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ORIGINAL ARTICLE

Taming the energy use of gaming computers

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Abstract One billion people around the world engage in some form of digital gaming. Gaming is the most energy-intensive use of personal computers, and the high-performance "racecar" systems built expressly for gaming are the fastest growing type of gaming platform. Large performance-normalized variations in nameplate power ratings for gaming computer components available on today's market indicate significant potential for energy savings: central processing units vary by 4.3-fold, graphics processing units 5.8-fold, power supply units 1.3-fold, motherboards 5.0-fold, and random access memory (RAM) 139.2-fold. Measured performance of displays varies by 11.5-fold. However, underlying the importance of empirical data, we find that measured peak power requirements are considerably lower than nameplate for most components tested, and by about 50 % for complete systems. Based on actual measurements of five gaming PCs with progressively more efficient component configurations, we estimate the typical gaming computer (including display) to use approximately 1400 kWh/year, which is equivalent to the energy use of ten game consoles, six standard PCs, or three refrigerators. The more intensive user segments could easily consume double this central estimate. While gaming PCs represent only 2.5 % of the global installed PC equipment base, our initial scoping estimate suggests that gaming PCs consumed 75 TWh/year ($10 billion) of electricity globally in 2012 or approximately 20 % of total PC, notebook, and console energy usage. Based on projected changes in the installed base, we estimate that consumption will more than double by the year 2020 if the current rate of equipment sales is unabated and efficiencies are not improved. Although they will represent only 10 % of the installed base of gaming platforms in 2020, relatively high unit energy consumption and high hours of use will result in gaming computers being responsible for 40 % of gaming energy use. Savings of more than 75 % can be achieved via premium efficiency components applied at the time of manufacture or via retrofit, while improving reliability and performance (nearly a doubling of performance per unit of energy). This corresponds to a potential savings of approximately 120 TWh/year or $18 billion/year globally by 2020. A consumer decision-making environment largely devoid of energy information and incentives suggests a need for targeted energy efficiency programs and policies in capturing these benefits.

Keywords Information technologies · Computing energy use · Gaming computers

Context

In the quest for technological performance improvements, the racecar is often invoked as a locus of innovation. In the energy sector, this analogy has been applied to data centers as energy-intensive environments where significant

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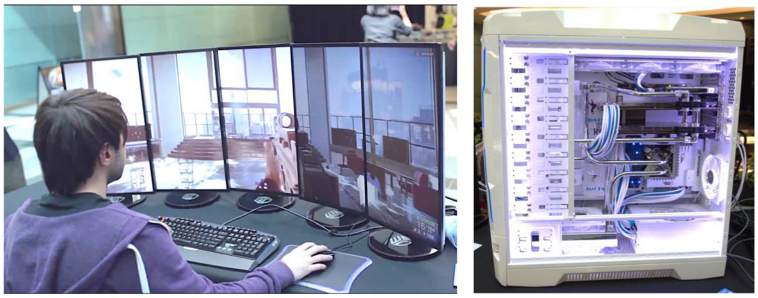

Fig 1 A surround setup representing the epitome of desktop gaming. A system such as this could approach 2000 W of nameplate power, including displays and peripherals. Based on actual measured demand, used 8 h/day in gaming mode, the system would consume roughly 3500 kWh/year (perhaps $1400 with aggressively tiered electric tariffs), comparable with a highly efficient home. The underlying machine possesses two 500-W AMD R9 295X2 graphics cards and a 1500-W power supply unit. Sources: HardwareCanucks (2014) and https://twitter.com/elmnator

innovations have been made in IT equipment as well as the surrounding heating, cooling, and power-delivery infrastructure (Mills et al. 2007). Similarly, at the distributed scales of personal computing, the high-performance gaming computer (we subsequently refer to these by the shorthand "gaming computers") (Fig. 1) has been the focus of efforts to boost performance in order to meet rapidly increasing user expectations (Short 2013).

Estimates placed the flow of digital media to US households at 6.9 zettabytes (ZB; 10^{21} bytes) per year in 2012, of which 2.5 ZB (34 %) was attributed to gaming (Short 2013). US households are projected to spend 211 billion hours of gaming in 2015, more than the time spent on the telephone, mobile computing, or messaging. Use has doubled since 2008. The 43.6 million "extreme" and "avid" gamers spend 4.4 h/day in the activity (all platform types) versus 7.2 h/day for the 10 million "extreme" gamer subgroup (Short 2013).

An estimated one billion people globally engage in some form of personal computer gaming (PC Gaming Alliance 2013). A small subset of people use their computers exclusively for gaming, while most engage in the typical array of computer activities. Even game consoles have become general media devices. Game consoles (e.g., PlayStation, Nintendo, and Xbox) have received most of the attention within the energy community, often to the exclusion of far more energy intensive gaming computers (Urban et al. 2014). There are wide variations and strong trends in the choice of platforms, with the installed base of game consoles projected to decline and that of desktop gaming computers to increase (Fig. 2).

The global count of people utilizing gaming computers was estimated at 54 million in 2012 (33 countries studied) and projected to grow to 72 million together with sales of related computer hardware of $32 billion by 2015 (Business Wire 2012). About half of the 100 million PCs with discrete graphical processing units (GPUs) shipped in 2014 were purchased by consumers, with the other half destined for workplace environments (Peddie 2014).

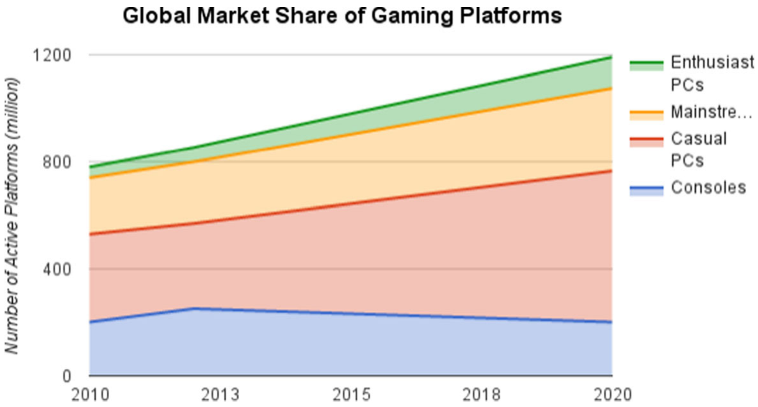

Fig. 2 "Enthusiast" gaming computers are a small but growing segment of gaming platforms (a rough proxy for the aforementioned "Extreme" and "Avid" user groups), with consoles projected to decline. This chart shows the installed base (stock), with projections from 2014. Excludes mobile platforms (adapted from Open Gaming Alliance 2015; Business Wire 2012)

Computer gaming is engaging an increasingly diverse user base. These consumers spent $22 billion on gaming software in 2013 (ESA 2014), with the global market estimated at $100 billion (Brightman 2013). The scale and growth of this activity calls for assessment of the associated energy use.

Just over half of all US households own a game console, with the average player being 31 years old and with males and females engaged in roughly equal proportions. Previous studies exploring the energy implications of game console use found average unit electricity use to be 102 kWh/year for the installed US stock (excluding the connected display) and 64 kWh/year for new sales as of mid-2012 (Webb et al. 2013).[1] There is ongoing debate about game console utilization, with recent studies finding that this may have been previously overstated (Desroches et al. 2015).

We found no prior studies focusing on the aggregate energy used by gaming computers. One assessment (Ecova 2012) examined the idle power demand of graphic processing units embedded in gaming computers, and another (Brocklehurst and Wood 2014) explored whether these machines would be able to meet the ENERGY STAR v6.0 requirements, based on pooling diverse test results from third-party sources (not standardized for factors such as choice of motherboard, duration of sleep mode, overclocking, operating system, software running during testing, etc.). Their results were confounded by differences in test procedures.

