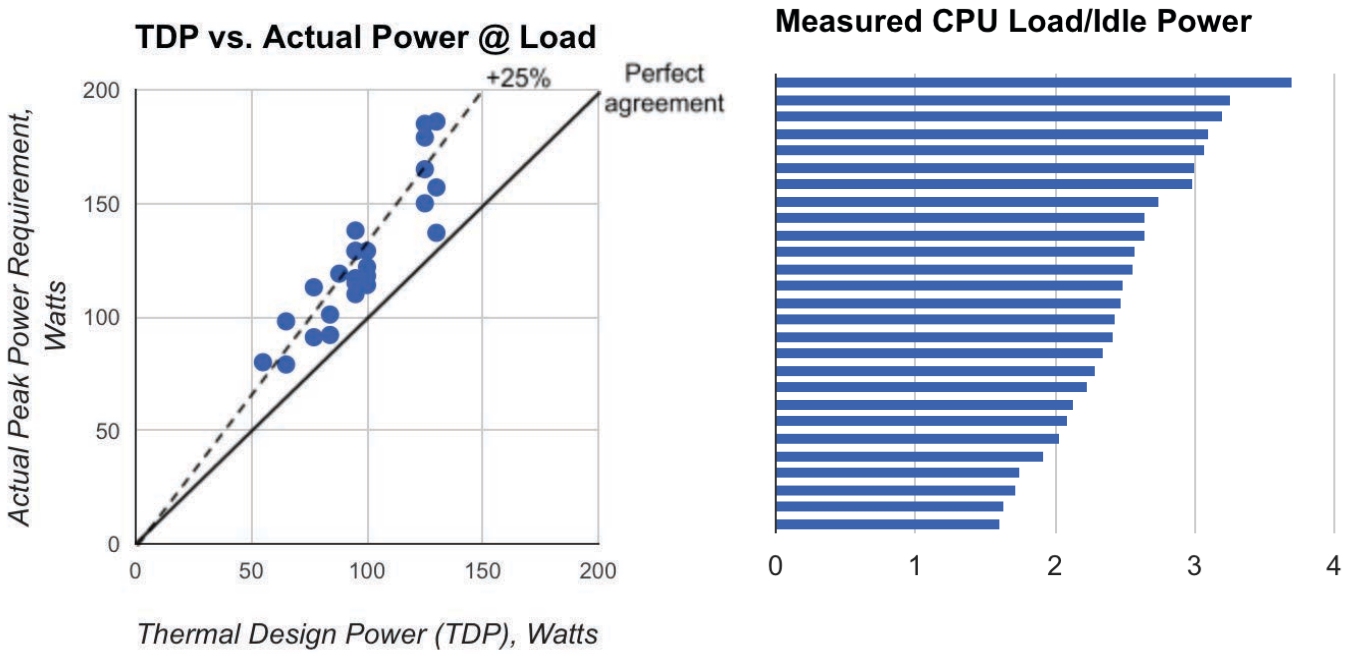


Figure 8a-b. (Left) CPU trials by Tom's Hardware compared to manufacturer-reported TDP values (per WPrime CPU benchmark). While consumers have access to the TDP values, system-level power under load is often 25% or more higher. This reflects real-world performance, ancillary power required by the motherboard, as well as PSU losses. These trials are all on a standardized PC, including the NVIDIA GTX 670 GPU.[19] (Right) Ratio of power requirements in peak vs. idle modes. The higher the ratio the better the power management and lower overall energy use across a diversified duty cycle. These tests covered 26 CPUs. Measurements of 10 GPUs found idle power ranging from 7-16W (GTX 670 not included).[20]

3.2.3 Motherboards

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. As seen in Figure 9, nameplate power consumption varies between 30 and 150 W across a sampling of devices found in the market between 2014 and 2016.

[19] See http://www.hardwarecanucks.com/forum/hardware-canucks-reviews/62166-amd-fx-9590-review-piledriver-5ghz-17.html and http://www.hardwarecanucks.com/forum/hardware-canucks-reviews/67240-intel-haswell-e-i7-5960x-review-14.html

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

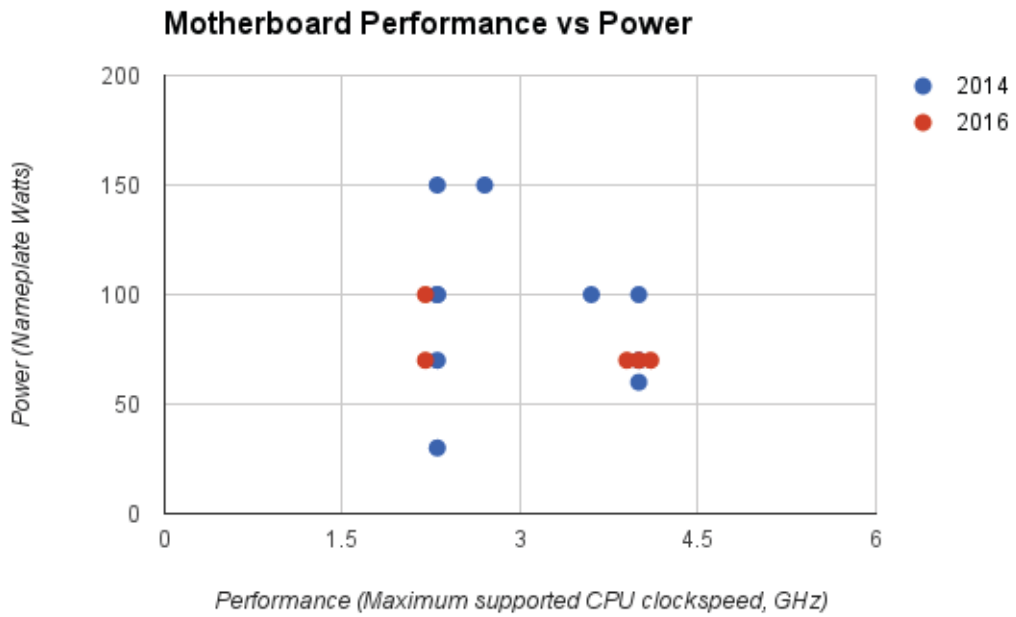


Figure 9. Examples of motherboards on the market between 2014 and 2016.
Sampling of available models using manufacturer data

3.2.4 Graphics Processing Units

The 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 typically the single-largest node of energy use. Gaming computers rely heavily on discrete GPUs, which are typically more power-intensive than CPUs. Steady progress has been made in the energy-efficiency of the GPU architecture. This is driven by an imperative to control heat production, as opposed to saving energy *per se*. One metric of efficiency is the ratio of peak power requirement to corresponding floating-point operations per second (FLOPS). As seen in Figure 10, nameplate power consumption varies between 60 and 500 W across a sampling of gaming-specific devices found in the market between 2014 and 2016. The performance levels provided by these devices vary as well, and they can be overclocked to frequencies above stock settings.

As seen in Figures 5 and 10, performance (per TDP) seems to have been advancing in recent years. Laptop GPUs have historically had both lower computing performance and lower TDPs, a reflection of space constraints as well as need to maximize battery life.

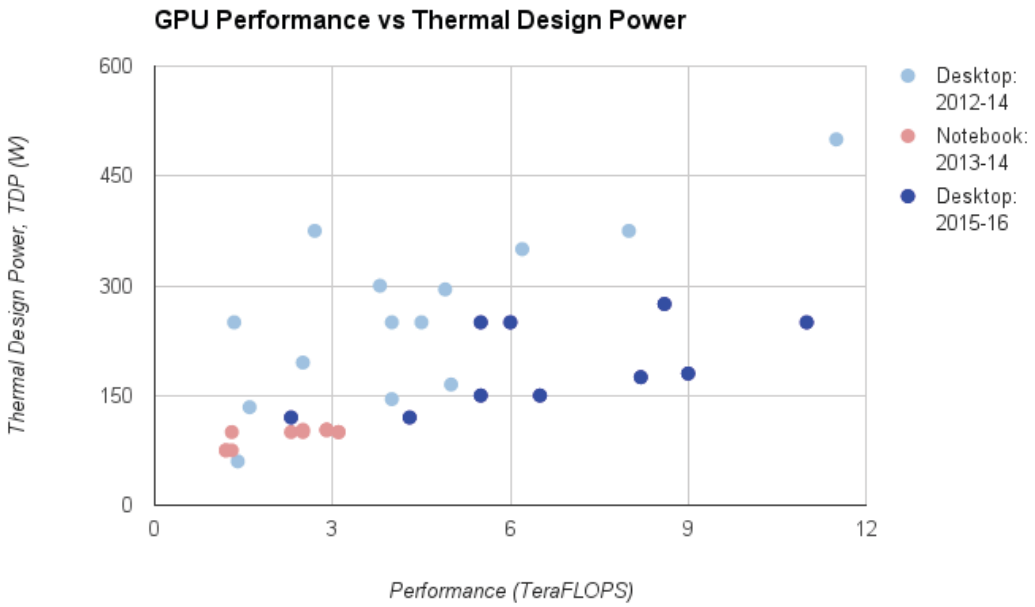


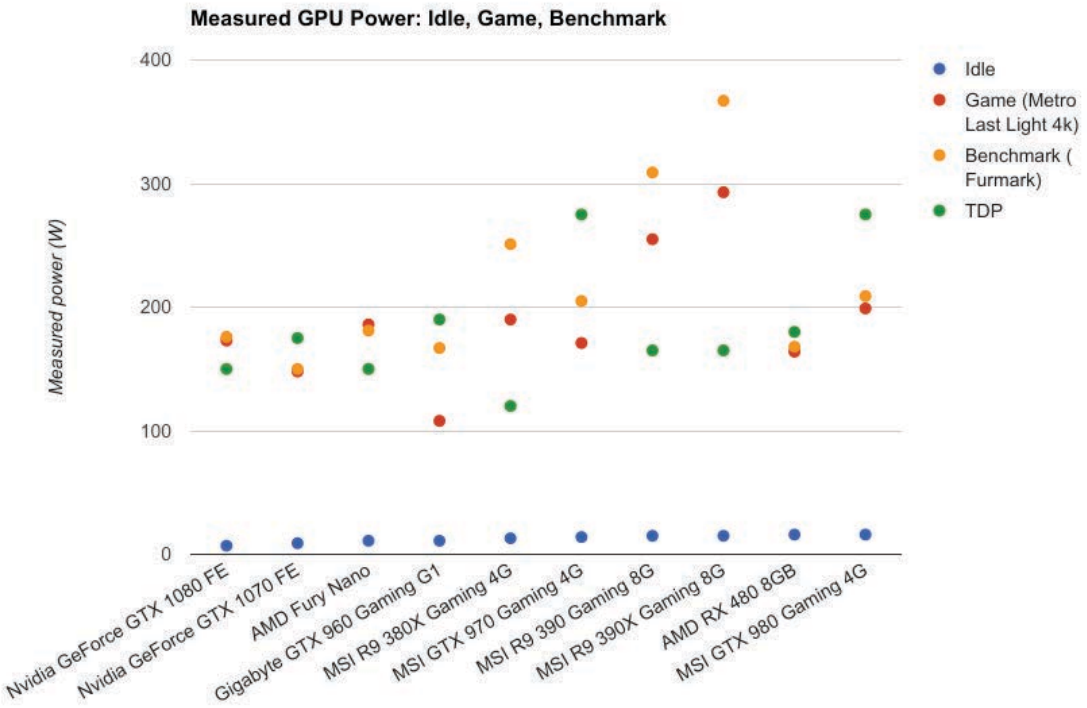
Figure 10. Examples of GPUs on the market between 2014 and 2016. The more recent additions clearly indicate a frontier of improving energy efficiency.
Sampling of available models using manufacturer data.

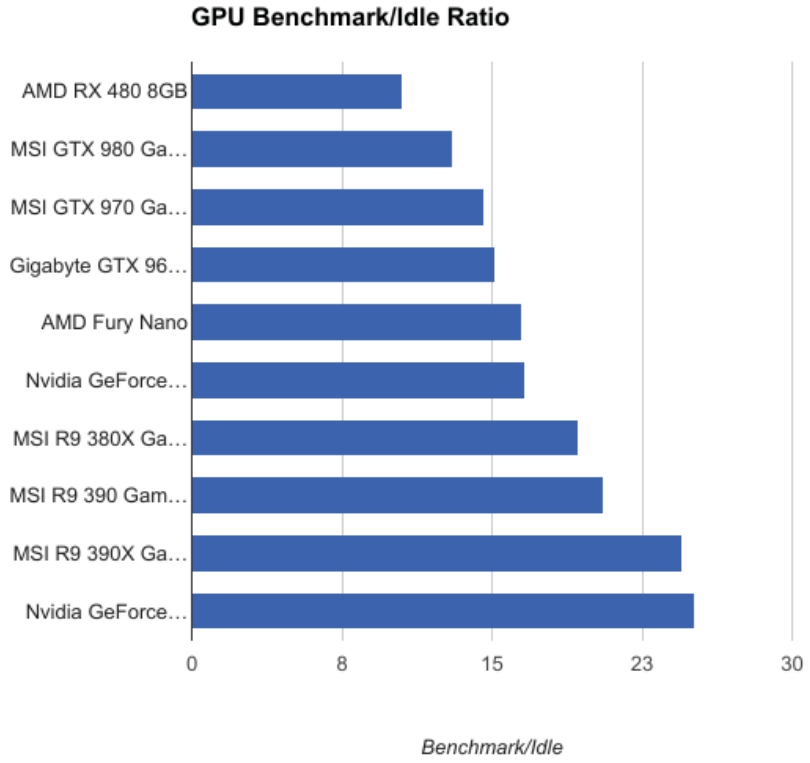
There is no consistent consumer information on actual power requirements for graphics cards in the marketplace. Direct GPU energy measurement is quite difficult, and they are rated by manufacturers in terms of Thermal Design Power (TDP).

As noted above, TDP is a poor proxy for actual power requirements. One review estimated that a graphics card with a TDP of 120W actually drew 175W of power, and another with a TP of 170W actually drew 235W.[21] Active power measurements of 10 GPUs found idle power ranging from 7-16W (GTX 670 not included) and active power ranging from 150W to 367W under the Furmark benchmark (Figure 11a-b). The ratio of idle to active power ranged from 11 to 25, indicating the importance of system integration.

Figure 11a is also illustrative of the variability in match between synthetic benchmarks and actual power requirements under specific games.[22] As found in other product reviews, actual power tends to be significantly higher than TDP, with some exceptions.

[21] https://linustechtips.com/main/topic/453630-graphics-card-tdp-and-power-consumption-explained/
[22] http://www.tomshardware.com/reviews/amd-radeon-rx-480-polaris-10,4616-9.html





Figures 11a-b. Measured power for 10 popular graphics cards as of 2016: idle, active gameplay (Metro Last Night), synthetic stress-test benchmark (Furmark), and TDP.
Source: Tests per Tom's Hardware[23]

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

3.2.5 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 typically multiple sticks per machine. Efficiencies have improved dramatically over time. The current range is represented by the spectrum of the DDR standard (2.5 volts, 17.5 W) to DDR4 (1.2 volts, 1.3 W) (Figure 12).

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 W (1 TB) while solid-state drives of the same capacity and interface draw as little as 2.6 W. Operational savings occur depending on whether or not a sleep mode is employed.

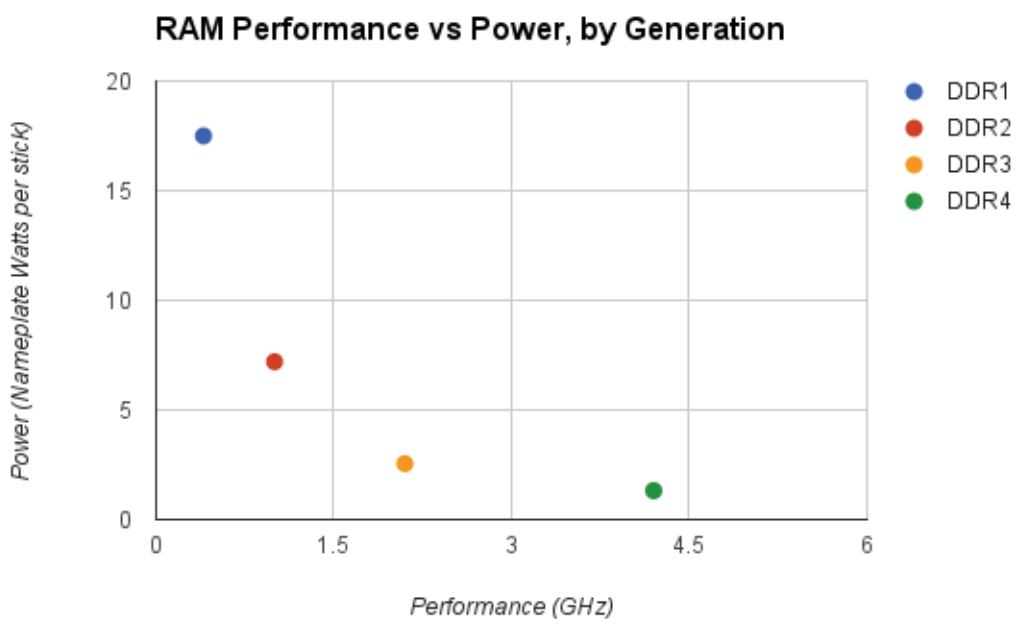


Figure 12. Power requirements for four generations of DDR RAM.
Sampling of available models using manufacturer data.

3.2.6 Cooling

Gaming computers require dedicated cooling systems in order to avoid overheating, even at idle. Increases in energy use are often compensated for by these systems. Active cooling is typically provided to each PSU, CPU, GPU and motherboard as well as to the general environment within the computer chassis. 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). Some prior measurements of CPUs with and without liquid cooling found no change in energy use (Mills and Mills 2015). However, efficiency metrics may improve if the performance metric increases while energy holds constant.

3.2.7 Power Supply Units

All power delivered to the gaming computer's internal components (and displays in the case of laptop computers) passes through a power supply unit (PSU). Because power supplies are upstream from the other components and have intrinsic inefficiencies due to AC-DC power conversions, the losses (and associated unwanted heat gains) can be significant, usually second only to the energy used by the GPU.

The efficiencies of PSUs located within the PC typically peak around 50% load. Power supplies formerly had particularly poor efficiencies at part load, below 50-70%. Significant PSU improvements occurred following the introduction of the voluntary 80Plus testing and rating program in 2004. As seen in Figure 13, efficiencies vary among a sampling of desktop-gaming PSUs found in the market today, from 69% to 94% depending on the project and degree to which it is loaded. Right-sizing power supplies is thus important for optimizing operating efficiency. Most PSUs have dedicated fans for cooling, which typically always run, although some have temperature-based cooling. As actual power requirements tend to be unknown by gamers, sizing involves guesswork and typically results in enormous safety margins.

PSUs are uniquely important contributors to gaming PC and laptop energy use. While highly successful, PSUs achieving 80Plus ratings are far from universal. Of 323 manufacturers (5949 products) listed as of June 2017, 58% make entry-level models (just achieving 80% efficiency), 77% Bronze, 34% Silver, 48% Gold, 23% Platinum, and 6% Titanium.[24] Only in 2016 did the highest-rated Titanium models become available in wattage ranges appropriate for typical gaming PCs (previously they were in the 1500W range). Amazon best-sellers tend to be 80+ or 80+ Bronze (the lower end of the scale. Many power supplies found on the shelves of retailers catering to gaming PC do-it-yourself community are misleadingly packaged to imply 80Plus compliance.

Industry analysts have noted that outdated power supplies are still being used in systems that have been otherwise upgraded to use newer (and potentially less power consuming) componentry. Even at the time they were oversizing ("overbuying") PSUs in anticipation of rising power requirements.

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

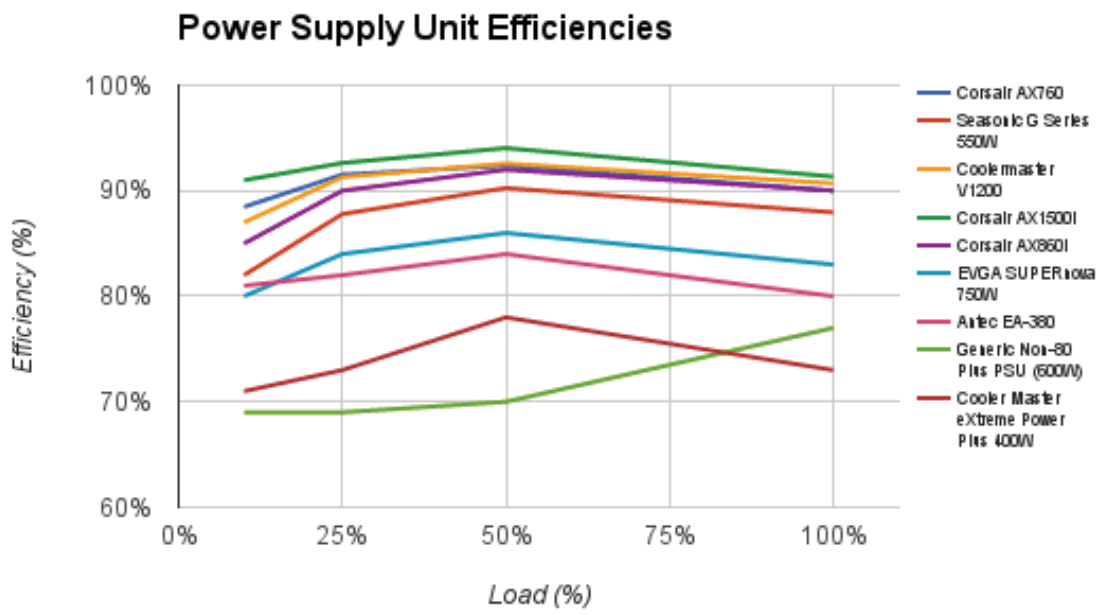


Figure 13. Power supply unit efficiencies as a function of load.
Sampling of available models using manufacturer data.

Power supplies used in gaming laptops are covered under the International Efficiency Marking Protocol for External Power Supplies, rather than 80Plus.[25] The associated discrete mark on the PSU's label is not tailored for consumers.

3.2.8 Desktop Displays

While typically not hardwired to the gaming computer itself, with the exception of laptops and consoles, displays are integral and energy-intensive elements of the system and user experience. Moreover, although independently powered, display choice influences power requirements and performance of the GPU in gaming mode. Energy use varies widely as a function of technology, screen size, and resolution. The dramatic technology transitions that have occurred in displays, resulting in significant energy benefits, have been driven more by the desirable form factors and image quality than by energy savings. Countervailing trends are the transition from VGA/SVGA to HD/1080p, to 4K displays, as well as the use of multiple displays. The net effect is that GPUs must drive many more pixels than was the case just a decade ago.

A survey by *PC Gamer* magazine suggests that 28% of gamers use more than one display, with about 70% of this group using two displays (Figure 14). This is the only published source of information we have been able to identify, although the survey data collection method involved an unsecured webpage with no registration process, and the

25 https://www.energystar.gov/ia/partners/prod_development/revisions/downloads/International_Efficiency_Marking_Protocol.pdf

likelihood that survey participants may have answered without considering the precise use of the additional displays. We more conservatively estimate that 10% of gamers use multiple displays, based on industry interviews.

Gamers have historically been irked by visual anomalies in 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 V-Sync (Vertical Sync) where tearing is eliminated by forcing the GPU to wait until the monitor is ready to refresh the next frame. However, this can cause unacceptable delays in screen refreshes. 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 may 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.

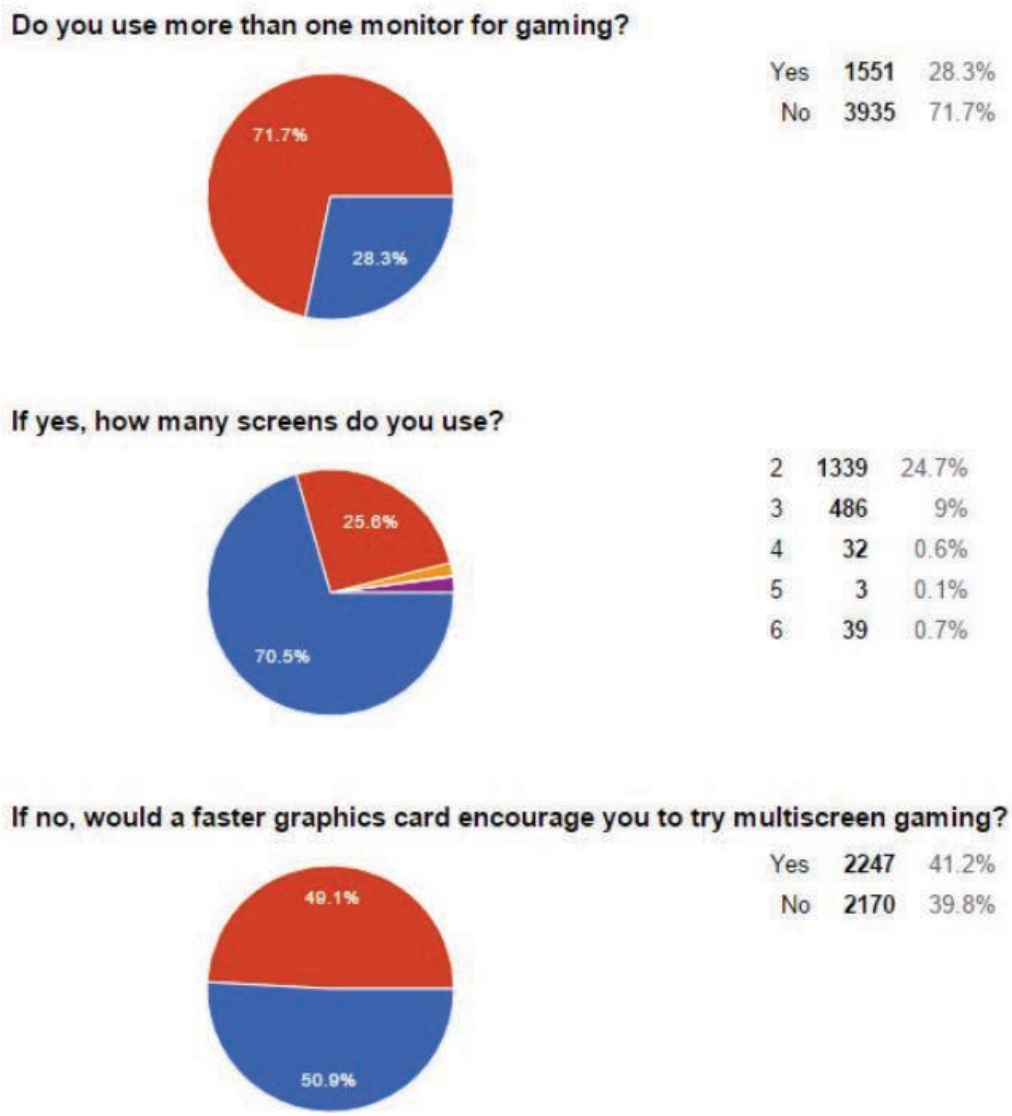


Figure 14. Gamers' use of displays: based on 5496 survey responses.
Source: Oxford (2012)

Both variable-refresh technologies rely on a combination of hardware and software. G-Sync supplies a custom monitor control module based on an FPGA chip to monitor makers. That chip also handles things like scaling images and user control user interfaces and menus. For FreeSync, vendors of monitor-control chips produce custom ASICs that support FreeSync along with their other functions.

One metric of display energy performance is the ratio of the peak power requirement (in "on" mode) to corresponding pixel count. As seen in Figure 15, measured power consumption varies between 15W and 77W across a sampling of displays found in the market between 2014 and 2016, with wide variations on power consumption even within the constraints of a given display size and resolution.

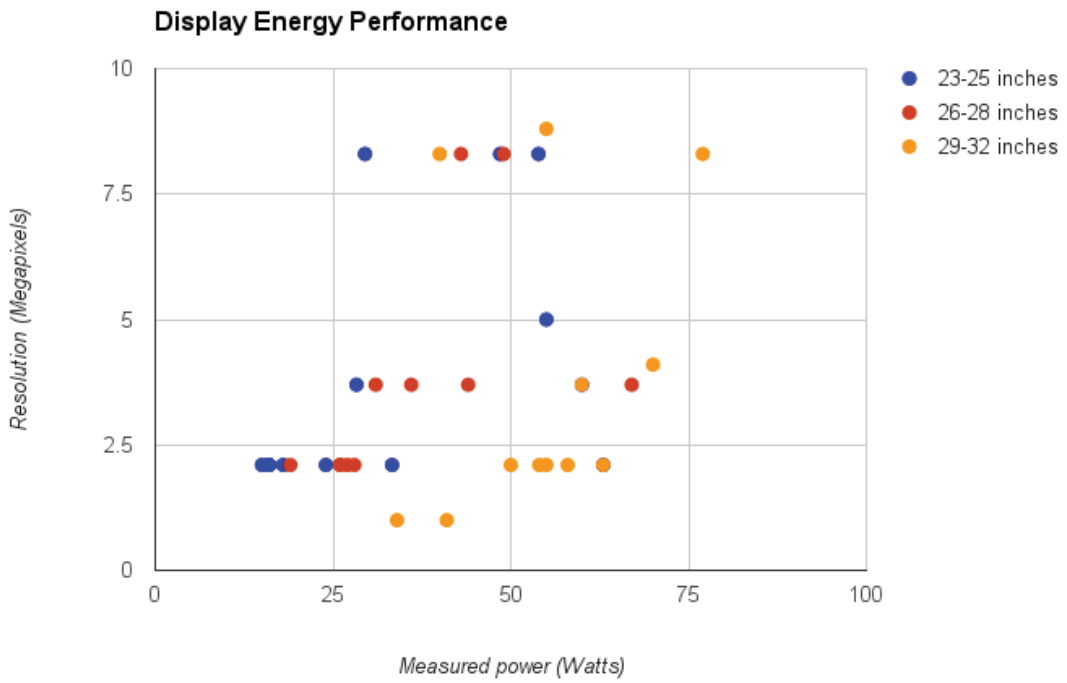


Figure 15. Desktop gaming PC displays.
Source: http://energystar.gov

3.2.9 Virtual Reality headsets

Virtual reality (VR) is an emerging technology in the gaming world. Reported interest in the technology is highest among console gamers (74%), less so among desktop gamers (38%) (Nielsen 2016a).

Data on market penetration on VR headsets is scant and varies by source. The Entertainment Software Association reports that 11% of US households own virtual reality headsets (ESA 2017), but other sources suggest the value is closer to 1/10th of that (Liptak 2017). Market uptake has not been as rapid as some bullish predictions, although $1.5 billion was invested in VR startups in 2016 alone (Wingfield 2017). According to one source, sales of Sony's Playstation VR units surpassed 2 million globally as of October 2016 (Swingle 2016). Another source reports 360,000 Oculus headsets and 450,000 HTC Vive headsets to have been sold (Wingfield 2017). Some projections are quite bullish, e.g., 40 million units in use by 2018 (Statista 2016b).[26] Analysts' forecasts vary dramatically (Pressman 2016). Some see sales falling off rapidly (Noonan 2016). EEDAR places 2016 sales at 10 million units, corresponding to an expenditure of $1 billion (Walker 2017). Future price reductions, more applications that support VR,

[26] https://www.statista.com/statistics/426429/hmd-virtuial-reality-unit-sales-worldwide/

resolution of user issues such as nausea, and wireless connectivity will be needed to boost market uptake.

There are currently no published measurements of how energy use might vary in comparison to use cases with desktop displays. It is anticipated that energy use will rise (at least in PCs) in proportion of the greater frame rates required, and new associated plug loads (sensors and display). VR gamers typically leave the external display running, even while wearing the headset, so that companions can have a sense of what they are seeing.

3.3 User Behavior

User behavior and gameplay choices shape the ultimate use of energy as much as does the underlying gaming hardware. The various modes of use of gaming equipment – from active gameplay to web browsing to idle time to periods when the equipment is truly off – each have their own distinct energy signature. User-determined system-level settings such as OS power management modes, deeper BIOS settings, and in-game settings all effect energy use.