This article provides new information based on nameplate performance of gaming computers and their components together with direct measurements. Efficiency opportunities are identified. Using measured data, we produce the first global estimate of the associated current and projected energy consumption and savings potential.

Components, architecture, and efficiency options

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., GPUs, hard drives, displays) are used. Protocols for benchmarking the computational performance of gaming computers involve 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 Heaven; see http://www.maxon.net/products/cinebench/overview.html and https://unigine.com/products/heaven/). Component product literature, however, emphasizes nameplate estimates of power requirements, rather than actual performance or power needs under a given mode of operation. As discussed below, accurate energy use calculations cannot be made with nameplate data. However, no standardized test procedures exist for evaluating gaming actual computer energy use, which perpetuates market reliance on over-estimates of 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 opportunities exist for improved energy efficiencies in each component, through hardware as well as control improvements (Table 1). 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 inputs per unit of performance provided. Here, we have picked metrics that are either industry standards or otherwise readily available in product technical specifications. However, nameplate power ratings should not be used to estimate energy use.

Motherboard

Most 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 random access memory (RAM) clock speeds rise. As seen in Fig. 3, nameplate power

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[1] It is important to consider learning-curve effects. Console launch models are typically two or more times as energy intensive than the given model's stabilized performance once several generations of design refinements have been made (Delforge and Horowitz 2014); for example, the 2006 release version of PlayStation 3 required 180 W in "game play" mode, which ultimately stabilized at 70 W in the 2013 version.

Table 1 Components of gaming computers and efficiency opportunities

	Nameplate/rated power[a]	Efficiency range[a]	Energy saving strategies
Motherboard	30 to 150 W	13–65 W/GHz of max supported CPU	More efficient capacitors; improved power delivery efficiency and control. Some motherboards allow the user to disable components not in use (e.g., HDMI, PCI-E slots, or SATA ports).
Central processing unit (CPU) architecture	37 to 220 W	15–63 W/GHz	Decreased size and increased transistors per unit area (less leakage). Power scaling (e.g., Intel Sandy Bridge (85 W) vs. Ivy Bridge (77 W) vs. Haswell (65 W) illustrate the generational progression). C-state (aka “C-mode”) capabilities enable CPU to vary power draw as a function of workload, with particular emphasis on increasingly sophisticated sleep modes. There are currently 13 C-state gradations, some of which can be changed by the user in the Basic Input/Output System (BIOS). Selected voltages can be reduced within the CPU without reducing performance (but with reduced stability CPUs can be underclocked to reduce power consumption (but with reduced performance). Multiple cores may or may not affect efficiencies, depending on computational activity and software.
Graphical processing unit (GPU)	75 to 500 W	32–187 W/TeraFLOP	Decreased size and increased transistors per unit area (less leakage). Power scaling (e.g., NVIDIA Fermi vs. Kepler vs. Maxwell). GPUs can be underclocked for additional energy savings (but with lower performance). Modes exist for disabling GPUs when the display is off. Displays with “anti-tearing” features enable use of lower-power GPUs.
Fans	Low single-digit watts, but can be many fans (typically 5–6) in a single computer	W/CFM	Efficiency of air movement. Automated power-down at low loads. Improved blade designs. Reduced fan count commensurate with efficiency improvements elsewhere in the system.
Memory	DDR (2.5 V)≥DDR2 1.8 V)≥ DDR3 (1.5–1.65 V)≥DDR4 (1.2–1.35 V)	13–65 W/GHz	Reduced voltages. Fewer higher-capacity modules (“sticks”).
Storage	HD (~10 WW)≥SATA SSD (~5 W)≥PCI-E SSD (~3 W)	44–139 W/GHz	Switch from mechanical to solid state with significant performance boost in reads and writes.
Power supply unit (PSU)	Intrinsic energy use only from dedicated fans. Indirectly associated with losses due to power conversions for downstream loads.	70 % efficiency≥80 % (80Plus threshold)≥94 % (80Plus Titanium; all at 50 % load)	Efficiency; some units are fan-less, saving several watts; others curtail fan use until high power thresholds are reached. Sizing to match load is important for peak efficiency, although less so as the industry has attained more consistent efficiencies across the load range.
Displays	15 to 77 W (23–34 in. size range)	4.8–41 W/megapixel	Technology choice (CRT vs. LCD/LED, +backlighting strategy, as well as techniques to avoid image tearing with lower GPU speeds. Power management (e.g., sleep mode), dynamic dimming as a function of room light levels, and occupancy-sensor-initiated sleep mode. Improving transmissivity of film stack to improve luminous efficacy. Display-specific PSUs also present efficiency opportunities.
Operating system			Various energy management tools are available via the OS.
Voltage levels			Tuning voltages to required performance level. Constant voltage vs. ASUS EPU engine.
Power down			Curtailing operation of some or all components after designated time. Monitor sleep functionality; GPU staged control where unit has multiple processors

Table 1 (continued)

	Nameplate/rated power[a]	Efficiency range[a]	Energy saving strategies
			(e.g., AMD "zero-core" technology) or thermostatically controlled fans.
Intelligent automatic fan control			Variable speed control as function of eight internal temperature sensor signals. Some GPUs allow user to specify desired fan speeds as a function of temperature. T-Balancer: Big NG.

[a] Ranges apply to units included in the Figs. 3, 4, 5, 6, 7, and 8, and generally reflect conditions at peak loads

consumption varies between 30 and 150 W across a sampling of devices found in the market today.

Central processing unit

The central processing unit (CPU) conducts the primary computing tasks and is one of the important nodes of energy use. 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 Fig. 4, nameplate power consumption varies between 37 and 220 W across a sampling of devices found in the market today. The service levels provided by these devices vary as well, as reflected in their differing clock speeds (measured in gigahertz). CPUs can be "overclocked" to above the rated performance levels indicated here, increasing power consumption.

Graphics processing unit

The graphics processing unit (GPU) provides computing power associated with visual display of information, including two- (2D) and three-dimensional (3D) rendering and animations and is typically the single-most important 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 the 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 Fig. 5, nameplate power consumption varies between 60 and 500 W across a sampling of gaming-specific devices found in the market today. The performance levels provided by these devices vary as well, and they can be overclocked (to frequencies above stock settings).

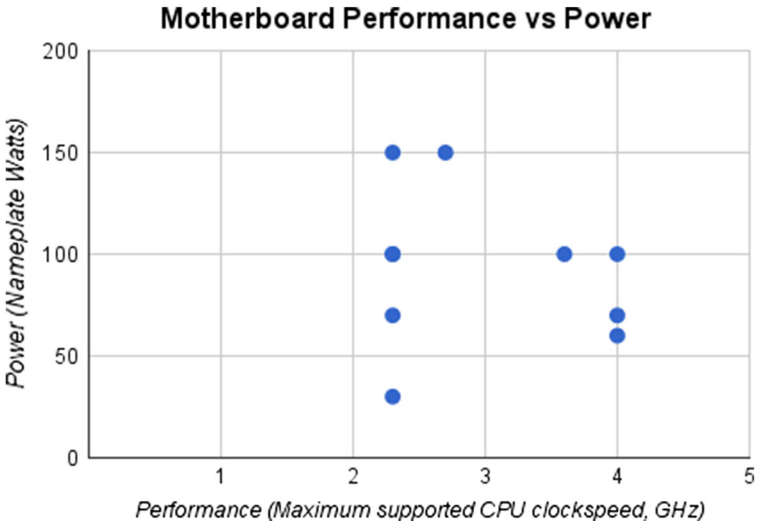


Fig. 3 Performance-power relationships for nine motherboards suitable for use in gaming PCs in the marketplace as of December 2014. Performance of the products shown here varies considerably, from about 13 to 65 W/GHz, representing a variation of 5-fold