One particularly impactful user behavior *within* active gameplay mode involves stepping up the computing speed of gaming system components in order to obtain enhanced performance. GPUs and CPUs are commonly overclocked. Initial tests suggest a considerable energy penalty in some cases. Mills and Mills (2015) found that a 16% increase in frame rates achieved with overclocking led to a 23% increase in energy use (i.e., a drop in efficiency). Online calculators offered to assist with PSU sizing attempt to estimate these effects, as illustrated in Figure 16. Notable are the differences in slopes of the resulting curves (which represent % increase in power per % increase in processor clock speed). For the cases shown, variations in power use varied from 9% to 12% across this over clocking range for the CPUs shown in overclock mode and -10% to -15% in underclock mode, and from 26% to 61% for the GPUs shown in overclock mode. The general pattern is that for every percent increase in clock, CPU energy use increases by about ½%, whereas for GPUs power use increases substantially more quickly than performance. These numbers haven't yet been validated with measured data.

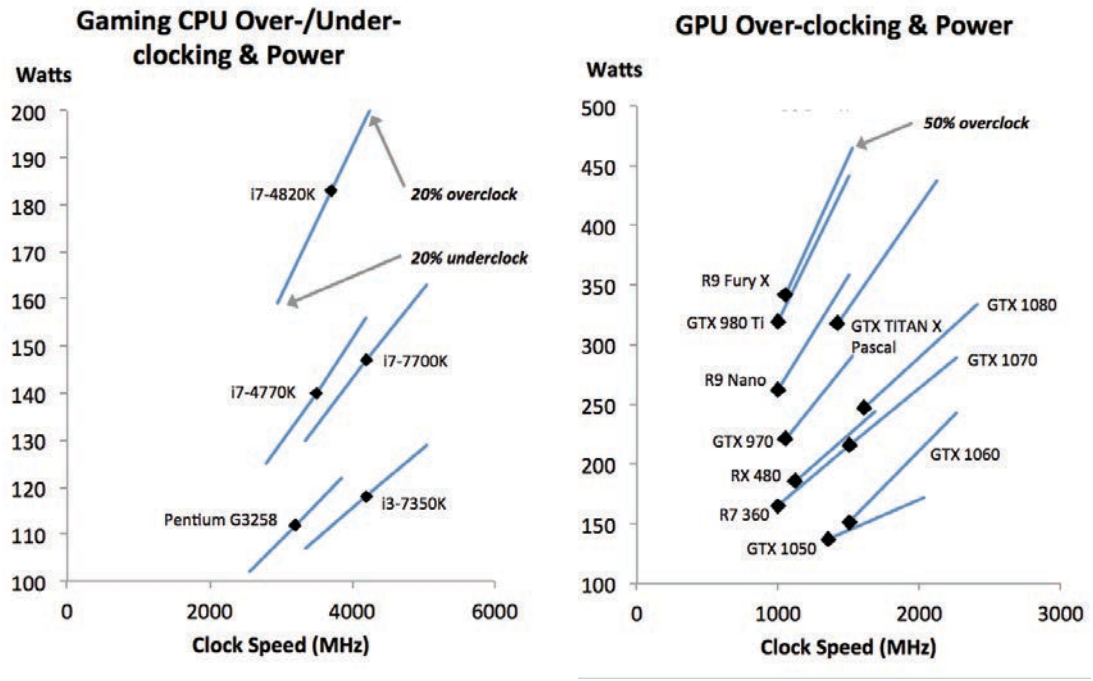


Figure 16a-b. Overclocking power and performance per OuterVision's calculator
Source: https://outervision.com/power-supply-calculator

Perhaps no single variable has a greater influence on gaming computer energy use than time spent in gameplay. This metric can be expected to vary widely, based on type of platform, game, and gamer. In addition, the preferred modes of gaming have evolved over time, most notably towards mobile gaming in recent years, which in turn implies a shift in time budgets among competing platforms with widely differing energy intensities. While some sources report highly aggregated values representing some semblance of "all gamers", for energy analysis purposes finer distinctions are required. There is no existing study or database that characterizes time in gameplay at the necessary level of detail for comprehensive macro-level energy analysis.

To be useful in estimating energy use across a population of gamers, time spent in gameplay must be associated with a particular installed base of equipment. All other things being equal, the more inclusive an installed base value the greater the number of casual and intermittent gamers that will be included, in turn reducing the weighted-average time in gameplay (but of course across a larger population). Conversely, small intensive gamer cohorts will likely have high per-platform energy use but relatively low energy consumption in aggregate. At one end of the spectrum, 213 million people in the US game at least 0.5 hours/day, as noted previously. At the other end of the spectrum, 7 million people game 7 or more hours per day (NPD 2010). McGonigal (2011b) states that over 5 million game more than 40 hours per week. Midway along this spectrum, NPD defines a subset of about 14 million "core gamers" who game 1.3 hours per day (NPD 2014a). Each of these values is nominally "correct" for the populations they seek to

describe. Thus, a nuanced map of the market comprising multiple tiers of gaming equipment together with tiers of user types and levels of activity must be assembled. Section 4 of this report presents our integrated assessment and characterization of the diversity of gamer types, gameplay patterns, and types of platforms used.

Most existing estimates of time in gameplay are found in market research reports, with few from academia. The results vary by type of gamer, demographics, and for specific game titles. Definitions of gamer types are non-standardized while methodologies are rarely explained in an unambiguous manner or the level of statistical significance noted. For example, the period over which users are actually asked to average their gaming activity (days, weeks, etc.) is often not documented; nor is the inclusive period of time (weeks, months, undefined) over which the gamer is asked to consider. The underlying survey questions are rarely disclosed, further confounding efforts to qualify the resulting information. These studies are rarely published in the peer-reviewed academic literature. Examples of best practices include Tarng *et al.* (2008), Rideout *et al.,* (2010), and Gentile *et al.,* (2011).

Figure 17 and Appendix A compile diverse estimates, normalized here to hours to day to facilitate comparisons (survey periods tend to span many days or even weeks). Aggregate estimates for the broader U.S. gaming population (all platforms combined) are around 1-2 hours/day. Interesting points along the spectrum include: 0.7h/d for console players, 1h/d for all PC gamers, 1.9h/d for online PC gamers, 2.3h/day for teen and tween PC gamers, 3h/d for selected online multiplayer gamers, 7.5h/d for “extreme gamers”. Despite the number of sources, a coherent and comprehensive picture of the marketplace does not emerge. Note that the vintages of the information as well as the gamer populations and equipment types reflected vary from study to study.

Some providers of data on gaming behavior do not clearly identify the corresponding populations and/or types of systems and sample sizes for their samples. This is problematic in part given the wide range of ways of defining users and the amounts of time spent in very energy-intensive “active gaming” mode. In an example of better practices, NPD (2014a) identifies 118 million people (42% of US population) who play on a “core” device (PCs and consoles), of which about 53 million play five or more hours per week. Of these, an aforementioned 33.7 million play what they define as “core games”, which appear to be intensive games as distinct from casual ones. In other reports, NPD has defined still narrower groups of “extreme gamers”, representing only 4% of the overall gaming population, who game more 7 hours per day on average (NPD 2010). At that time, according to NPD, the broad population of all gamers (ages 2 to 65) spent only about 1 hour per week gaming. Other reports from NPD (2014b) specify an average of 6.4 hours per week across 37% of the U.S. population (a larger demographic than that underlying the aforementioned estimates).

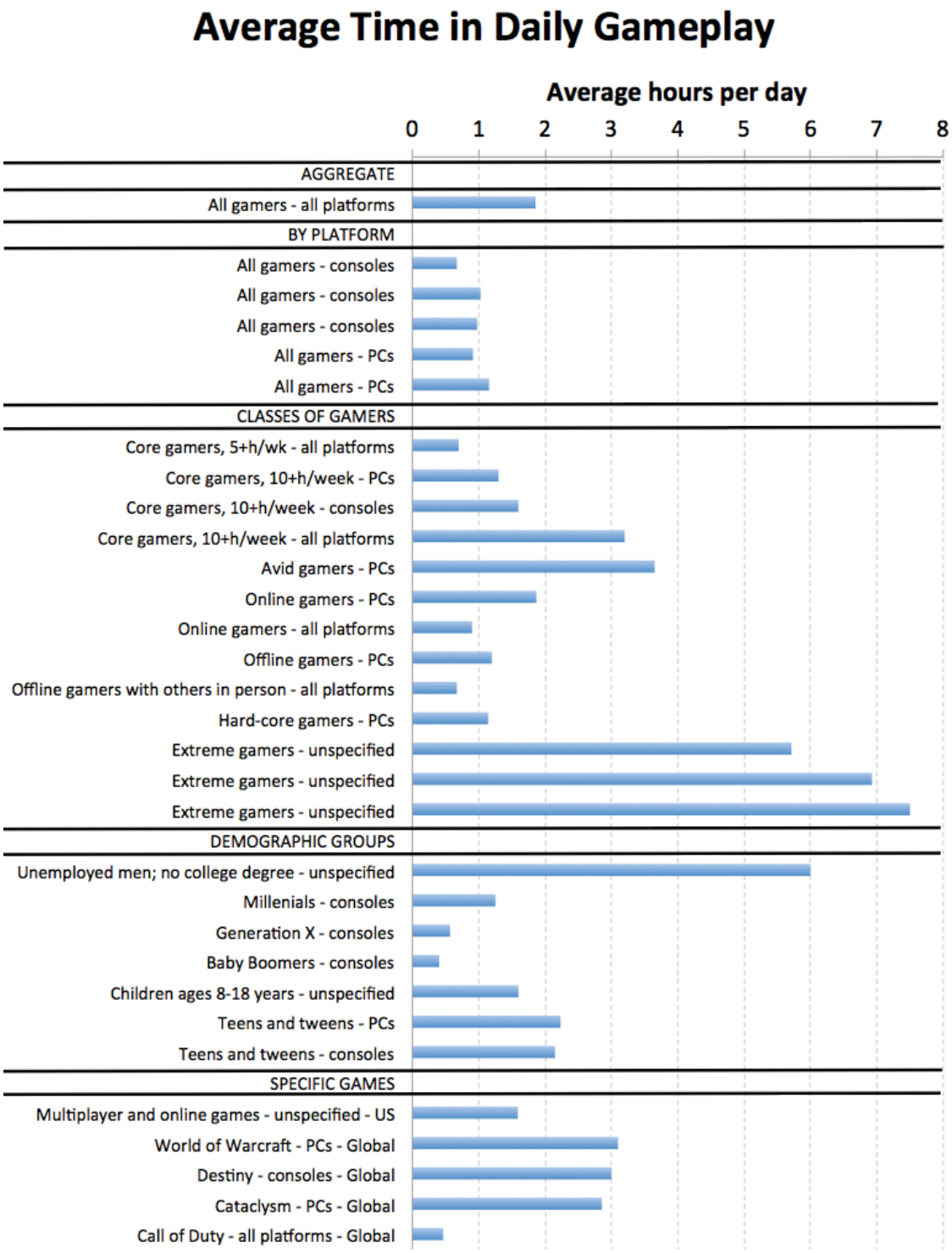


Figure 17. Disparate estimates of daily time spent actively gaming for gamers based in the United States, except were indicated. Applicable populations, gaming platforms, survey designs, and years of data vary among the sources.
Sources: See Appendix A, including population sizes)

While segmentation can be highly useful, omission of groups can easily shift averaged results up or down from those of the population as a whole. For example, where children game more than adults and are not directly polled (and polled adults are not aware of their children's true level of immersion) reported results skew downwards for the population as a whole even though they ostensibly represent the whole population. Results from Rideout (2015) indicate gameplay among tweens and teens at about twice that found by other studies providing estimates for the population as a whole (NPD 2014a).

A few studies have made the effort to differentiate gameplay findings by device type. NPD's core-gamer cohort spends an average of 3.2 hours per day (h/d) on all types of gaming devices across the United States, of which consoles represent 1.6h/d, PCs 1.3h/d, phone/mobile 0.9h/d, and the balance to other types of systems (NPD 2014a) (Figure 18). A contemporary survey by Deloitte found a much larger share of time spent on PC gaming, when desktop and laptop PCs are counted (Figure 19). A 2015 Nielsen survey focused on teens suggests that 26% of weekly gaming time is on PCs, 22% on smartphones, 39% on consoles, and 11% on tablets (Nielsen 2016a). Their results for gaming PCs are consistent with other more in-depth surveys (Rideout 2015).

Very few studies provide a sense of the variance around average gameplay results. Gentile *et al.,* (2011) conducted a three-year study of gaming among 3,034 children in grades 3 to 8 in Singapore. Average time in gameplay was approximately 22 hours per week, with a large standard deviation. A highly detailed and statistically representative survey of media use by U.S. teens in early 2015 found median gameplay time on computers among gamers to be 2:14 hours per day, and median game console to be 2:09 hours per day (Rideout 2015). Within these groups, approximately 15% of desktop gamers and 12% of console players gamed more than 4 hours per day.

Other sub-demographics exhibit interesting use patterns. Thompson (2016) cites findings that 22 percent of men without a college degree aged 21 to 30 had not worked at all during the prior twelve months, with three quarters of their "additional leisure time" spent playing video games. If the additional leisure time is eight hours per day, this suggests that 6 hours per day are spent gaming within this group.

Some studies report playtime for specific games, notably Tarng *et al.* (2008) followed 7,043 World of Warcraft players globally over an extended period and found average playtime of 3.1h/d (quintiles: 0.5, 1.6, 3.1, 5.1, and 8.8h/d). In contrast, Gatson (2011) reports 0.43h/d spent playing Call of Duty.

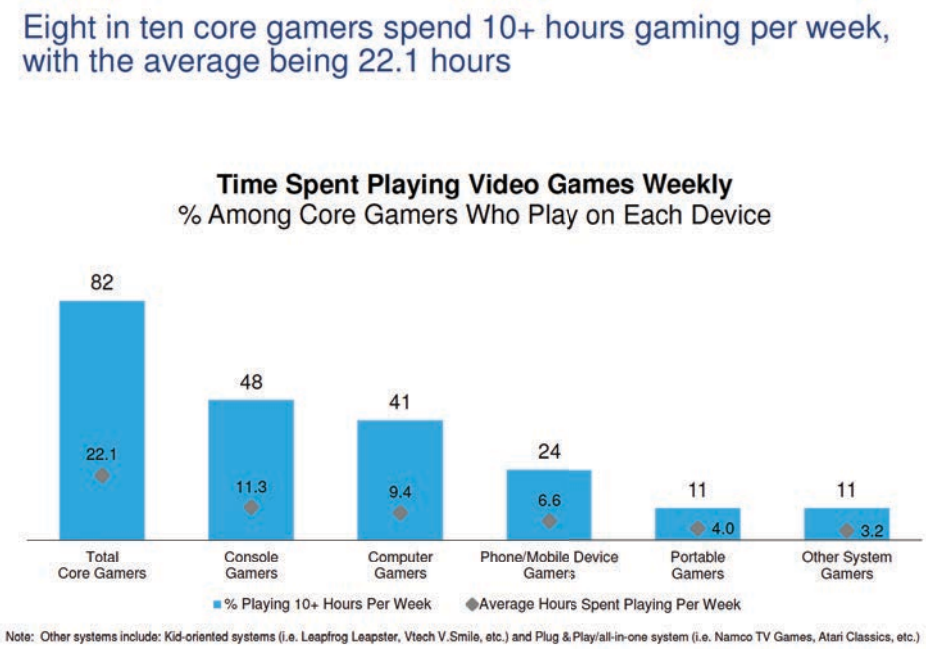


Figure 18. These estimates apply to 14 million "core gamers" as defined by NPD.
Source: NPD (2014a)

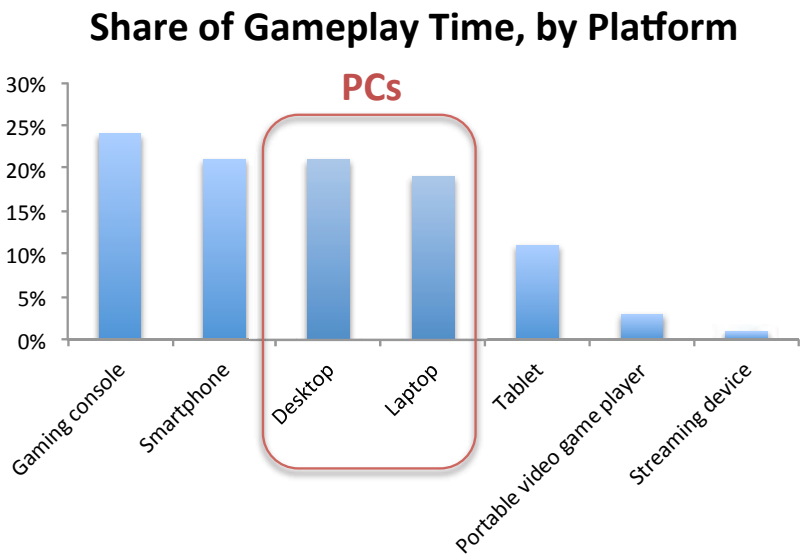


Figure 19. Gameplay among individuals playing video games on a daily or weekly basis, representing 38% of all US consumers.
Source: Deloitte (2015)

Complicating the characterization of playtime is that many gamers multi-task while consuming media, sometimes on multiple media devices. For example, a 2010 study of children between the ages of 8 and 18 found that this group multitasked for 29% of their overall media use, compressing 10 hours of aggregate media use into 7.5 elapsed hours (Rideout *et al.*, 2010).

Gaming platforms are used for purposes other than gaming. According to Nielsen's survey, only half of the time in-use by consoles was spent gaming, with the remainder in other activities. Half of console owners report using them to watch movies, 34% television, 28% for listing to music, and 21% for other (non-gaming) content (ESA 2016).

There are indications that the time spent gaming is on the rise. Nielsen surveys found that overall time spent gaming (all platform types combined) increased by 12% in 2012, 12% again in 2013, and 13% in 2014 (Nielsen 2015). Nielsen data on the time televisions are used for console play increased from approximately 0.7h/d in 2007 to 0.9 in 2012, a rate of 7%/year (Desroches *et al.* 2013). NPD has also reported increases, e.g., 9% year over year between 2009 and 2010 among console players and 6% for PC players (NPD 2010). Consoles are of course used for additional hours when not connected to the television. The fraction of the average gamer's time spent gaming on PCs fell from 38% in 2012 to 25% in 2014, while use of other devices, particularly smart phones, rose; video gaming rebounded slightly in 2015 (Nielsen 2015; Nielsen 2016a). These dynamics have important implications for aggregate energy demand.

Short (2013) presents a more segmented assessment than most other studies, but it contains various ambiguities and lacks documentation of methodology. Of potential value, Short distinguishes among three types of gamers as well as online gaming (1.9h/d) and offline PC gaming (1.2h/d). The 34 million Avid PC gamers, for example, are reported to game 3.7h/d. A category referred to as "Extreme" gamers (7.5h/d) appears to mix different platform types across 10 million gamers. The author estimated that 46 million console users engage in gaming 2.4h/d. According to this source, time in gameplay is trending upward in most cases and is projected to continue doing so (Figure 20), although it should be kept in mind that modal mix is also changing, driven particularly by the rising popularity of mobile gaming.

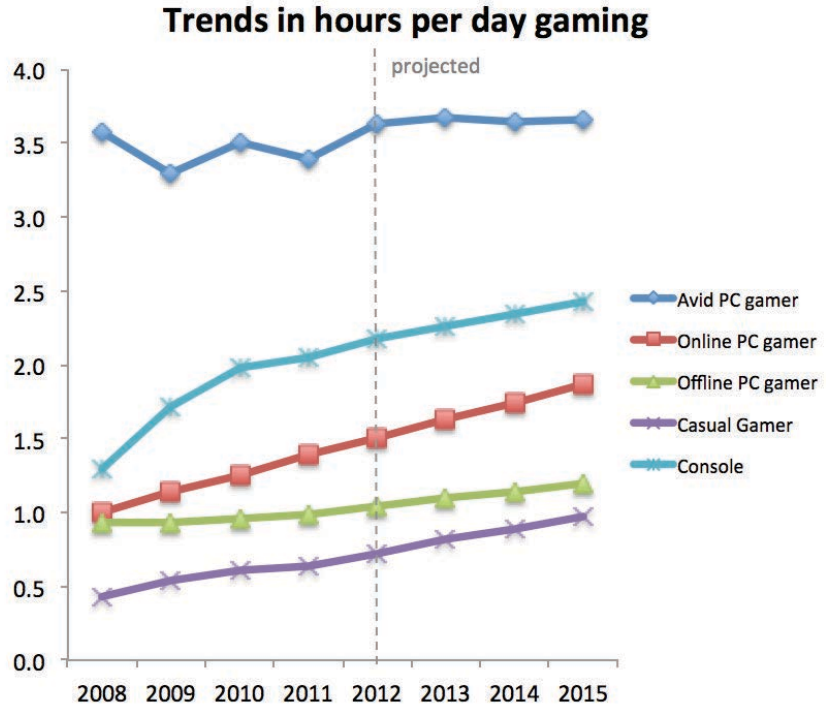


Figure 20. Actual and projected trends in time spent gaming, by category.
Derived from Short 2013

Very few studies from the energy literature allocate total console on-time to different segments of the duty cycle (Table 3). Urban *et al.* (2014) provide values for "active use" versus "on" for 8 console makes and models, varying from about 2 hours per day for PS4 to just over 6 hours per day for the Xbox. The proportion of these periods in "active" mode varies from approximately 30 to 90 minutes. The active periods are further broken down into gaming, video streaming, and video playback, with active gaming ranging from approximately 25% to 95% of the overall time in active mode.
With Generation 7 consoles (e.g. Wii, PS3, Xbox 360) there was some concern that consoles were left on while the user was away in order to avoid losing progress in a game (e.g., Neugebauer *et al.* 2008). This left the machine at full or nearly full power for a significant fraction of the day, even if time spent actively gaming was low, leading to very high annual energy consumption. However, there was significant uncertainty regarding the prevalence of this behavior, leading to a wide range of energy consumption estimates in the literature (Roth & McKenney 2007; Neugebauer *et al.,* 2008; Desroches & Garbesi 2011; Urban *et al.,* 2011; Hittinger *et al.,* 2012; Webb *et al,.* 2013; Desroches *et al.,* 2015). The more recent studies, some based on field measured data, found that this behavior was less common than originally assumed. Furthermore, the later versions of these Generation 7 consoles, as well as the newer Generation 8 consoles, incorporate automatic power-down features to mitigate this behavior. The evolution of console technology has largely addressed this issue. The fraction of consoles where this feature is disabled remains a source of uncertainty, however.

Table 3. Console duty cycle by make and model *(Urban et al. 2014)*

Table 3-76: Usage by different video game consoles (CE Usage Survey).

	Years	Usage [h/yr] Gaming	Video Streaming	Video Playback	Navigation	Standby
Nintendo						
Wii U	2012-2013	108	293	-	1,205	7,154
Wii	2006-2013	100	82	-	876	7,702
Microsoft						
Xbox 360 S/E[a]	2008-2013	365	146	37	693	7,519
Xbox 360	2007	402	146	-	693	7,519
Xbox	2001-2008	183	-	-[b]	2,154	6,424
Sony						
PS3 Slim & Super Slim	2006-2013	394	115	44	657	7,550
PS2	2000-2013	197	-	22	1,059	7,483
Total/Wt. Avg.	-	**245**	**89**	**21**	**885**	**7,521**

a Xbox 360 S and Xbox 360 E are two redesigned model released in 2010 and 2013, respectively, of the Xbox 360 video game console (released in 2005).

b The Xbox has an accessory that enables the playing of DVDs. Eight percent of CE Usage Survey (2013) respondents reported that they played DVDs on their Xbox "yesterday" (See AppendixB.3). However, we did not use this data in our usage and energy consumption estimates because we did not have power draw data for Xbox gaming consoles using this accessory.

A survey by Deloitte of gamers 14 years and older found that 85% used their consoles for gaming. Seven other uses were identified, led by movie-watching via local optical media and streaming (Figure 21). Other uses include Internet browsing, fitness training and education, listening to music, and viewing home-generated video and photos.

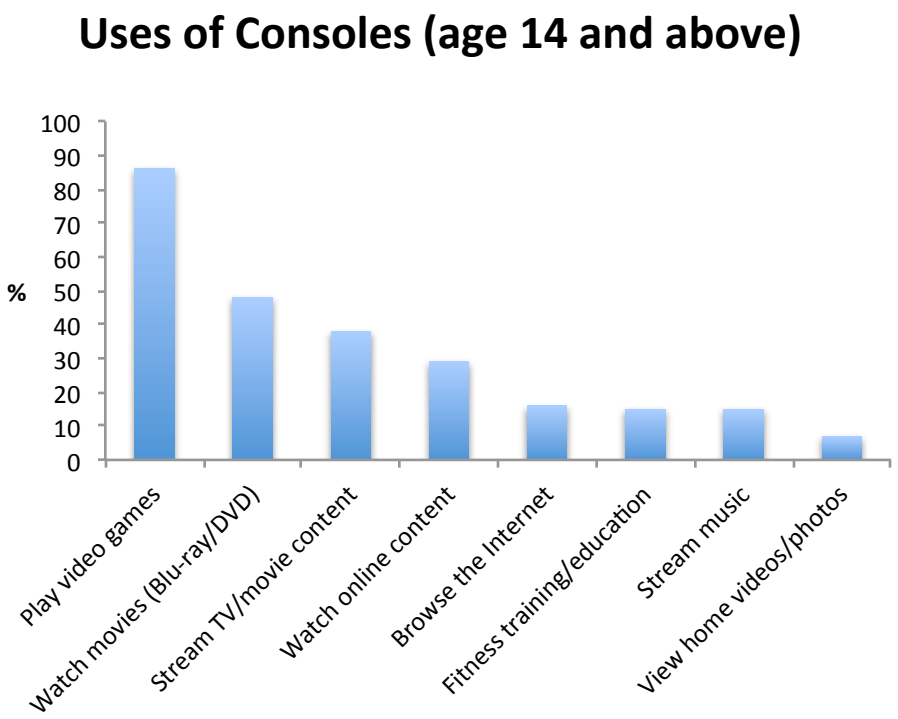


Figure 21. User-reported activities on consoles.
Source: Deloitte (2015)

3.4 Game Titles

As noted above, an enormous global industry is associated with creating and selling electronic games, currently valued at approximately $100 billion annually.

3.4.1 Game Genre

Segmenting the market by types (a.k.a., genre) of games (Figure 22) is important for energy analysis because some genres may entail greater computing demands and proportionately even greater energy use. An additional factor that complicates the segmentation process is that genre sales distributions vary considerably across platform types (PC, console, or TV Device). Figure 22 clearly shows this difference, as well as sometimes significant differences in estimates between two prominent industry sources. An important caveat is that gaming software genres are of course not defined with energy in mind. It may in fact be the case that developing "energy genres" would yield different groupings of games. This is a question that will be explored in future reports under this project.

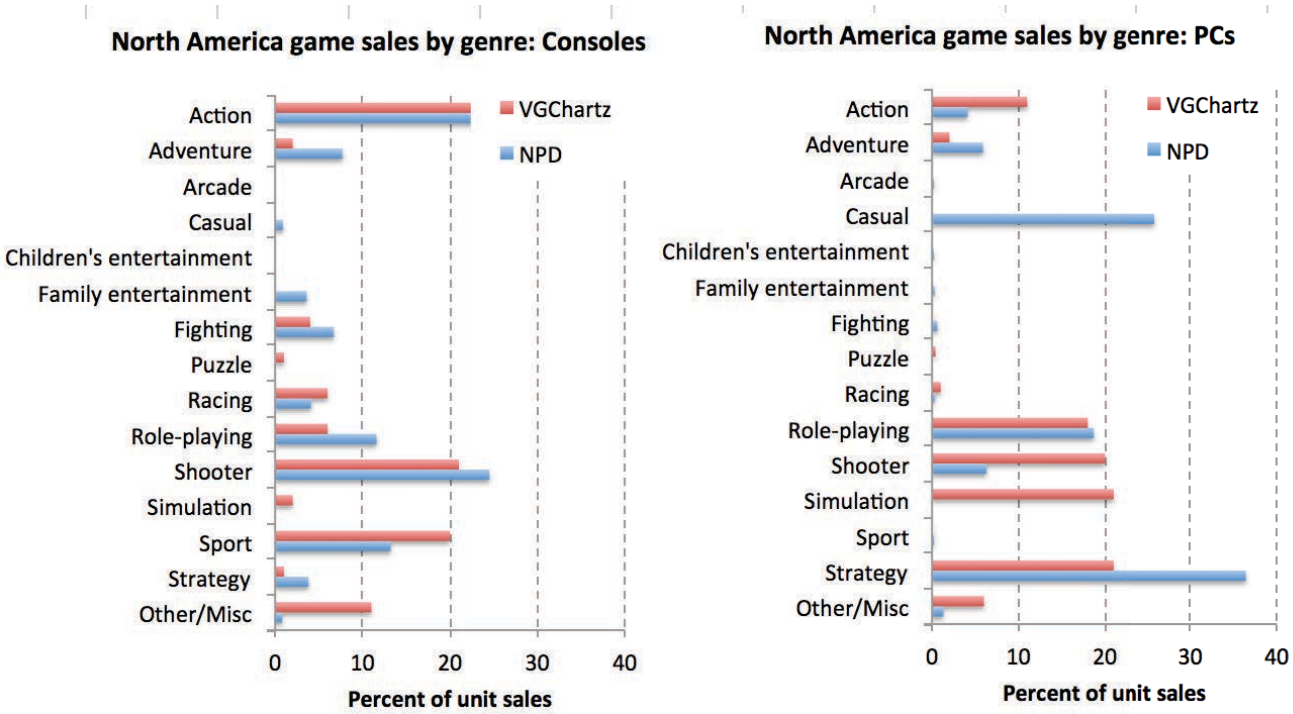


Figure 22. Distribution of North America game sales by genre and platform for two data sources. Based on numbers of units sold.

Source:NPD data from ESA (2016). VChartz from http://www.vgchartz.com/gamedb

Another confounding factor in categorizing games is the abundance of genre categories in use, together with the fact that assignment of a genre to an individual title can be quite subjective. For example, an Internet search on the genre for "Minecraft" quickly shows that it is not universally categorized as being of the "Sandbox" sub-genre, its

most common genre assignment. Many discussion threads debate that Minecraft is also an Adventure, First-Person-Shooter or even a new genre sometimes called a "voxel format" which has been emulated by new titles (Trove, Portal Knights or Terraria and Starbound to a lesser extent).

3.4.2 Top Titles

Many market research outlets publish lists of top games. An important caveat in using such data is that the rankings are pedominantly based on sales, which excludes free-to-play (f2p) titles, and also does not reflect numbers of units or actual time in gameplay. Sales-based rankings as of late 2015 are show in Table 4, while usage-based rankings are shown in Table 5. Topping the latter list is League of Legends (f2p), with a remarkable 67 million users globally (NewZoo 2016c).