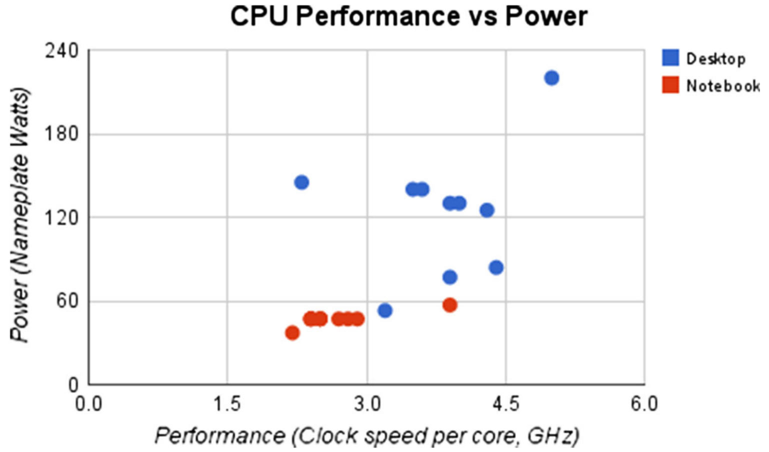


Fig. 4 Performance-power relationships for 23 CPUs suitable for use in gaming PCs in the marketplace as of December 2014. Metrics are based on "boost clock speeds" from manufacturer spec sheets. There are no universally appropriate metrics for CPUs, as performance varies based on many contextual factors as well as the degree of parallel versus linear processes that are running for a given task, and the degree to which a given application allows multi-threading. The performance-normalized energy efficiency of CPUs shown here varies considerably, from about 15 to 63 W/GHz based on rated clock speed, representing a variation of 4.3-fold (without overclocking)

Memory and storage

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 double data rate (DDR) standard (2.5 V, 17.5 W) to DDR4 (1.2 V, 1.3 W) (Fig. 6). 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.

Cooling

Gaming computers require dedicated cooling systems in order to avoid overheating, even at idle. Active cooling is typically provided to each power supply unit (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

Fig. 5 Performance-power relationships for 27 GPUs suitable for use in gaming PCs in the marketplace as of December 2014. Metrics are based on manufacturer-reported "boost clock speeds" from manufacturer spec sheets. The performance-normalized energy efficiency of the GPUs shown here varies considerably, from about 32.3 to 186.6 W/TeraFLOP, representing a variation of 5.8-fold (without overclocking)

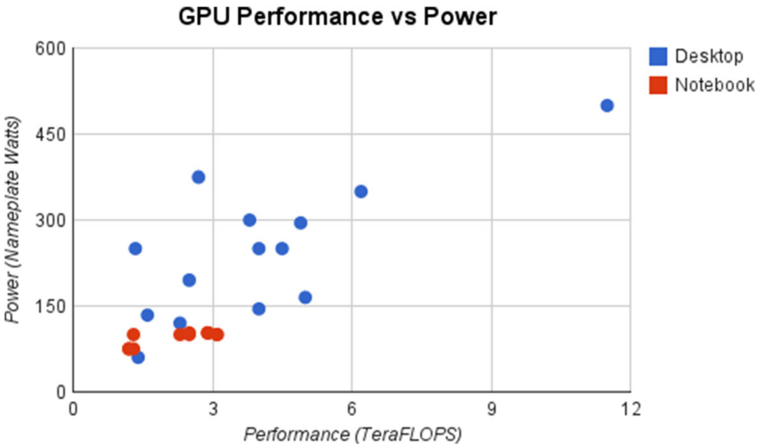
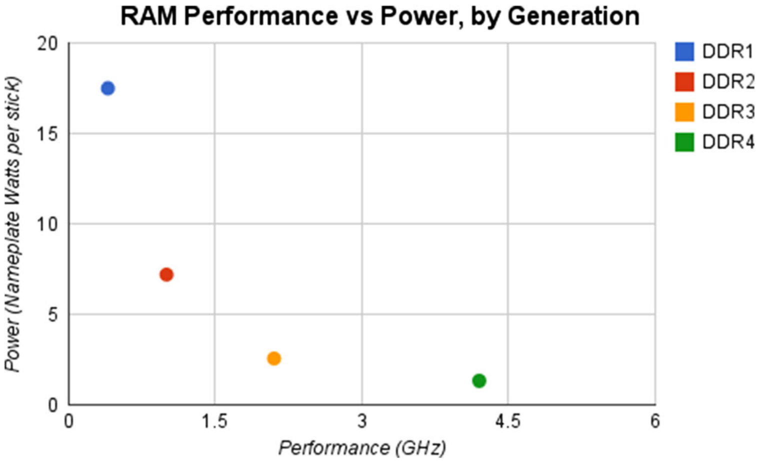


Fig. 6 Performance-power relationships for four generations of 1-DIMM 8 GB DDR memory. Performance (W/GHz) varies by a factor of 139. From left to right: DDR4, DDR3, DDR2, and DDR. DDR and DDR2 are early generations, no longer in use. DDR3 was introduced in 2008. DDR4 was introduced in late 2014. Some versions of server DDR3 approach the efficiency of DDR4 (Koomey 2012)



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 overclocks (enhancing computational performance at lower temperatures). We measured CPUs with and without liquid cooling, and no change in energy use was observed.

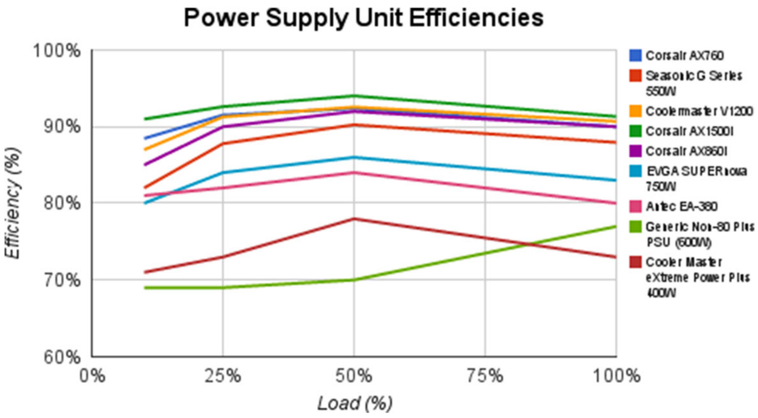
Power supply units

All power delivered to the gaming computer's internal components passes through a power supply. 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 very 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 70 %. Significant improvements occurred after the introduction of the voluntary "80Plus" testing and rating program in 2004. As seen in Fig. 7, efficiencies vary among a sampling of devices found in the market today, from 69 to 94 % depending on the project and degree to which it is loaded. Right-sizing power supplies are thus important for optimizing operating efficiency. Most PSUs have dedicated fans for cooling, which typically always run, although some have temperature-controlled cooling.

Displays

While typically not hardwired to the gaming computer itself, with the exception of notebooks and consoles, displays are integral and energy-intensive elements of the system. 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

Fig. 7 PSU efficiencies vary by load, particularly among lower-efficiency models. Each curve represents one of nine devices in the marketplace as of 2014. Values do not include dedicated fan energy. Actual losses depend on weighted-average load over the utilization period. Note that 80Plus requires efficiencies over 80 % at all loads, and the current (USEPA 2013) requirements are 82, 85, and 82 % at 20, 50, and 100 % load, respectively



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 4 K 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.

Gamers have historically been irked by visual anomalies such as image "tearing" and "stuttering". Tearing occurs when a frame is outputted by the GPU when 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. This can cause unacceptable delays in screen refreshes, i.e., stuttering. New technologies such as G-sync (NVIDIA, hardware) and FreeSync (AMD, software) 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 saves energy since, even at around 30 to 50 frames per second (FPS), the gaming experience becomes smoother to the gamer's eye, enabling 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.

One metric of display energy performance is the ratio of the peak power requirement (in on mode) to corresponding pixel count. As seen in Fig. 8, measured power consumption varies between 15 and 77 W across a sampling of displays found in the market today, with wide variations on power consumption even within the constraints of a given display size and resolution.

Nameplate power estimates and energy use of gaming computers

The capabilities and performance of gaming computers vary widely, depending on which components are selected. Components with similar computing performance must be compared in order to evaluate baseline energy use and savings potential in a meaningful way. While many other consumer products (including game consoles) are typically evaluated in terms of total system load, gaming computers can also be evaluated at the component level. However, it must be kept in mind that nameplate power values are often far higher than maximum power use.

We identified commercially available components that would be used to build three gaming computers with similar performance but with progressively lower power requirements. As seen in Figs. 9 and 10, nameplate power estimates vary substantially for the individual components and for the systems as a whole.

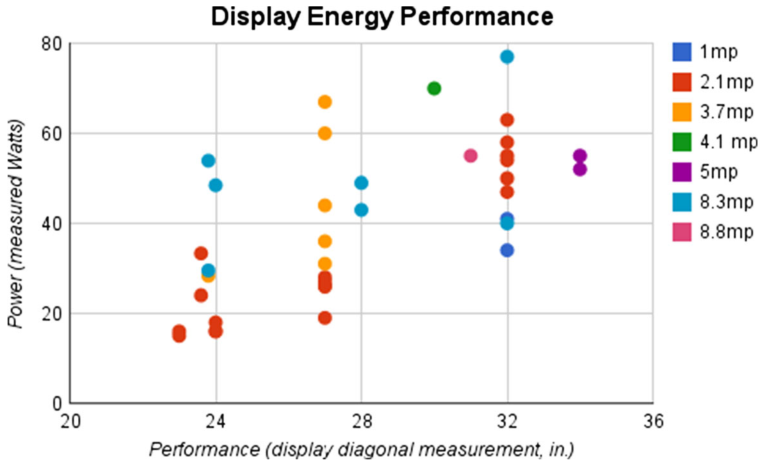


Fig. 8 Performance-power relationships for 37 displays in the 23- to 34-in. size range suitable for use with gaming PCs in the marketplace as of December 2014 (measured values, based on the ENERGY STAR test procedure in active mode). The displays chosen are those within the category favored by gamers (high refresh rates) and reflected the overall variance seen among the superset of displays meeting those criteria. The performance-normalized energy efficiency of the displays shown here ranges from 3.6 to 41 W/megapixel, representing a variation of 11.5-fold

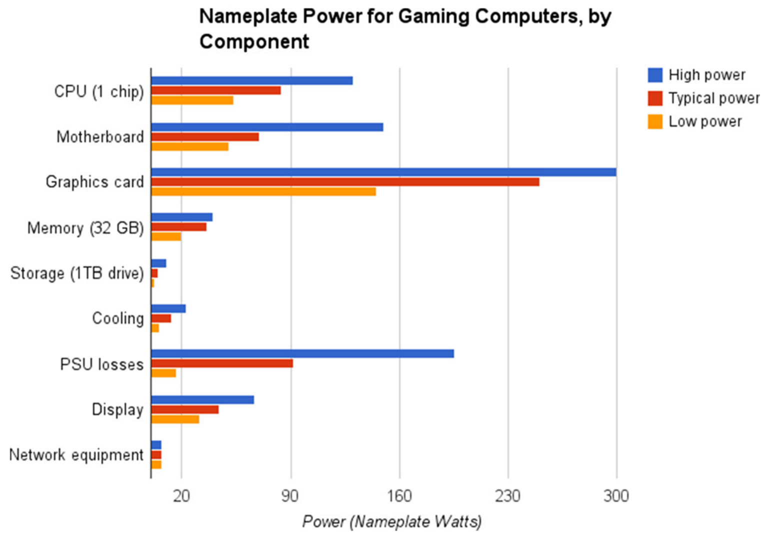


Fig. 9 Differences in nameplate/rated power levels result in differences in annual electricity use. The components have comparable performance levels in games: One CPU (Intel Core i7 4960X 3.6 GHz, Intel Core i7 4770 K 3.5 GHz, and Intel Pentium G3258 3.2 GHz); One GPU (AMD Radeon HD 7970 GHz Edition, NVIDIA Geforce GTX 780, and NVIDIA Geforce GTX 970, with corresponding TeraFLOP benchmarks of 3.8, 4, and 4, respectively); displays—all 27 in. and 3.7 MP (Apple Thunderbolt, ASUS PA279Q, and ASUS PG278Q). No refresh-rate overclocking assumed. Power supply draw is computed by multiplying the sum of component power by one minus PSU efficiency at 50 % load. Excludes space-conditioning energy impacts outside the computer. Assumes one display

Brocklehurst and Wood (2014) similarly found that efficiency and performance were not correlated.

The resulting scenarios for high-power, typical-power, and low-power configurations nominally draw 923, 601, and 331 W, respectively (including displays). Note that in many warm locations, or in many large commercial buildings, significant additional electricity use would be required for air conditioning (not accounted for here) needed to remove the heat produced by these machines. In other locations the computer's waste heat may be useful for part of the year.

Individual gaming computers could have higher power consumption than these reference machines. This can arise not only where less efficient components are used but also where multiple monitors, GPUs, or storage devices are employed. Additional discretionary energy-using components (internal or external) include sound cards, digital-analog converters (DACs), headphones, amplifiers, speakers, networking equipment, RAID cards, powered keyboards, pointing devices, and decorative lighting. The most energy-intensive component in the gaming computer is the graphics processing unit (GPU), and 1.4 graphics cards were sold for each computer sold in 2014 (JPR 2014)[2]; only one GPU is assumed in these reference machines. Overclocking also increases power consumption and waste heat, as does disabling power management features.

Applying our methodology we estimated nameplate power for the "Top-10" gaming computers as ranked by *PC Magazine* for the year 2014 (Fig. 11). We found that the top-rated computer also had the highest nameplate power. It was also the highest performing machine. The ranking, however, would be quite different were the set of machines ranked by relative power draw per unit of performance.

While on the one hand, the above-referenced market data suggest exceptionally high energy use, it is also important to observe the large variation in the various intensity metrics. The history of computing has shown sustained and significant strides in intrinsic energy efficiency (e.g., calculations per second per watt) and that is

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[2] This industry-wide statistic includes all types of desktop computers, while virtually all machines incorporating multiple graphics cards are gaming PCs (which are a small segment of the overall market). Thus, this value is likely a conservative reflection of the actual practice. Having multiple graphics cards is a very widespread practice among gamers, and some machines are even shipped from the factory with two installed.