Table 4. Top 20 games, by revenues (PCs and Consoles) *(ESA 2016)*

Top 20 Selling VIDEO GAMES of 2015

BY UNITS SOLD

RATING	
1	CALL OF DUTY: BLACK OPS III (M)
2	MADDEN NFL 16 (E)
3	FALLOUT 4 (M)
4	STAR WARS BATTLEFRONT 2015 (T)
5	NBA 2K16 (E)
6	GRAND THEFT AUTO V (M)
7	MINECRAFT (E 10+)
8	MORTAL KOMBAT X (M)
9	FIFA 16 (E)
10	CALL OF DUTY: ADVANCED WARFARE (M)
11	BATMAN: ARKHAM KNIGHT (M)
12	LEGO: JURASSIC WORLD (E)
13	BATTLEFIELD HARDLINE (M)
14	HALO 5: GUARDIANS (T)
15	SUPER SMASH BROS. (E)
16	THE WITCHER 3: WILD HUNT (M)
17	DYING LIGHT (M)
18	DESTINY: THE TAKEN KING (T)
19	NBA 2K15 (E)
20	METAL GEAR SOLID V: THE PHANTOM PAIN (M)

Source: The NPD Group/Retail Tracking Service

Top 20 Selling COMPUTER Games of 2015

BY UNITS SOLD

RATING	
1	THE SIMS 4 (T)
2	FALLOUT 4 (M)
3	THE SIMS 3: STARTER PACK (T)
4	THE SIMS 4 GET TO WORK EXPANSION PACK (T)
5	STARCRAFT II: LEGACY OF THE VOID (T)
6	ELDER SCROLLS V: SKYRIM (M)
7	FALLOUT ANTHOLOGY (M)
8	GRAND THEFT AUTO V (M)
9	WORLD OF WARCRAFT: WARLORDS OF DRAENOR EXPANSION PACK (T)
10	STAR WARS BATTLEFRONT 2015 (T)
11	THE SIMS 3: PETS (T)
12	THE SIMS 3 SEASONS EXPANSION PACK (T)
13	DIABLO III: REAPER OF SOULS (M)
14	DIABLO III (M)
15	THE SIMS 3: ISLAND PARADISE EXPANSION PACK (T)
16	THE SIMS 3: UNIVERSITY LIFE EXPANSION PACK (T)
17	THE SIMS 3: SUPERNATURAL EXPANSION PACK (T)
18	STARCRAFT II: WINGS OF LIBERTY (T)
19	SIM CITY 2013 (E 10+)
20	WORLD OF WARCRAFT: BATTLE CHEST 2013 (T)

Source: The NPD Group/Retail Tracking Service

Table 5. Most played core PC games *(NewZoo 2016c)*

1	League of Legends	11	Grand Theft Auto V
2	Minecraft	12	ARMA 3
3	Heartstone: Heroes of Warcraft	13	Guild Wars 2
4	Counter-Strike: Global Offensive	14	Heroes of the Storm
5	World of Warcraft	15	Gary's Mod
6	Overwatch	16	Grand Theft Auto: San Andreas Multiplayer
7	World of Tanks	17	The Elder Scrolls V: Skyrim
8	Tom Clancy's Rainbow Six: Siege	18	Ark: Survival Evolved
9	Battlefield 1	19	H1Z1
10	Rocket League	20	Rust

Wikipedia also maintains a list of best selling video games,[27] in which Tetris and Minecraft are listed in the number 1 and 2 positions. However, it is notable that the top 6 titles listed by Wikipedia all are identified as having been shipped within a hardware bundle at some point in their sales history (Table 6), showing that bundled game sales can skew game rankings and their usefulness towards predicting game-related energy use in the market, as bundling does not predict actual time in gameplay.

Table 6. List of best-selling video games *(Wikipedia 2017)*

List of best-selling video games on all platforms

No.	Title	Developer(s)[a]	Publisher(s)[a]	Release date	Sales	Ref.
1	*Tetris* †	Elektronorgtechnica	Spectrum HoloByte[b]	June 6, 1984	495,000,000	[2]
2	*Minecraft* †	Mojang	Mojang	November 18, 2011	122,000,000	[4]
3	*Wii Sports* †	Nintendo EAD	Nintendo	November 19, 2006	82,810,000	[7]
4	*Grand Theft Auto V* †	Rockstar North	Rockstar Games	September 17, 2013	80,000,000	[8]
5	*Super Mario Bros.* †	Nintendo R&D4	Nintendo	September 13, 1985	40,240,000	[9]
6	*Mario Kart Wii* †	Nintendo EAD	Nintendo	April 10, 2008	36,950,000	[7]
7	*Wii Sports Resort* †	Nintendo EAD	Nintendo	June 25, 2009	33,040,000	[7]
8	*Pokémon Red, Green* and *Blue*	Game Freak	Nintendo	February 27, 1996	31,380,000	[10]
9	*New Super Mario Bros.*	Nintendo EAD	Nintendo	May 15, 2006	30,800,000	[11]
10	*The Elder Scrolls V: Skyrim*	Bethesda Game Studios	Bethesda Softworks	November 11, 2011	30,000,000	[12]

Key

†	Game was shipped with a console during its lifetime

Fortunately, VGChartz summarizes game sales by numbers of game units and by platform (weekly or yearly).[28] For consoles the top three as of mid 2017 were Wii Sports, Grand Theft Auto V, and Mario Kart Wii with 83 million, 60 million, and 36 million units sold, respectively. However, it is important to note that Wii Sports and Mario Kart Wii were both shipped with new consoles as a bundle, which boosts the unit count

[27] https://en.wikipedia.org/wiki/List_of_best-selling_video_games
[28] http://www.vgchartz.com/gamedb/

considerably. Since its initial release in 2003, Call of Duty has tallied an incredible 264 million units sold globally across all releases, exceeding $15 billion in revenues.[29]

3.4.3 Energy Analysis Considerations

What emerges from the preceding discussion is a complex matrix of existing data sources, and corresponding considerations for selecting a representative set of games titles for use in energy analysis. Ideally, one needs to estimate the game titles actually being played, the amount of gameplay, and the game types and the relative distribution among the various hardware platforms.

3.5 Online Gaming

Gaming is rapidly expanding into the cloud, thereby extending the associated energy use into data centers. No information is available on the relative allocation of energy use between the local client and the network of supporting core and edge data centers.

According to Entertainment Software Association surveys, 51% of the most frequent gamers play cloud-based games at least once weekly (ESA 2016), for an average of 0.9 hours per day.[30] Among college students, approximately 35% play daily and 75% play at least weekly (Statista 2016c).

The shift towards online gaming is strong, with 21% of 7th-generation console hours spent in that mode in 2010, increasing to 28% for 8th-generation consoles in 2014 (Nielsen 2016b). Console players now spend more time playing on-line games than offline games. One estimate placed the value at 46 million console gamers in the US in 2014 (Statista 2016a).

An entire gaming genre—Massively Multiplayer Online Role Playing Games (MMORPG)—is intrinsically cloud-based. Statista (2016a) reports that one third of all US gamers engage in MMORPG gaming; NPD finds that 70% of the 34 million "core gamers" do so (Siegal 2014). As far back as 2012, PC gamers reported spending 34% of their total gaming time in on-line mode (PWC 2012).

On-line gaming is projected to be the fastest-growing segment of residential Internet service, with the 1.1 billion users in 2015 growing to 1.4 billion by 2020 (Cisco 2016a). Cisco notes that "if cloud gaming becomes popular, gaming could quickly become one of the largest Internet traffic categories" (Cisco 2016b). Virtual-reality streaming could become an important additional driver. The global volume of online gaming traffic was estimated at 82 petabytes per month in 2015, and projected to grow seven-fold by 2020 (Cisco 2016c) (Figure 23). These estimates are up sharply from values produced just two years earlier (Cisco 2014). Notably, "online gaming" is one of only four segments that

[29] https://charlieintel.com/2016/02/11/call-of-duty-has-surpassed-over-15-billion-in-sales-since-2003-launch-bo3-season-pass-sales-rate-highest-in-franchise-history/

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

the types of "consumer internet traffic" data that Cisco disaggregates, the others being internet video, web/email/data, and file sharing, and is the fastest-growing at 47%/year. Gaming devices are also used for other cloud-based activities such as web-browsing and video streaming.

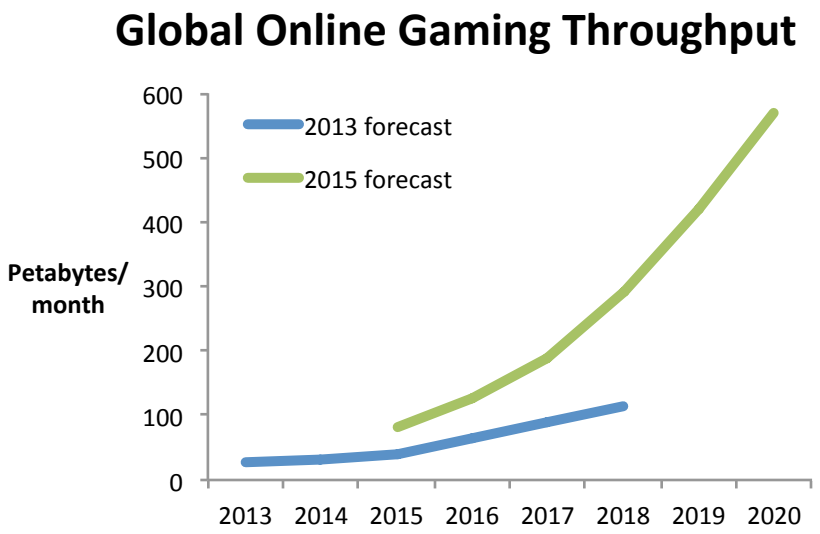


Figure 23. Evolving projections of online gaming Actual values shown in base year. One Petabyte is 10^{15} bytes. Approximately 60% of global traffic is in North America.
Source: Cisco 2014; 2016b

Some gaming equipment manufacturers are exploring the establishment of data centers dedicated solely to supporting gaming. As of early 2017, NVIDIA had installed several hundred thousand of its high-power GeForce GTX 1060 and GTX 1080 graphics processing units in data centers, which can be "rented" by gamers seeking a peak gaming experience.[31]

3.6 Consumer Energy Information Environment

While many gamers are highly literate regarding their technology options, some building their systems from scratch, the energy information available to them is scant and unstandardized. This represents an important barrier to understanding and managing energy use.

Most relevant information is based on rough proxies of power requirements, with virtually nothing on actual energy use (combination of power and duty cycle assumptions). These proxies include Thermal Design Points (TDP), discussed above, rather than measured electrical wattage, rough ratings on certain power supply units (several grades of 80-Plus), and Energy Star ratings on displays. PSUs for gaming laptops

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

and consoles are not rated/labeled for consumers. There are no energy-relevant ratings for CPUs, GPUs, or motherboards. The selection of type and number of case fans is more art than science.

Comparisons of system-level power to CPU TDPs (see Figures 8 and 11) 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 PSU it happens to be paired with. Component manufacturers do not include measured power requirements in product literature or packaging, and third-party reviews are sparse and do not use standardized test protocols

There are at present no game-specific energy ratings. Thus, consumers cannot know in advance how their choices among different titles or genres may impact their energy use and costs. Preliminary findings of ongoing research at LBNL indicated at least a factor-of-two variance in energy use for a given PC gaming platform across types of games, and at least a factor-of-four variance in energy use for a given game across types of PCs.

Insights into energy per unit of performance are also highly approximate. Metrics for graphics cards such as TeraFlops are only loose proxies for performance. Numbers of cores in CPUs may or may not matter, depending on how an application is coded, and frame rates are only one of many factors determining user experience and enjoyment.

3.7 Baseline Energy Use

Gaming system energy use is driven by the duty cycle (time spent in active mode versus other modes, discussed above), and the system's power requirements associated with each mode. Estimating energy use is complicated by the lack of good data. Moreover, virtually all gaming devices have non-gaming uses, ranging from movie and television viewing to web browsing to the wide range of uses to which a personal computer can be placed. Comprehensive energy analyses must consider the combined energy use of these devices, including but not limited to that in active gaming mode.

Consoles are the most well studied gaming platform, with considerable measurements having been performed over multiple generations. These are well summarized by Webb *et al.* (2013), who found values from past studies to range from 33 to 330 kWh/year, and placed their own value at 102 kWh/year for the installed base of units purchased between 2005 and 2011, of which half is consumed in gaming mode. Urban *et al.,* (2014) estimated unit energy consumption from 43 to 250 kWh/year for consoles present in the installed base as of mid-2013, depending on model and generation of console device as well as mode-specific duty cycle, with an installed-base-weighted average of 88 kWh/year. They found that prior studies placed the value between 10 and 213 kWh/year across the period ranging from 1995 to 2013. Unit consumption has fallen over time for most console devices, even as performance has significantly improved (Figure 24).

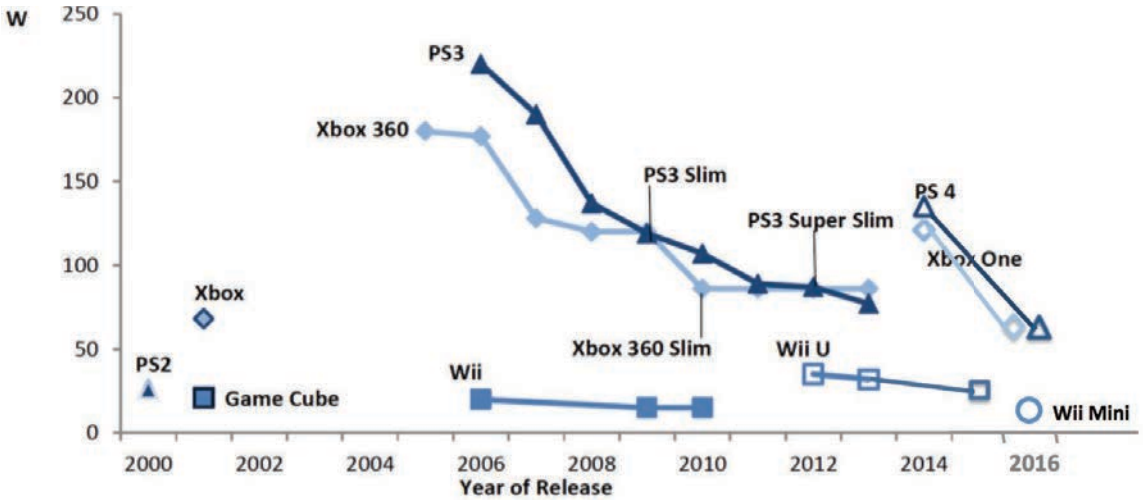


Figure 24. Historical active-gaming mode power draw for video game console systems through 2013 (Urban et al. 2014) with updates to 2016 (EU 2016). Each sub-release within a given product line tends to yield improved energy efficiency.

A number of studies have estimated U.S. energy use for gaming consoles, placing the value at 0.5-1.5 TWh in the 1995-1999 timeframe (Sanchez *et al.,* 1998, Rosen *et al.,* 2001). Later studies placed the value between 2.4 and 16.3 TWh (Urban *et al.,* 2014). Desroches *et al.,* (2015) estimated annual energy use at 7.1 TWh in the year 2012. In perhaps the most detailed recent estimate, Urban *et al.*, (2014) estimated national energy use for gaming consoles at 11 TWh/year, reviewing the literature and providing substantial detail on unit energy consumption as well as the installed base. Table 7 provides a summary of the various studies to date on console energy use. Koomey *et al.,* (2017) have performed recent power measurements in active gaming mode, but these are not translated into annual energy use.

It is important to note that the above studies all utilized different methodologies, each with their own benefits and drawbacks. Some studies rely upon a bottom-up approach, utilizing laboratory testing and usage estimates to arrive at total energy use (e.g. Neugebauer e*t al.,* 2008, Desroches & Garbesi 2011, Hittinger *et al.,* 2012, Webb *et al.,* 2013). While easier to perform, such studies are naturally sensitive to the duty cycle assumptions. Studies with properly field-metered data provide the most robust usage data, however these are expensive and often restricted to small sample sizes, which may not be representative (e.g., Bensch *et al.,* 2010, Larson *et al.,* 2014, Desroches *et al.,* 2015). Finally, some studies rely on survey data to estimate usage (e.g. Urban *et al.,* 2011, 2014). Surveys are less expensive to deploy and can reach a large sample size, although survey responses can suffer from social desirability and recollection biases, as well as calculation/estimation errors on the part of respondents, especially for low intensity activities such as leaving a console on while away. Nevertheless, the various studies help to constrain the range of energy consumption and usage of game consoles.

Table 7. Console energy consumption estimates from the literature.