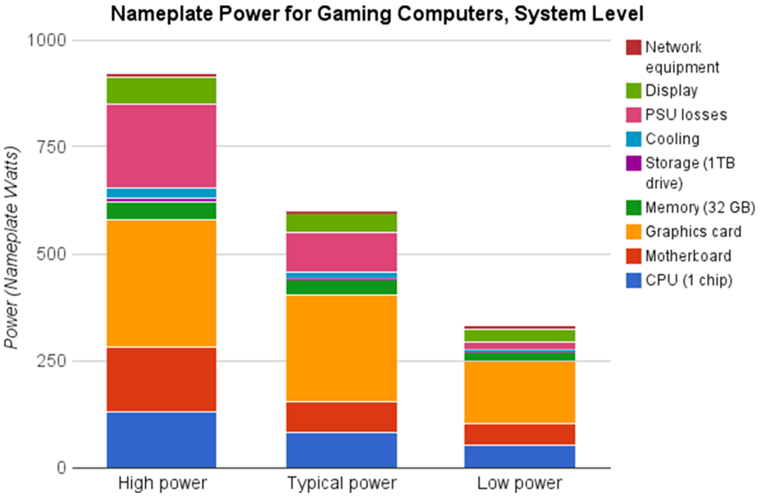


Fig. 10 This particular selection of low-power components results in a system that nominally draws 66 % less power than the highest-wattage choices available. These values reflect nameplate operation (same systems as described in Fig. 9); in-use, components often have substantially lower power demand. Assumes one display. Excludes associated space-conditioning energy impacts outside the computer

evident in the gaming PC arena where efficiencies double every 18 months (Koomey et al. 2011). That said, consumer demand for increased performance has risen even more quickly, with the net effect of rising absolute energy use. These points notwithstanding, given the limitations of nameplate information it is important to explore the actual outcomes by examining measured data.

Measured power and energy benchmarks

Extending nameplate power to estimates of actual energy use is not straightforward. The resultant energy use depends on differences between actual and nameplate capacity as well as the mix of usage modes and duration of use in each mode (e.g., off, sleep, idle, active gaming, video/movie playback, and Web browsing). For example, Webb et al. (2013) found that approximately half of the on-time for game consoles is in "gameplay" mode. Each game or process (e.g., 3D rendering) has its own energy intensity. Moreover, there are a variety of levels of computing demand even within the general activity of "gaming," and energy use is also software specific.

Little measured data has been collected for gaming PCs and their sub-components. The performance of a given component relative to that of other components in

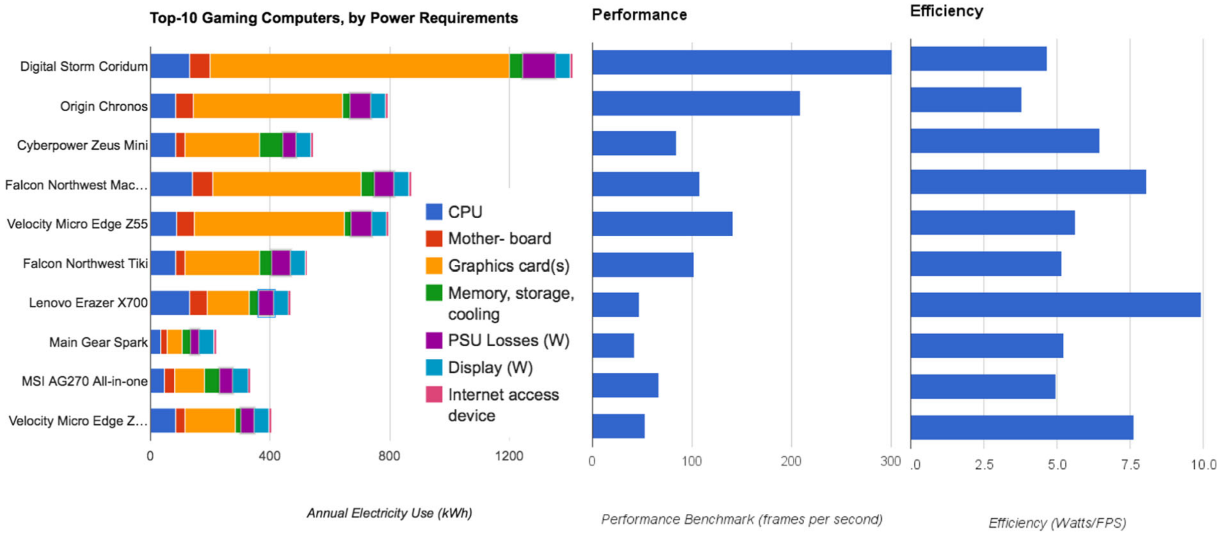


Fig. 11 PC Magazine ranks the (highest energy-using) machine in first position (*left*). Unigine Valley performance benchmarks range from 42 frames per second (FPS) to 302 FPS (*middle*). Benchmarked nameplate watts per FPS, as a proxy for efficiency, varies by a factor of 30 (*right*). Excludes associated space-conditioning energy outside the computer (Ragaza 2013)

the system will also vary significantly depending on the mode of operation. In one example, a particular motherboard ranked average compared with 11 others (using identical CPU) when in long-idle mode, above average in idle mode, and lower than average in active computing mode (Cutress 2014).

We constructed a baseline gaming computer using popular components on the US marketplace as of December 2014. We then measured power requirements and energy use by mode while running common gaming performance benchmark software. Our test-bench machine contains a motherboard that utilizes the X79 (aka *Patsburg*) chipset and an LGA 2011 CPU, noted by others (Brocklehurst and Wood 2014) to be among one of the highest performance Intel platforms on the market. (As of August 2014, X79 was succeeded by the X99 (Wellsburg) chipset and LGA 2011–3 Socket).

We performed a range of system-level measurements in different modes of operation, capturing loads from "off" to full gaming mode status. We adopted estimates by Short (2013) for average times spent by US gaming computer users in various modes of operation. We included short idle times (measurements over the interval of 5 to 10 min after cessation of user inputs) as well as long idle times (after idle for 10 min of idle) per the ENERGY STAR v6.0 test procedure and no "2D" operation (only benchmarking software was running during tests) (USEPA 2013). Established software performance benchmarking tools were utilized to stress test the components and create replicable results under conditions used more broadly in the industry. One-second power data were taken with Watts-Up Pro ES data logger. Internal and after-market software enabled submetering in some cases (PSUs, CPUs, and GPUs).

Measured power consumption and energy use for our base case varied significantly as a function of usage mode. Measured peak electricity demand in active gaming mode at 512 W is six times that of a typical desktop computer and its associated display and three times that in idle mode (Urban et al. 2014). The mode-weighted-average power draw during on-time was 212 W.

Operational settings have significant impact on energy use as well as temperatures. In keeping with the "racecar" analogy used earlier, overclocking CPUs is a popular practice among gamers as a means for boosting computing performance. We evaluated our base CPU at rated and overclocked settings and found significant energy impacts. Elevating clock speed from 3.7 to 4.5 GHz increased peak power requirements during the Cinebench CPU test from 167 to 217 W (23 %). Performance (benchmark scores) increased by 16 %, indicating that energy efficiency declined by 9 %. Note, per Table 2, that half of this effect is upstream of the CPU itself (power supply losses, power delivery to CPU, chipset work, etc.) and that the CPU draws far less power than its nameplate rating, even when overclocked. Some operational strategies seem to have relatively little effect.

We document differences in nameplate and measured power values in Table 2. This effect is compounded where multiple components are evaluated when assembled as a system, with a 49 % disparity during gaming mode in the case of our built-up system. One important ramification of

Table 2 Disparities between nameplate and actual component power requirements

	Nameplate rating (W)	Measured power (W, at peak)	Difference (%)
CPU: Intel Core i7 4820 K (at 3.7 GHz, rated)[a]	130	70	−46
CPU: Intel Core i7 4820 K (at 4.5 GHz, overclocked)[a]	130	79	−39
CPU: Intel Pentium G3258 (at 3.2 GHz, rated)[a]	54	27	−50
CPU: Intel Pentium G3258 (at 4.0 GHz, overclocked)[a]	54	43	−20
GPU: NVIDIA Geforce GTX 970 (at 1102 MHz, rated)[b]	145	145	0
Apple HD Cinema Display	90	75	−17
Apple Thunderbolt Display	165	106	−36
ASUS VG248QE	45	18	−60
Full-base system benchmark: CPU test[a]	560	201	−64
Full-base system benchmark: gaming mode[c]	810	414	−49

[a] Measured value based on peak wattage using Intel Power Gadget over Cinebench CPU benchmark stress test

[b] Value measured with OC+ module, found on Zotac GTX900-series amp Omega and Extreme edition graphics cards

[c] Measured value based peak wattage over the Unigine Heaven gaming benchmark test

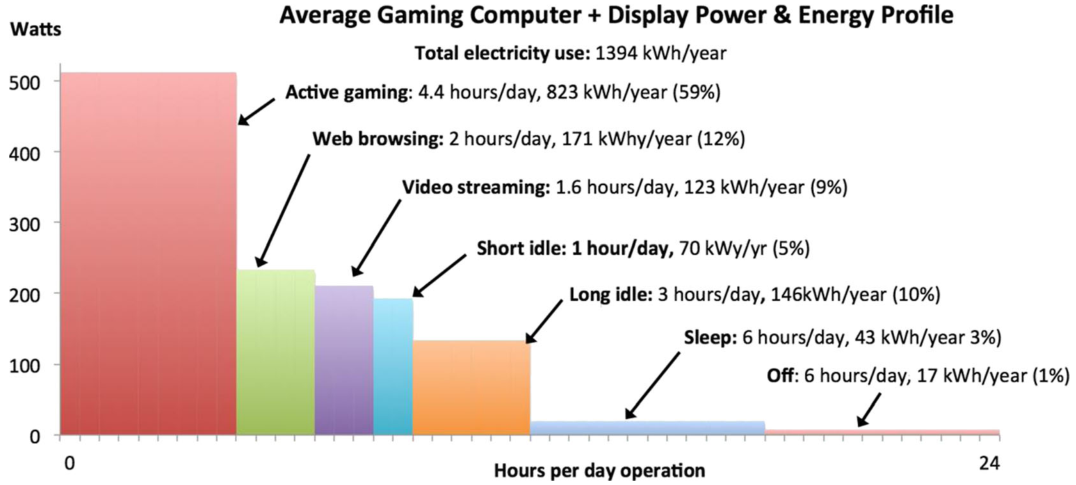


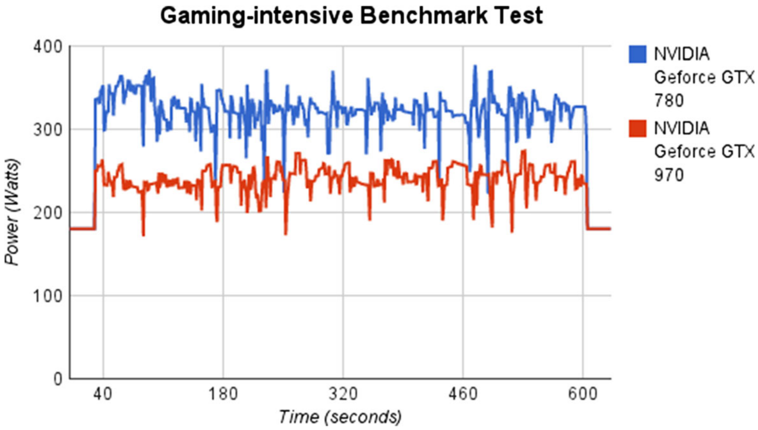
Fig. 12 Measured power and energy use for each mode of operation. The active gaming value is an average observed during the benchmark trials described below, with adjustments to reflect an 80 % efficient PSU and 1.4 GPUs (average in use). Components: PSU (Seasonic G Series, 550 W), CPU (Intel Core i7 4820 K—quad core, 3.7 base GHz), GPU (NVIDIA Reference Geforce GTX 780, 900 MHz boost), motherboard (ASUS P9X79-E WS), RAM (32GB (8×4 GB) Kingston HyperX Beast 1866 MHz, 1.65 V), display (Apple HD Cinema, 23 in.). Operating system: Windows 7 Professional 64 bit; "Power saver" energy management settings in Windows 7 OS. Operating hours: active gaming (Open Gaming Alliance 2015), Web browsing and video streaming (Short 2013), idle from Urban et al. (2014), and off/sleep is residual divided equally. Assumes one display

these disparities is the degree to which PSUs will likely be oversized if nameplate performance is relied upon.

Based on our measurements, Fig. 12 illustrates power and energy use as a function of time and mode for what we deem to be a "typical" vintage 2014 gaming computer over a 24-h duty cycle. While this initial scoping estimate is based on measurements of discrete assemblies, the components selected are representative of market tendencies and the weighted average attach rate of 1.4 GPUs/computer. The assumed time in each mode of operation represents population-level utilization rates for US conditions.

The results indicate unit energy consumption of 1394 kWh/year (based on an average of 4.4 h/day in gaming mode), including the display. The "Avid" user sub-segment (29.5 million people, USA) spends 3.6 h/day gaming, uses 1300 kWh/year, while the "Extreme" user segment (8.1 million people) spends 7.2 h/day uses 1890 kWh/year (36 % more; utilization rates from Short 2013). For the typical gamer (4.4 h/day, weighted average of Avid and Extreme), we found that a much larger proportion of total energy (80 %) occurs in modes above idle than is the case for traditional personal computers, which have low computing loads (Beck et al. 2012). High-performance computers in work environments (not included in this analysis) will also have high consumption where there are more average daily hours of use.

Fig. 13 System power consumption throughout the 10-min Unigine Heaven gaming benchmark. A 25 % reduction in energy use between the two GPUs is achieved. Excludes display. Note: brief drops are transitions between 3D-rendered scenes



The cost of this electricity would be on the order of \$200/year at typical household electricity prices (and easily \$500/year where tariffs are usage dependent, e.g., with an inverted-block design). This, in turn, corresponds to emissions of approximately 1700 lbs (780 kg) of carbon dioxide/year at US-average electricity emissions factors (USEPA 2010).

These estimates are likely conservative, as we assume only one display per user, no peripherals such as audio equipment, and no overclocking of CPUs or GPUs, and "Power saver" settings in the operating system.

Energy efficiency potential

To explore the potential for efficiency improvements and corresponding energy savings, we made a series of progressive hardware improvements to the system and measured the response. These included a more efficient PSU, GPU, CPU, motherboard, and display.

Each of these improvements had a significant effect on measured energy use. For example, we installed and evaluated two graphics cards under the Unigine Heaven benchmark test (Fig. 13). Peak demand was 19 % lower with the more efficient GPU, and 25 % energy savings was achieved across the test cycle (excluding display). Energy use for the system was reduced by 13 % across all modes of operation, with no reduction in GPU computing performance. Many examples of the lack of performance-energy relationship can be observed in Figs. 3, 4, 5, 6, 7, and 8.