Study	National Energy Use (TWh/yr)	Average Unit Energy Use (kWh/yr)	Average Usage[a] (h/yr)	Average Standby Usage (h/yr)	Units in Stock (millions)	Applicable Year
Desroches et al. (2015)	$7.1^{+1.8}_{-1.3}$	68^{+17}_{-12}	1109^{+645}_{-384} [b]	4684^{+954}_{-974} [b]	105	2012
Urban et al. (2014)	11	88	1239	7521	128	2013
Larson et al. (2014)	-	90.5 ± 15.3	2883± 511	3285 ± 584	-	2013
Webb et al. (2013)	-	102[c]	694	8066	-	2005-2011
	-	64[c]	694	8066	-	2012
Hittinger et al. (2012)	11	213[d]	2890[e]	5870[e]	52	2007
	16	213[d]	2890[e]	5870[e]	75	2010
Zimmerman et al. (2012)	-	47.6	-	-	-	2010
Desroches & Garbesi (2011)	3.5	55[f]	-	-	63[g]	2006
	6[g]	55[f]	-	-	109[g]	2010
Urban et al. (2011)	14.6	135	1450	7310	109	2010
Bensch et al. (2010)	-	1 – 45[h]	183 – 438[h]	8322 – 8577[h]	-	2009
Neugebauer et al. (2008)	16[i]	-	-	-	52	2007
Roth & McKenney (2007)	2.4	36	964	7796	64	2006

[a] Includes active gaming, viewing video, menu navigation, idle, and other media functionality.
[b] Active plus Standby usage does not equal 8760 hours, due to time in Off mode.
[c] Includes high-definition consoles only.
[d] Extrapolated from national energy use and units in stock.
[e] Assumes a weighted average of 6.3 hours per week per user spent actively using console, and two users per console. Further assumes that 30% of consoles are left in idle when not in use.
[f] Assumes 20% of consoles are left in idle when not in use, but only for 2000 hours per year.
[g] The original national energy use estimate relied on an older stock estimate, and thus the applicable year is 2006. Using an updated stock estimate for 2010 yields a national energy use estimate that would have been more representative at the time of publication.
[h] This study only measured the energy consumption of 13 game consoles for 1 month each, and is likely not representative of average national usage.
[i] Assumes that 50% of consoles are left in idle when not in use.

We have identified no literature on the energy use of other TV-linked gaming products.

Numerous estimates exist of the energy use of conventional PCs (e.g., Delforge 2016), although no national or state-level energy demand estimates have been made for desktop gaming PCs. Mills and Mills (2015) combined market data and measured energy use for the purpose of estimating aggregate energy demand and savings potential

globally. This was a simplified approach insofar as it used a single “average” desktop computer (circa 2013 technology) to characterize the stock with a single duty cycle and set of user settings. They estimated an average unit energy consumption of approximately 1400 kWh/year across the duty cycle for the narrow segment of the overall gaming population known as “extreme gamers”. This group corresponded to about 54 million people globally, or about 2-3% of all gamers and 5% of all PCs. Where a more inclusive base of PC gamers is to be considered, the unit energy consumption would of course need to be lower as a reflection of a more diverse risk of relatively casual gaming behavior.

No prior studies have considered gaming energy attributable to conventional PCs and laptops, gaming laptops or non-console devices that display games on television. Similarly, energy use for virtual reality technologies have not yet been assessed or compared to the incumbent technology (desktop displays)

4 Integrated Characterization of Baseline Gaming Hardware and User Preferences

As can be seen from the foregoing discussion, the current characterization of the market is patchy and has rarely been conducted with energy analysis in mind. Thus, significant critical information is lacking, e.g., installed base by type of equipment, duty cycles (including but not limited to time spent in active gaming mode), and user settings.

This section assembles a unified characterization of the market. The technology assessment process was led by Jon Peddie Research, in collaboration with Lawrence Berkeley National Lab, based on published and unpublished data, and in consultation with product manufacturers and industry experts.

The result is a more granular analysis than offered in earlier literature. It identifies a representative set of platforms (within the broad categories of PCs, laptops, consoles and other TV gaming devices) mapped to estimates of the associated installed base centered around these benchmark systems. Integral to the analysis is type, quality, and numbers of displays, both desktop monitors as well as virtual reality. The assessment excludes battery-powered devices and arcade games.

Together with the distinctions among platforms, a variety of user-driven parameters are defined, broadly including system settings, gaming titles, in-game settings, and time spent gaming. The prevalence of other energy-relevant behaviors such as overclocking CPUs and GPUs are also considered. While time spent gaming is a critical variable, as active gaming mode is the most energy intensive, we also consider the full duty cycle, which we categorize into various steps. Four types of users are defined, based on increasing levels of gaming activity, to which total gaming time is proportioned for each platform.

4.1 Hardware

With the exception of consoles, no prior study has attempted to characterize disaggregate the installed base in any detail. Doing so is important if energy use is to be well understood and the drivers pinpointed.

To enable a detailed characterization of the installed base of video gaming equipment, we first segment the market into four very broad categories, reflecting key hardware types: Desktop computers, laptop computers, and video game consoles and other TV-based gaming devices. The most heterogeneous category, from an energy perspective, is desktop computers. We have thus further disaggregated this into three subcategories that reflect different levels of affordability.

Within each category and subcategory we have identified specific equipment and its associated installed base for the state of California. In the case of desktop computers, some are pre-built, name-brand systems while others are customized to reflect nuances in the market and that many gamers in practice build their own systems from individual components. For desktops and laptops, the lower end of the spectrum includes mainstream computers not designed specifically for gaming yet nonetheless used quite widely for that purpose.

We considered Amazon best-selling CPUs and recommendations from leading consumer publications such as *PC Gamer* and *Maximum PC Magazine*, as they influence consumer decision-making. Slight adjustments are made to national indicators given the relative wealth effect in California will tip some buyers towards incrementally higher-end component choices. Gaming-grade motherboards were chosen for multiple reasons including their targeted marketing for gaming and that they support unlocked processors, which are sought by many gamers. A mix of leading-brand graphic processing units (NVIDIA, AMD, and Intel) are chosen. Popular configurations of RAM and storage, cases, and cooling systems are chosen as well. For DIY systems, Amazon's best-selling PSUS (White and Bronze) are preferred, although some more efficient units are included to reflect some consumer preferences and that major manufacturers report significant popularity of Gold ratings (and above) among US gamers. Pre-built PCs are believed to have a higher proportion of low-quality PSUs, and users are not able to customize or otherwise specify upgrades at time of sale.

The resulting desktop PC equipment choices range in retail cost from approximately $550 to $4500, while laptops range from $700 to $2500. These systems have a corresponding variety of CPUs, GPUs, motherboards, power supplies, cooling strategies, and displays. Historical coverage includes the latest two generations of equipment, as older components are difficult to procure for testing purposes and are in any case fading rapidly from the installed base. In all, ten representative PCs and five laptops devices are defined. The resulting system specs are summarized in Appendix B.

Ten additional console and other TV-linked gaming devices included in the assessment are: Sony (PlayStation models 3, 4 Slim, and 4 Pro). Microsoft (Xbox models 360, One, and One S), and Nintendo (models Wii and U). Representative non-console devices include Apple TV and NVIDIA SHIELD (Android TV). These are paired with a variety of displays ranging from Sub 720p to 1920x1080.

4.2 Installed Base

Defining the installed base of gaming devices in California is not straightforward, particularly in the case of desktops and laptops. On the one hand, many conventional computers are used for gaming, while on the other hand some computers that could be characterized as "gaming PCs" are not in fact used for gaming. Reasons for the latter instance include equipment used for other graphically intensive tasks such as architectural rendering or video production, as well as retired or repurposed equipment.

The process of estimating the installed base for desktop and laptop PCs begins with a count of GPUs entering the market as a proxy for numbers of overall systems. Downscaling is conducted in order to exclude systems used by businesses, educational institutions, and public-sector entities. Consideration is given to the relatively rare situations in which more than one GPU is used in a given system. The resulting inventory is further reduced to include only those systems used no less than one hour per week (on average) for gaming. Separate data on the ratios of desktop to notebook GPU production are used to estimate the population of conventional gaming-grade laptop computers used for gaming.

The installed base of consoles and other TV-gaming devices is estimated from cumulative sales to the date in question, adjusted for physical attrition. A rising market share for Sony is projected based on the strength of the brand, likelihood of larger game library, or processor, high degree of gamer-focus, and aggressive promotion of VR. Our estimates were produced prior to the introduction of Nintendo Switch.

Methodologies for estimating the installed base must stipulate a cutoff point below which the systems are assumed not to be used for a material amount of gaming. Some gaming-capable computers are used for gaming only exceedingly rarely, e.g., 1 hour per month, or not at all (broken or dormant status). As increasingly inclusive definitions of installed base are selected, the average utilization assumptions must be attenuated accordingly. For the purposes of this study, we have established a normative cutoff point of 1 hour/week in active gameplay as a criterion for inclusion in the installed base. Such an assumption is of course subjective, with a lower bar corresponding to a larger installed base with lower *average* implied energy use per device, but of course relatively more devices. As an illustration of this last point, for the cohort of "core gamers" described by NPD as gaming five or more hours per week, the average time spent in gameplay is 0.7 hours per day, whereas the average time for the smaller cohort playing 10 or more per week is 3.2 hours per day (NPD 2014a).

In upcoming research, our installed-base information will be paired with bench-top power measurements of the representative individual systems so as to estimate aggregate gaming energy in California. Past and projected values for the installed base have been estimated so as to give shape to the trends in aggregate energy use.

Importantly, market factors drive strong trends influencing the total installed base as well as the proportions of various platforms over time. Table 8 and Figures 25 and 26 represent the resulting installed base for desktop PCs and consoles for the years 2011, 2016, and 2021. Entry-level systems dominated in the past, but have lost significant market share to Mid-range and High-end systems and will continue to do so in the coming years. We estimate that, as of 2016, 3.1 million computers (both desktop and laptop) are used for gaming in California, plus 12.4 million consoles and other TV gaming devices. The significant reduction in 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 stayed with that type of platform. Additional sources of attrition were broken or dormant systems and those that are used less frequently than the one-hour-per-week cutoff we adopt to define our use model. Looking forward, the base of the most energy intensive high-end desktops will grow from about approximately 150,000 to nearly 400,000 units. We estimate that 7.5% of all desktop PCs used for gaming are built by their users in 2016 (DIY), largely concentrated in the Mid-Range and High-end tiers.

Table 8. *Breakdown of California desktop and laptop PCs used for gaming by year and performance level.*

	Desktop			Laptop		
Total Units	**Entry-Level**	**Mid-Range**	**High-End**	Entry-Level	Mid-Range	High-End
Total Units 2011: 4,127,160	2,367,830 (57%)	471,587 (11%)	155,294 (7%)	793,266 (34%)	241,892 (10%)	97,291 (4%)
Total Units 2016: 3,130,613	1,331,621 (43%)	726,290 (23%)	290,517 (22%)	570,695 (43%)	160,236 (12%)	51,254 (4%)
Total Units 2021: 3,455,916	1,404,168 (41%)	843,816 (24%)	390,877 (28%)	569,498 (41%)	179,521 (13%)	68,036 (5%)

We project the California installed base of desktops and laptops to rebound in the coming five years from 3.1 to 3.5 million units, while that of consoles and other gaming devices other platforms declines from 12.4 million to 10.9 million. This will be accompanied by a notable structural shift away from the less energy-intensive "Entry-level" gaming PCs and towards more "High-end" (and typically higher power) PCs, as well as away from the lower-energy-use console product lines. That said, the industry is today making efficiency gains in virtually every product line.

For desktop and laptop computers, the installed base is further decomposed into 10 bins, based on purchase price deciles. Figure 27 indicates the resulting allocation.

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, of which 15% are used for gaming. Of the 10 million laptops, 8% are used for gaming.

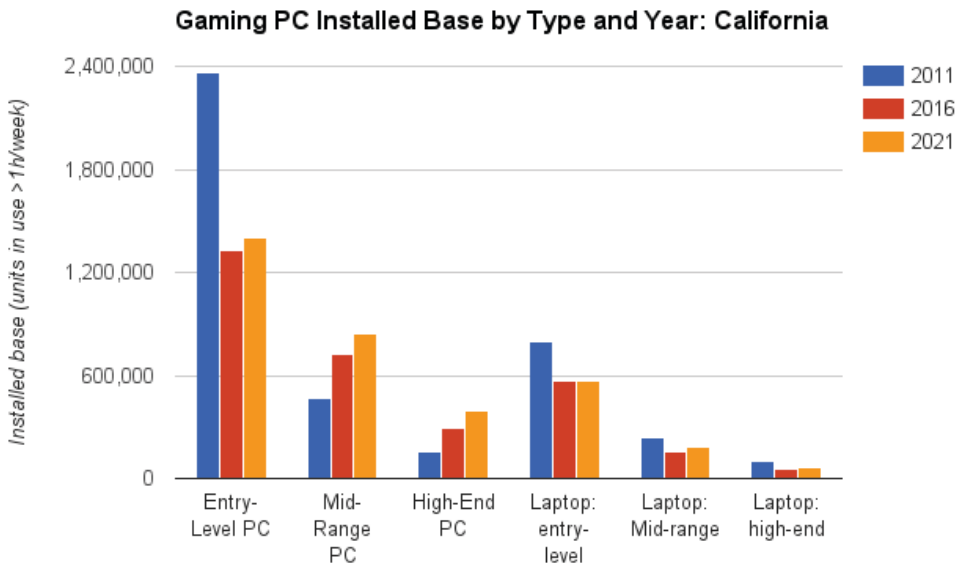


Figure 25. Trends in California desktop PC installed base
Source: Prepared by Jon Peddie Research for LBNL

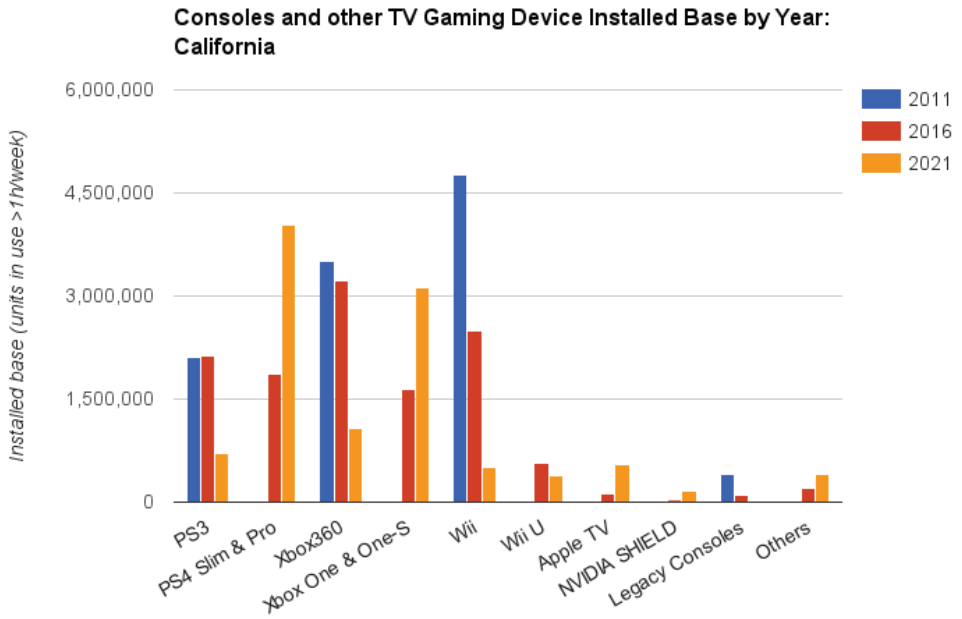


Figure 26. Trends in California video game console installed base.
Note that these estimates precede introduction of the Nintendo Switch.
Source: Prepared by Jon Peddie Research for LBNL

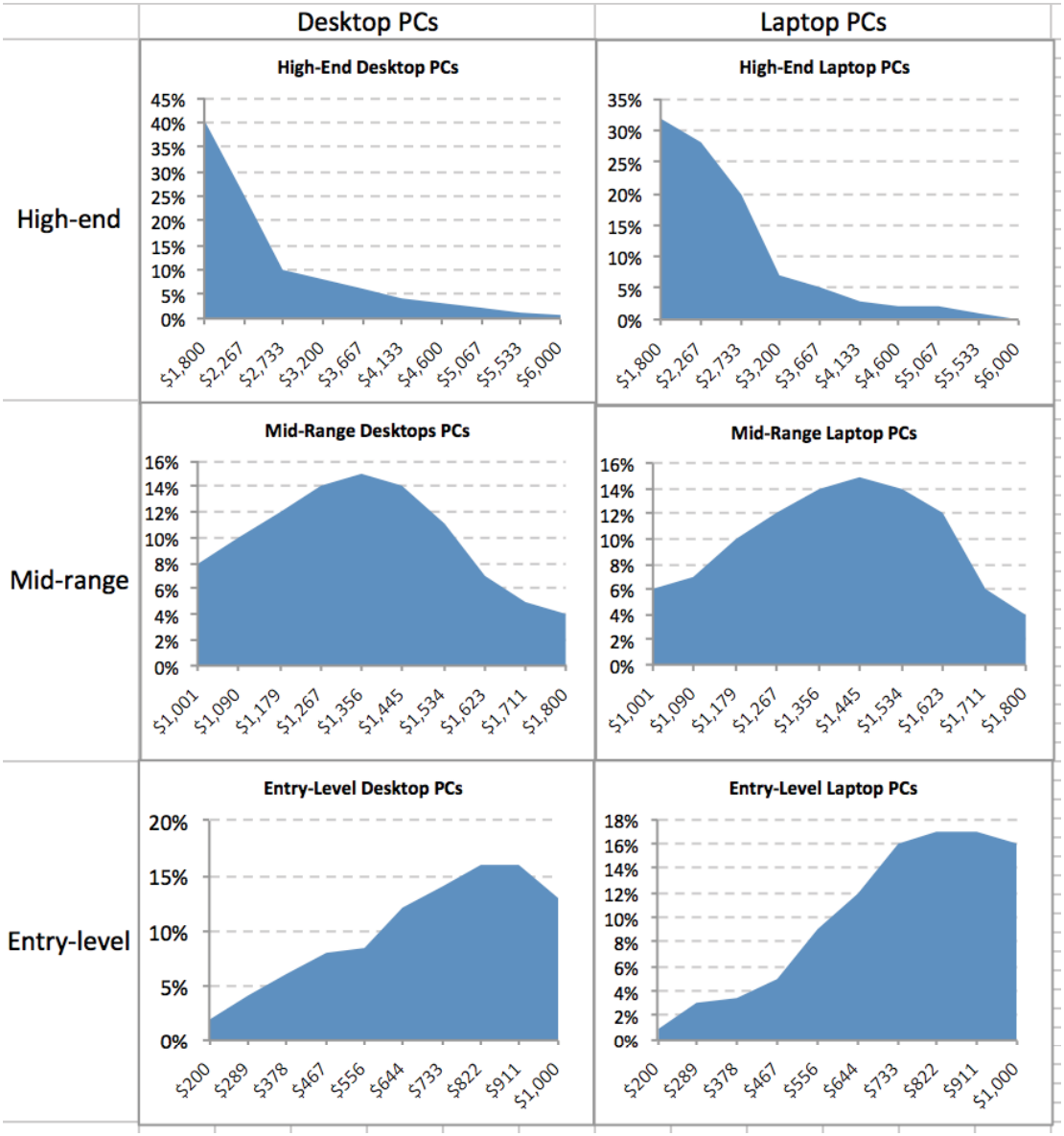


Figure 27. Price-based distribution of the installed base of Gaming PCs and Laptops used for gaming at least 2h/week.

Source: Prepared by Jon Peddie Research for LBNL

4.3 User Behavior

User behavior (software choices, settings, and gaming activity preferences) is arguably as influential for overall energy use as are hardware choices. Thus, in order to properly characterize energy demand, we also developed profiles for the gaming duty cycle, with disaggregation of preferences for each of the baseline systems. This information will be used in subsequent reports to estimate per-machine and aggregate energy requirements.

We define four user types, with increasing daily time spent in active gameplay (Figure 28). For PCs, time in active gameplay ranges from approximately 30 minutes per day for Light users to 5 hours per day for Extreme users. For consoles and other TV gaming devices, the time in active gameplay varies from 15 minutes to 6 hours per day, respectively. For the intensive gamers, time in sleep/standby/off modes is proportionately lower.

Light users dominate among entry-level PCs and laptops, while Mid-range and High-end systems have heavier use (Figure 29). Consoles have heavier use regimes than other TV gaming devices.

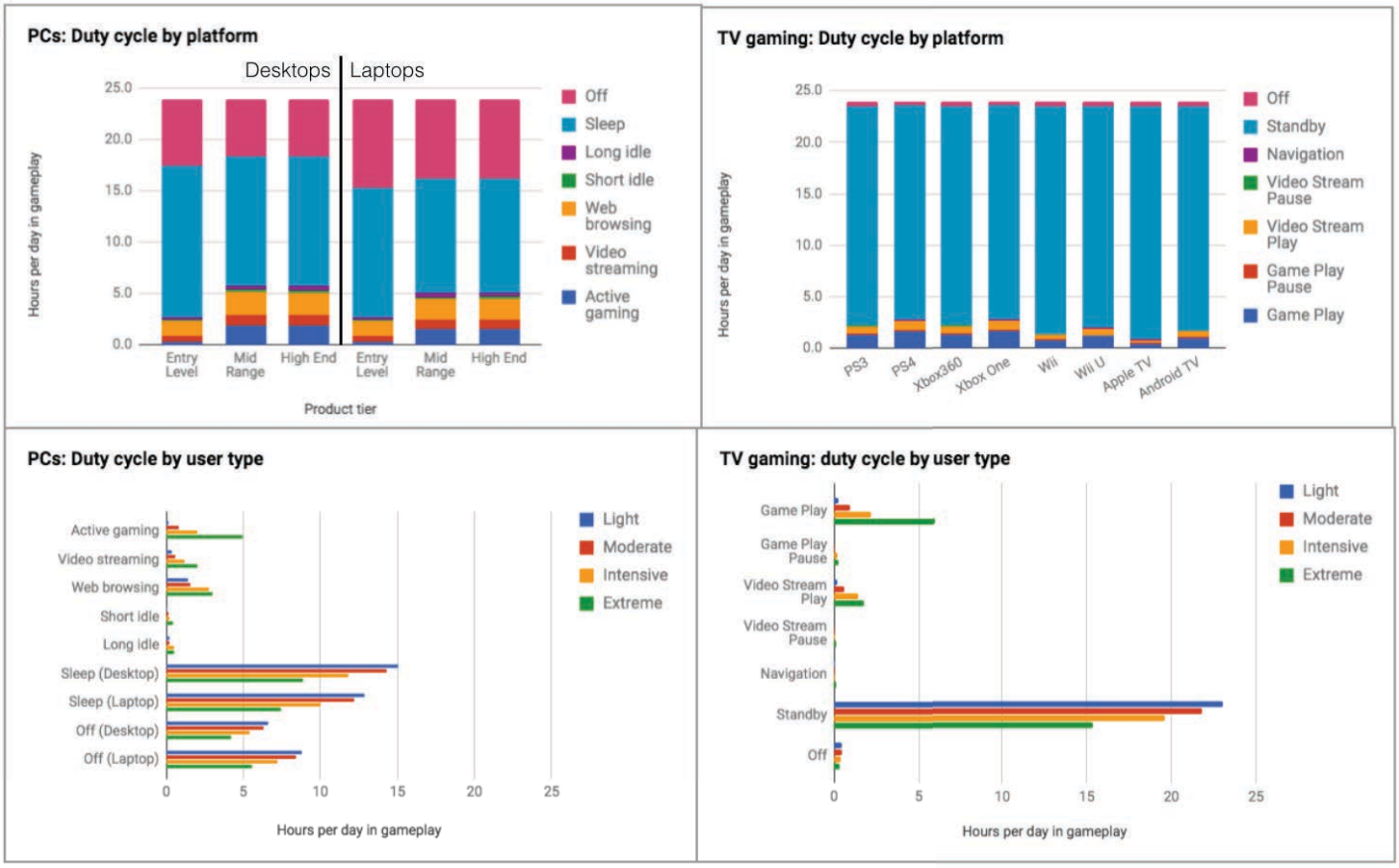


Figure 28. Gaming duty cycle by user type and platform: PCs, Consoles, and other TV gaming devices

Source: Prepared by Jon Peddie Research for LBNL

Figure 29. Gaming platform installed base by user type: PCs, Consoles, and other TV gaming devices

Source: Prepared by Jon Peddie Research for LBNL

4.4 Game Choice and Settings

4.4.1 Game title selection

As discussed in Section 3.4, many complexities are involved in determining currently available game title rank and utilization. In planning a physical testing strategy for the gaming systems described in Section 4.1, we sought to limit the number of game titles to a manageable number. Appendix C provides a matrix view of the numerous game attributes we considered. Over 50 game titles were evaluated in light of three major factors:

- Game genre
- Cross-platform availability
- Relative market popularity using the following sources:
    - ESA Essential Facts about the Computer and Video Game Industry (ESA 2016, ESA 2017)
    - VGChartz online game database (http://www.vgchartz.com/gamedb/)

- Top-5 game ranks for each gaming PC market segment provided by Jon Peddie Research (not shown in table)
- Steamspy[32], the online sales data portal for the Steam Store[33] (not shown in table)

The Nintendo Wii and WiiU consoles have virtually no game titles in common with the other console manufacturers and as such the game genres selection also included a Side Scroll category for the immensely popular Mario Brothers and Super Smash Brothers game titles.

In addition to standardized test bench measurements of the gaming systems described in Section 4.1, upcoming testing will include energy measurements of the systems while under human gamer load conditions. Volunteers will be able to choose from a long list of game title choices and genres, thus providing real-world energy measurements among a larger range of game types than provided by standardized tests and simulated benchmarks.

Choosing a representative set of game genres for the standardized bench tests will allow for a better estimate of macro-level energy consumption since the real-world use of some hardware platforms are over represented by one or two game genres. For example, Sony and Microsoft consoles are dominated by Shooter games. The multiple baseline energy measurements spanning the major genres will be weighted by the relative genres distribution for each platform during our estimate of aggregate gaming energy in California.

4.4.2 Game software settings

The choice of settings within the game software that control game appearance and play experience is highly variable from game to game. There is no acknowledged settings standard within the game development industry. The following types of settings are often found at either the operating system level of the gaming system or within game software as user-selectable settings.

- Image Resolution – The total amount of individual pixels in a displayed image.
- Texture Quality – Typically these settings turn on texture skins that lay over the three-dimensional environment for the purpose smoothing color and managing edge treatments to provide a deeper texture appearance.
- Anti-Aliasing – Software correction methods to smooth jagged line artifacts caused by individual pixel visibility in lower-resolution images.
- VSync – A Vertical Synchronization setting which slaves the frames per second (FPS) output of the game system to the refresh rate of the monitor in order to prevent image tearing.

[32] https://steamspy.com
[33] http://store.steampowered.com

- Tessellation – Another image texture setting which allows graphics cards to repeat the rendering of polygonal shapes (made of triangles) in multiple passes over a given surface. The repeated pattern thereby creates bumps and more realistic surface effects. Tessellation is usually very demanding on the GPU.
- Ambient Occlusion – A setting to create more realistic shadow transitions between different physical objects in an image.
- Anisotropic Filtering – A filtering effect to create more realistic blurring of far away items in an image.

Software settings that explicitly affect the energy performance of gaming systems are not currently offered in any game that we have identified. While some commonly available software settings may have an energy consumption impact, we haven't identified any existing literature that documents the presence or degree of this process. During the course of our standardized testing, this project will document available settings within each game title and among the various system platforms and conduct exploratory sensitivity tests on the relative energy impacts of the various options.

4.5 Future Scenarios for the year 2021

Gaming technology innovation is taking place at a rapid pace, consumer preferences are evolving rapidly, and the Internet is becoming increasingly amenable to high-performance online 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. Meanwhile, the definition of user amenity ("energy services") is vastly more difficult to establish than would be the case for energy uses such as food preservation or thermal comfort.

As shown in Figure 25, between 2012 and 2021 we project a 12% increase in desktop PCs, 4% increase in laptops, a 18% reduction in the base of consoles, and a 212% increase in other forms of TV gaming. Within this, there is structural shift towards higher-end PCs. Drivers of the rebound in desktop and laptop gaming reflect multiple factors, including that entry-level PCs have now eclipsed console-gaming capabilities, high-resolution (1080) desktop displays are priced just over $100, popularity of e-sports is rising, and a degree of fatigue with mobile gameplay. New PC users will likely be seeking higher-end gaming equipment, compared to those migrating from PC gaming to consoles.

In addition to the baseline scenario, we have defined two distinct alternate scenarios for the year 2021. Longer-term projections are highly uncertain given the dynamism in the gaming marketplace. Neither of these alternate scenarios are forecasts *per se*, but, rather, depict plausible trajectories through which technology and user behavior could manifest in the coming five years. Scenario 1 combines trends that could lead to more energy-intensive gaming, while Scenario 2 combines modal shifts to less energy-

intensive platforms with a continued migration to online gaming, driving energy use from the local client to the cloud.

Scenario 1 – Increased popularity of energy-intensive gaming activities as PCs and VR capture increased market share. Falling prices of high-resolution desktop displays and a swing of consumer preferences away from mobile and console gaming contribute to renewed growth in PC gaming. This trend is magnified by increased focus on PC operating systems tuned for gaming and a strengthened trend towards availability of console titles for PC gaming,[34] as suggested by recent indications that Microsoft may essentially convert its Xbox line into compact television-linked PCs (Plante 2017). Of most importance in terms of energy, the 2021 projections reflect an underlying shift towards higher-performance, and potentially more energy-intensive desktop PCs. Under this scenario, 20% of console users convert to PCs, while Generation-7 consoles are replaced with Generation-8 models. In parallel with these developments, virtual reality technology becomes more affordable, comfortable, convenient thanks to wireless support, with far larger libraries of applicable titles, and lower purchase costs, resulting in 20% penetration of VR headsets into the gaming system installed base. The trend towards increased time spent gaming continues to grow at a rate of 10% per year.

Scenario 2 – Faster networks lead to more reliance on centralized computing, which triggers some restructuring of the installed towards less energy-intensive system choices. The uptake of streaming gaming technology explodes due to revolutionary compression techniques and an intensive infrastructure push associated with an Internet-of-Things evolution that lays fiber to over 50% of California households. This is coupled with increasing preferences for subscription pricing over purchasing gaming titles. This reduces the amount of time spent in "local" gameplay by 25%, shifting a portion of the corresponding computing load to data centers. The impact on energy use in networks and data centers will depend on energy efficiency trends in those facilities. Meanwhile, taking advantage of the increased availability of fiber, the number of TV gaming platforms increases by five-fold while the installed base of consoles declines by 35%. As consumers' appetite for gaming saturates, time spent in active gameplay holds constant across the various platform types.

Each of these scenarios can be evaluated with varying degrees of energy efficiency. The range of possible energy futures can be characterized by a "three-by-four" set of scenarios, incorporating the baseline projection plus the two alternate scenarios described above, together with baseline gaming system energy efficiency, augmented with scenarios incorporating only operational efficiency improvements, hardware improvements, and the combination of both types of improvements.

[34] See, e.g., http://www.xbox.com/en-US/windows-10

5 Conclusions

Extensive gaming market data are available, although the information is almost universally collected and analyzed without energy analysis in mind. Survey methods also vary widely, and are often undisclosed. The marketplace is highly heterogeneous—from both technology and user-behavioral standpoints—representing perhaps the most complex energy end-use. Measured energy use estimates for gaming PCs and laptops are almost non-existent. Console energy use estimates vary widely, with a range of 10-fold.

Other highly energy-relevant questions not adequately addressed in the existing market data are:

- The changing size and mix of gaming technologies in the installed base
- Total time spent in active gaming and non-gaming modes, by platform type
- User behavioral choices (activation of power management, overclocking, etc.)
- Changing performance expectations and power requirements of gaming software and associated hardware.
- The popularity of cloud-based gaming will shift significant workload, and thus energy, from local clients to data centers.
- Emerging technologies. Virtual reality may prove to be the most important emerging technology. From an energy perspective new power requirements will be created by VR equipment. Perhaps more importantly, it will place extra computing demands and performance expectations on the gaming PC's graphics processor.