As shown in Fig. 14, total energy use for the collection of upgrades was reduced by almost 50 %. Gaming performance remained essentially unchanged with Unigine Heaven FPS benchmarks and declined for CPU tasks because the new CPU had fewer cores. A system-level gaming-mode

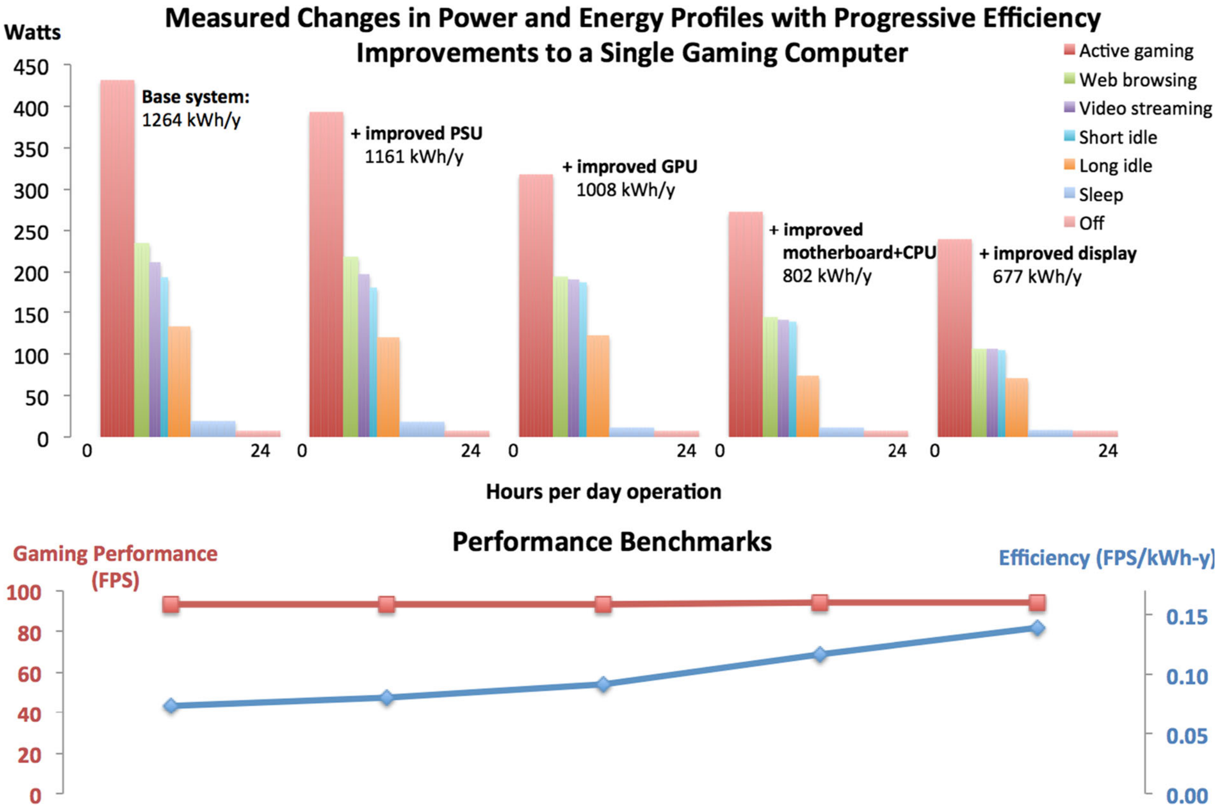


Fig. 14 The Base system is described in Fig. 12, although here we have only 1 GPU. The energy efficiency improvements, from left to right, were progressively upgraded to a 92 % efficient PSU (Corsair AX760), improved GPU (Zotac Geforce GTX 970 AMP! Omega edition), improved motherboard (ASUS Sabertooth Z97 Mark I) and CPU (Intel Pentium G3258), and improved display (ASUS VG248QE modified with NVIDIA G-sync). Gaming performance remained essentially unchanged, resulting nearly a doubling of system energy efficiency

efficiency metric defined as peak FPS/annual electricity use nearly doubled.

We find that each gaming computer is a significant energy user. For context, the average energy use of our "typical" machine is equivalent to that of ten game consoles, six conventional personal computers, and three ENERGY STAR refrigerators (Fig. 15). The efficient case corresponds to the most efficient configuration depicted in Fig. 15.

Additional savings can be achieved through operational settings. One analysis based on adjustments to the CPU and motherboard achieved 27 % savings in standby power, and 26 to 30 % savings in active mode (3DMark and Cinebench benchmarks, respectively) without a reduction in performance (Crijns 2014). Additional adjustments involving underclocking and voltage management yielded 44 and 64 % allowing for 16 and 30 % reductions in performance under the same benchmarks. Combined with the efficiency gains achievable with improved CPU, GPU, and motherboards can thus be expected to yield a total of more than 75 % annual energy savings.

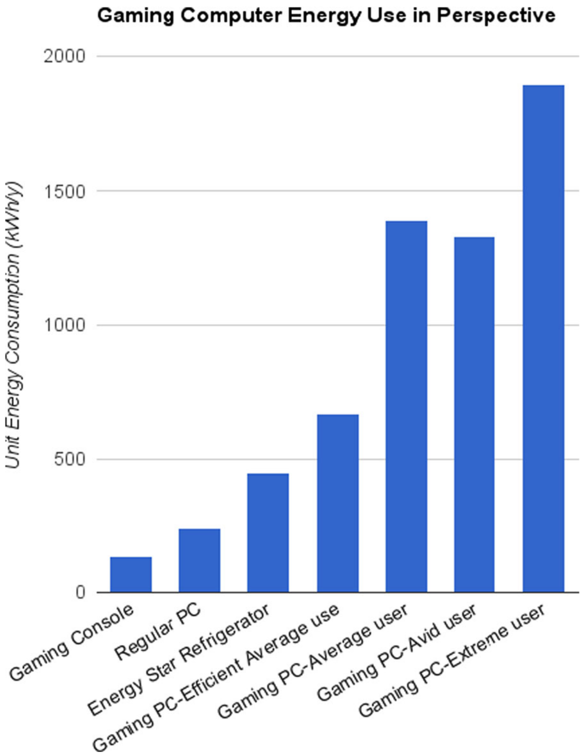


Fig. 15 The average new console uses approximately 134 kWh/year (including the console unit at 62 kWh device as per Webb et al. 2013 connected to an average television with energy use per Urban et al. 2014, with 2.2 h/day utilization as per Short 2013), and the average personal computer 246 kWh/year (Urban et al. 2014). All values include external displays. Values for average refrigerators from www.energystar.gov. Values for gaming computers are from this study

Some efficiency improvements have ancillary benefits. For example, the base GPU in our comparison experienced internal temperatures of 91 °C during the Unigine Heaven benchmark trial, which fell to 65 °C with the more efficient unit due to improved cooling, power delivery, and power consumption. This supports increased reliability and service life, while reducing fan speeds and noise and achieving lower temperature environments for nearby components.

Role of consumer information environment, decision-making and behavior

Gaming computer purchasers face many barriers to making energy-efficient choices. Most components bear no energy-related information on their packaging or when bought on-line without packaging. This includes the most energy-intensive components (graphics cards and CPUs), which do not even carry nameplate power estimates on their packaging or on the product itself. Even spec sheets do not always contain this information. Integrated systems also typically lack information on requirements, aside from the nameplate power of typically oversized PSUs.

Thus far, no labeling programs differentiate the energy performance of gaming computers. The highest long- and short-idle power requirement among ENERGY STAR-rated desktop computers are 33 and 63 W, respectively, which suggests that no gaming computers have received ENERGY STAR ratings. At least in the USA, mandatory energy efficiency standards do not exist for any components found in gaming computers.

Retail salespeople are poorly equipped to coach buyers. Some that we interviewed use highly imprecise rules of thumb when recommending power supplies, e.g., based on unreliable nameplate performance of the associated graphics card plus a "safety margin." It is encouraging that some industry watchers have proposed that metrics be developed to consider total cost of ownership (including energy costs) (Pollak 2010), but this has yet to become mainstream thinking.