This report assembles a comprehensive profile of the video gaming market in California for the purposes of energy analysis. We have identified gaming hardware configurations, and associated user settings. Combining these data streams produces a novel platform for integrated assessment of unit energy use and aggregate demand, based on best-available data, actual measurements, and industry expert opinions. This platform includes the installed base and duty cycles while defining specific, measurable gaming systems that span the full spectrum of gaming experience, performance, and power requirements. We find that there are multiple factors that stand to drive the energy use of gaming PCs higher in the near term. The next step in the process is lab-bench product testing to quantify the energy consumption in each major usage mode (active gaming, web browsing, idle, sleep, etc.). These results will be combined with information on the installed base to obtain baseline aggregate energy demand and develop scenarios for the future.

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7 APPENDICES

Appendix A. Summary of estimates of daily time spent actively gaming

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 (18872 consumer panel members aged 2 and older)	NPD (2010)
BY PLATFORM							
All gamers - consoles	0.67	US	128	Consoles	2014	Console players (range 0.27 for Wii to 1.10 for XBox 360, depending on model)	Urban et al. (2014)
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	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 B. Representative gaming platforms

The following pages describe an array of gaming systems we have identified that characterize the range of price and performance in gaming platforms across the marketplace as of 2016. Each is being exhaustively tested in order to determine energy use and the quality of user experience under a variety of game titles and synthetic benchmarks, as well as a wide range of operational conditions. The systems will then be modified in order to reduce power requirements and then retested to determine changes in energy use and performance.

Desktop PCs undergoing testing in the Green Gaming Lab

	Entry-Level PC				Mid-Range PC				High-End PC	
	2,367,830 (57%)				471,587 (11%)				155,294 (7%)	
	1,331,621 (43%)				726,290 (23%)				290,517 (22%)	
	1,404,168 (41%)				843,816 (24%)				390,877 (28%)	
Test System Code	E1	E2	E3	E4	M1	M2	M3	M4	H1	H2
CPU	Intel Core i3-4170T	Intel Core i5-6400T	AMD FX-6300	Intel Pentium G3258	Intel Core i5	Intel Core i5-4690k	AMD FX-8350	Intel Core i7-4790K	Intel Core i7 5820K	Intel Core i7 6700K
Processor Family	Haswell	Skylake	Piledriver	Haswell	Skylake	Haswell	Piledriver	Haswell Devil's Canyon	Haswell-E	Skylake
Cores	2	4	6	2	4	4	8	4	6	4
Clock (GHz)	3.2 GHZ Boost	2.2	3.5	3.2	2.8	3.5	4	4	3.3	4
Heatsink/Fan	Stock fan	Stock fan	Non-stock fan	Stock fan	Stock fan	CLC	Non-stock fan	CLC	CLC	OLC
Heatsink/Fan Model	Unknown	Unknown	Cooler Master Hyper 212	n/a	n/a	Cryorig A40	Noctua NH-D15	Cooler Master MasterLiquid Pro 280	Corsair Hydro H110i GT 280mm	HydroLux PRO: Exotic Custom Cooling System
Motherboard - Make & Model	Unknown	Unknown	MSI 970 Gaming	MSI Intel Z97 LGA 1150 DDR3	Apple	MSI Z97 Intel LGA 1150 DDR3	ASUS Crosshair V Formula Z	ASRock Fatal1ty Gaming Z97X Killer	EVGA X99 Classified	ASUS Z170-E
GPU - Integrated / Discrete	Discrete	Integrated	Discrete	Discrete	Integrated	Discrete	Discrete	Discrete	Discrete	Discrete
GPU - Make & Model	NVIDIA GeForce GTX850M GPU	Intel HD Graphics	AMD R7 360	AMD XFX R7 370 GAMING 2G Graphics Card	Intel Iris Pro Graphics 6200	NVIDIA GIGABYTE GeForce GTX 960 4GB WINDFORCE 2X OC EDITION	AMD Sapphire Radeon R9 Nano	NVIDIA ASUS GeForce GTX 970 STRIX-GTX970-DC2OC-4GD5	AMD 2x R9 Fury X	NVIDIA Titan XP
VRAM (GB)	2GB	Unknown	2GB	2GB	Unknown	4GB	4GB	4GB	8 GB	12GB
Number of GPUs	1	1	1	1	1	1	1	1	2	1
Storage 1- Type & Spec	HDD 7200 RPM 6 gb/s 500GB	HDD 5400 RPM 1TB	SSD Crucial MX300 275GB	SSD Samsung 850 EVO 250GB	HDD 5400 RPM 1TB	SSD SanDisk Ultra II 480GB	SSD Crucial MX200 500GB	SSD Samsung 850 EVO 500GB	SSD Samsung 850 EVO 500GB	SSD Digital Storm 480GB
Storage 2 - Type & Spec	n/a	n/a	n/a	n/a	n/a	n/a	n/a	HDD Western Digital Black Series 7200 rpm 1TB	SSD Kingston Hyper X Savage 480GB	HDD Seagate Barracuda 1TB
System RAM - Type & Spec	DDR3 4GB 1600MHz	DDR4 8GB 2133MHz	DDR3 Kingston Hyper X Fury 8GB 1866MHz	DDR3 Kingston Hyper X Savage 8GB 2133MHz	DDR3 8Gb 1866MHz	DDR3 Ballistix Tactical Low Profile 8GB 1600MHz	DDR3 Corsair Vengeance 16Gb 1600MHz	DDR3 G.Skill Sniper Series 16Gb 2400MHz	DDR4 Kingston Savage Black 16GB 2400MHz	DDR4 Digital Storm 16GB 2666MHz
Case - Make & Spec	Alienware Alpha	HP	Fractal Design Define S 6-fans	Cooler Master HAF 912	Apple iMac 2016	Corsair Carbide 500R Mid6-fans	Cooler Master HAF 932 6-fans	NZXT Phantom 410 Red ATX 5-fans	Corsair 600C 6-fans	Digital Storm Velox 6-fans
PSU - Make/Model & Rated Power	unknown	unknown	EVGA 500 W1 550W	EVGA 500 W1 550W	unknown	EVGA B1 700W	SeaSonic X Series X-850 850W	CS Series Modular CS750M 750W	EVGA Supernova G2 850W	Corsair HX1000i 1000W
PSU Efficiency	unknown	unknown	80+ White	80+ White	unknown	80+ Bronze	80+ Gold	80+ Gold	80+ Gold	80+ Platinum
Dislay - Recommended Resolution	FHD (1920x1080)	FHD (1920x1080)	FHD (1920x1080)	FHD (1920x1080)	FHD (1920x1080)	WQHD (2560x1440)	WQHD (2560x1440)	WQHD (2560x1440)	UHD (3840x2160)	UHD (3840x2160)
Multi-Display/External Display	n/a	n/a	n/a	n/a	n/a	3x1080p	3x1080p	3x1080p	3x1440p (if avail.)	3x1440p

Laptops undergoing testing in the Green Gaming Lab

	Laptop - Entry-Level		Laptop - Mid-Range		Laptop - High-End
	793,266 (34%)		241,892 (10%)		97,291 (4%)
	570,695 (43%)		160,236 (12%)		51,254 (4%)
	569,498 (41%)		179,521 (13%)		68,036 (5%)
Test System Code	L1	L2	L3	L4	L5
CPU	AMD FX Series	Intel i7-7500U	Intel Core i7	Intel i7-6500U	Intel i7 6700K
Processor Family		Skylake		Skylake	Skylake
Cores		4		2	4
Clock (GHz)		2.7-3.5	2.3 - 2.7	Up to 3.1	Up to 4.2
Heatsink/Fan	Stock fan	unknown	Stock fan	Fan	Fan
Heatsink/Fan Model	unknown	unknown	unknown	unknown	unknown
Motherboard - Make & Model	n/a	n/a	n/a	n/a	n/a
GPU - Integrated / Discrete	Integrated	Integrated	Integrated	Discrete	Discrete
GPU - Make & Model	Radeon R7	Intel	Intel Iris Pro	Nvidia GTX960m	Nvidia GTX1070
VRAM (GB)		unknown	up to 16MB	2GB	8GB
Number of GPUs		1		1	1
Storage 1- Type & Spec		SSD 128GB		SSD 256GB	m.2 SSD OS Drive PCIe 256GB
Storage 2 - Type & Spec	n/a	n/a	n/a	n/a	SSD
System RAM - Type & Spec	DDR3 8MB	n/a	DDR3 8 or 16MB 1600MB	DDR3 8GB 1600MHz	DDR4 Origin Approved 16GB 2400MHz
Case - Make & Spec	n/a	n/a	n/a	n/a	n/a
PSU - Make/Model & Rated Power		unknown		unknown	unknown
PSU Efficiency		unknown		unknown	unknown
Dislay - Recommended Resolution		2560x1440		2560x1440	3840x2160
Multi-Display/External Display	n/a	n/a	n/a	n/a	n/a

Consoles and other TV-gaming platforms Desktop PCs undergoing testing in the Green Gaming Lab

	Video Gaming Consoles								TV Gaming Devices		Legacy Consoles (PS, PS2, Xbox, Various Nintendos)	FireTV, Gaming Tablet connected to TV, Razer Forge, other Android Micro Consoles
Total Units 2011: 10,770,000	2,100,000	Unknown		3,510,000	Unknown		4,760,000	0	0	0	400,000	0
Total Units: 2016: 12,380,000	2,130,000	1,860,000		3,230,000	1,650,000		2,490,000	570,000	120,000	30,000	100,000	200,000
Total Units: 2021: 10,912,100	700,000	4,040,000		1,080,000	3,120,000		500,000	380,000	540,000	152,100	0	400,000
Test System Code	C1	C2	C3	C4	C5	C6	C7	C8	T1	T2		
Manufacturer	Sony Playstation	Sony Playstation	Sony Playstation	Microsoft	Microsoft	Microsoft	Nintendo	Nintendo	Apple	NVIDIA		
Model	PS3	PS4 Slim	PS4 Pro	Xbox360	Xbox One	Xbox One S	Wii	Wii U	Apple TV	SHIELD (Android TV)		
Output Resolution	1920*1080	1920*1080	1920*1080	1920*1080	1920*1080	1920*1080	Sub 720p	1280*720	1280*720+	1920*1080		
Displays	Display Monitors									Virtual Reality Headsets		
Test Display Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	VR1	VR2	VR3
Resolution	1920*1080	1920*1080	1920*1080	2560*1080	2560*1440	2560*1440	3840*2160	3440*1440	1920*1080	2160*1200	2160*1200	1920*1080
Size	21.5	24	27	29	27	28	32	34	40+	n/a	n/a	n/a
Aspect Ratio	16x9	16x9	16x9	21x9	16x9	16x9	16x9	21x9	16x9	n/a	n/a	n/a
Special Features			High Refresh Rate	Ultrawide				Curved Ultrawide				
Brand/Model	HP Pavillion	Acer R240HY	Acer GN276HL	LG 29UC88-B	Acer XG270HU	Dell Gaming S2716DG	BenQ 32-Inch IPS 4K Ultra High Definition LED Monitor (BL3201PH)	Acer Predator	LCD or Plasma TV	Oculus Rift	HTC Vive	Playstation VR
Technology	IPS	TN	TN	IPS	TN	TN	IPS	IPS				
Refresh Rate (Hz)	60	60	144	56-75	144	144	75	60				
Vsync Control	None	None	None	FreeSync	FreeSync	G-Sync	FreeSync	G-Sync				
Notes	On Hnad	Qty 2:FreeSync & G-Sync	Not finalized	Not finalized	Not finalized	Not finalized	Not finalized	Not finalized	For VGC, Not finalized			
Accessories	1	2	3	4	5	6	7	8	9	10	11	
Brand/Description	Razer Core External Graphics Dock	Alienware Graphics Amplifier	TrackIR 5 Head-Tracking System	Keyboards	Mice	Headset HyperX Cloud Revolver Gaming	Mainstream Speakers: Logitech Z313	Performance Speakers 1: Logitech Z623	Performance Speakers 2 :Corsair SP2500	Enthusiast Speakers: Logitech Z906	Flight/Driving Motion Simulator	
Notes			Not finalized	On hand	On hand	Not finalized	Not finalized	Not finalized	Not finalized	Not finalized	Not finalized	

Appendix C. Game selection criteria for energy analysis testing

		PC		Consoles						TV Streaming		Ranks	
Genre	Game Title	Win10	OSX	PS4	PS3	XBox One	XBox 360	WiiU	Wii	NVIDIA Shield	Apple TV	ESA (NPD)* 2015/2016	VGChartz (N. Amer.) (units)
First or Third Person Shooters	ARMA 3	✔											
	Battlefield 1	✔		✔		✔							3.02M
	BioShock-Infinite	✔	✔	✔	✔	✔	✔			✔			
	Call of Duty: Infinite Warfare	✔		✔		✔						nr / 1	
	Call of Duty: Advanced Warfare	✔		✔	✔	✔	✔					10 / nr	3.25M
	Call of Duty: Black Ops	✔			✔		✔			✔			3.25M
	Call of Duty: Black Ops 2	✔			✔		✔	✔		✔			4.49M
	Call of Duty: Black Ops 3	✔		✔	✔	✔	✔			✔		1 / 9	4.47M
	Call of Duty: Modern Warfare 3	✔			✔		✔			✔			5.54M
	Halo 5: Guardians					✔						14 / nr	2.9M
	Overwatch	✔		✔	✔					✔		nr / 7	2.6M
	Splatoon							✔					1.6M
	Team Fortress 2	✔	✔										
Massively Multiplayer Online	League of Legends	✔	✔							✔			
	World of Tanks	✔			✔	✔	✔						1.8M
Open World / Sandbox	DayZ	✔											
	Middle-Earth: Shadow of Mordor	✔	✔	✔	✔	✔	✔			✔			3.2M
	Minecraft	✔		✔	✔	✔	✔					7 / 8	24.5M
	Portal 2	✔	✔		✔		✔						2.1M
Platform - Side Scroll	New Super Mario Bros. U							✔					2.3M
	New Super Mario Bros. Wii								✔				14.5M
	Super Mario 3D World							✔					2.3M
	Super Smash Brothers							✔	✔			15 / nr	2.7M
Puzzle	Candy Crush Saga	✔	✔								✔		
	Words with Friends	✔	✔								✔		
Racing	F1 2016	✔	✔	✔		✔				✔	✔		
	Forza Motorsport 4						✔						
	Gran Turismo 5				✔								2.9M
	Mario Kart 8							✔					3.2M
	Mario Kart Wii								✔				15.7M
	Project Cars	✔		✔		✔							
Role Playing / Third Person	Fallout 4	✔		✔		✔				✔		2 / nr	5.8M
	Far Cry Primal	✔		✔		✔				✔		nr / 19	
	The Elder Scrolls V: Skyrim	✔		✔	✔	✔	✔			✔		6 / 13	4.0M
	The Legend of Zelda: The Wind Waker							✔					1.0M
	The Legend of Zelda: Twilight Princess								✔				3.7M
	The Witcher 3: Wild Hunt	✔		✔		✔				✔		16	1.1M
	Uncharted 4: A Thief's End			✔									8.7M
Sampler / Compilation	Kinect Adventures!						✔						15.0M
	Wii Fit								✔				8.9M
	Wii Play								✔				14.0M
Simulation	Farmville 2	✔	✔								✔		
	The SIMS 3	✔	✔		✔		✔	✔	✔			11** / nr	10.2M
	The SIMS 4	✔	✔									1 / nr	6.8M
Sports	FIFA 16	✔	✔	✔	✔	✔	✔			✔	✔	9 / nr	8.6M
	FIFA 17	✔		✔	✔	✔	✔			✔	✔	nr / 10	10.5M
	Rocket League	✔	✔	✔		✔							330k
	Wii Sports								✔				41.4M
	Wii Sports Resort								✔				15.6M

NOTES: * Ranks from ESA "Essential Facts about Computer and Video Game Industry" 2016 and 2017 reports; ** The highest of 5 ranks for The SIMS 3; "nr" and null entry indicates No Rank

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Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, [Building Technologies Program] or [Federal Energy Management Program], of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.