Power supplies have received more attention over the past decade than other gaming computer components, leading to the voluntary 80Plus program (Calwell and Ostendorp 2005). The program includes a staged rating

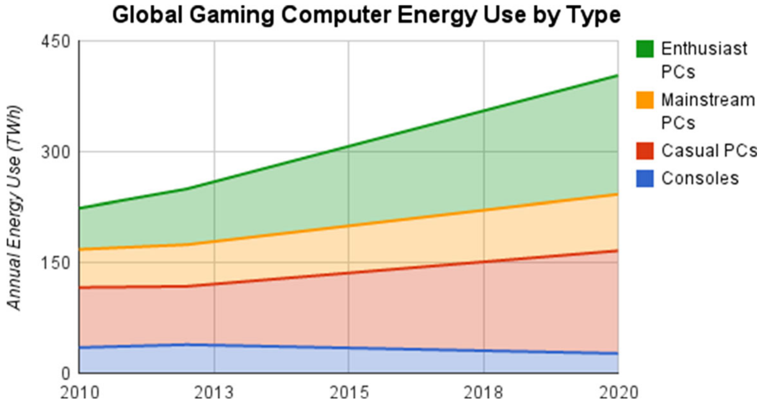


Fig. 16 Energy use estimates are the product of the number and type of platforms (Fig. 2) and unit energy consumption based on measurements, assumed constant at current levels: gaming computers used by "enthusiasts" (this article); other devices are defined in caption to Fig. 15. The fraction of energy use for non-gaming purposes is higher for mainstream and casual users than for the dedicated enthusiast platforms—average enthusiast use is 4.4 h/day; average mainstream and casual use is about 1.5 h/day (Short 2013). Values include computer, display, and network equipment. The proportion of energy used expressly for gaming on conventional ("casual") PCs has not been isolated. Excludes mobile platforms. Based on projections of installed base from 2015 forward per Open Gaming Alliance (2015)

system denoted by bronze, gold, platinum, and titanium. In retail environments, we observed misleading product labeling, where words like "gold" and "silver" were used in a way that masks the absence of an actual 80Plus rating.

Aside from 80Plus, energy test procedures are not standardized, creating considerable confusion in the consumer information environment. For example, three Websites rate an identical motherboard at 62, 92, and 98 W (a 58 % difference across the range)—all at idle and independent of associated CPU (see http://www.guru3d.com/articles_pages/asus_z97_sabertooth_mark_1_motherboard_review,8.html; http://www.kitguru.net/components/motherboard/luke-hill/asus-sabertooth-z97-mark-1-motherboard-review/12/; http://www.tweaktown.com/reviews/6345/asus-sabertooth-z97-mark-1-intel-z97-motherboard-review/index8.html). Such differences could arise from a range of factors not typically standardized (or even disclosed) in test reports. Examples include disparate power supplies or power management. Standardized test procedures are clearly needed.

Technical efficiency ratings reach only so far, as user behavior is an over-riding factor in ultimate energy use. As noted previously, hours of use vary widely, as do consumer desires regarding extreme performance capabilities, display count and area, peripherals, etc. The sports-car analogy applies here in that technical energy savings are easily "taken back" in return for increased performance and corresponding energy use.

The net "worst-case" effect of consumer-determined factors is the high-power multi-display system depicted

Table 3 Global gaming computer energy use in context: 2012

	Desktop PCs[a]	Notebooks	Tablets	Game consoles	Gaming PCs: pre-built[a]	Gaming PCs: user assembled	All devices	Gaming PCs as fraction of total (%)
Unit energy consumption (kWh/year)[b]	246	53	6	155	1394	1394		
Installed base in 2012 (million units)	801	882	184	250	36	18	2170	2.5
Total energy consumption in 2012 (TWh/year)	197	47	1	39	50	25	359	21

[a] Gaming pre-built base deducted from estimate provided by this source and reported in own column to the right

[b] Unit energy consumption follows Fig. 15. Installed base: conventional PCs from statista.com; Tablets Forrester Research (2013); consoles and gaming PCs: stock from Open Gaming Alliance (2015)

in Fig. 1. For perspective, that system entails three-times the nameplate power of our “typical-power” case and seven times that of the “low-power” case shown in Figs. 9 and 10.

Global energy use

Using the available data, we made an initial scoping estimate of global energy use by desktop gaming computers, and placed it in context with that of other devices used for gaming (Fig. 16, Table 3). Gaming computers are the fastest growing segment and have the highest unit energy consumption. This estimate should be considered approximate, pending further research to measure a larger number of actual gaming computers.

We find that, although they represent only 7 % of PC, notebook, and console gaming platforms, gaming computers were responsible for electricity use of 75 TWh/year in 2012 (or approximately $10 billion/year) equal to 30 % of all energy use across this array of devices. Placed in a broader context, this represents about 20 % of electricity used by *all* PCs, notebooks, consoles, and tablets (Table 3).

As noted previously, users with multiple displays, multiple graphic cards, or other discretionary components will require even more energy. Additional energy will also be used in association with air conditioning in hot climates. Trends in technology and behavior (hours of use, by mode) may prove to be as important determinants of energy demand as changes in the hardware itself. Prior macro-level studies have not isolated the energy use by these machines from that of conventional computers.

The potential to reduce energy demand from gaming computers by more than 75 % is enhanced by the very rapid turnover of equipment (several years at the most), the ability for individuals to specify high-efficiency components (new or retrofit), and the significant co-benefits of energy efficiency enhancements for equipment performance, thermal management, and reliability. One of the more pronounced historical examples of technological process is the simultaneous 10-fold improvement in speed of RAM, accompanied by a 13-fold reduction in power requirements (Fig. 6). A key illustration of current opportunities are fan-less PSUs, which not only save significant energy due to the high efficiency associated with eliminating the need for cooling but also trim approximately four constant watts of base load demand, while attaining reduced noise and increased reliability by eliminating the dedicated fan altogether.

Conclusions

There is a wide range of energy use among individual gaming computer components as well as integrated systems. The metrics we computed suggest a correspondingly wide range in efficiencies, i.e., energy use for a given level of computing performance. This demonstrates that high performance can be attained without compromising efficiency. The energy use of gaming computers is significant, and growing, and projected to more than double by 2020 assuming today’s efficiencies and current projections of an increasing installed base of equipment. Overall efficiency improvements of 75 % or more are attainable, which would translate to savings of approximately 120 TWh/year or $18 billion/year at a global scale in the year 2020. Assumptions underlying the typical computer modeled here likely understate energy use in practice.

The results of prior studies have been confounded by uncertainties introduced by relying on nameplate rather than measured data, as well as disparate test conditions and test procedures. We find that nameplate power estimates for the key components in gaming computers significantly exceed power use in practice (on the order of 50 %) and their direct use can thus yield overestimates of energy use. This problem requires attention through further testing under as-used conditions and applied towards improved consumer information and ratings. The energy requirements of specific gaming applications can also be evaluated.

From a technological standpoint, component efficiencies will no doubt continue to improve. Advanced control strategies are also important. Unlike almost all other energy-using products (including commodity PCs), a large share (one third) of gaming computers are specified and assembled by end users. This opens up a unique opportunity for interested consumers to attain efficiencies otherwise unavailable on the market. There is a promising trend towards more efficient notebook-format gaming computers. This has historically been difficult given the relatively large physical dimensions and weight of high-performance components and severe challenges in thermal management and battery life within the small form factor of notebook computers. Gaming notebooks, however, do not commonly deliver the same computing performance as do desktops but are improving.

Our macro-level results are certainly preliminary in nature, and suggest that the issue calls for much more rigorous analysis, which, in turn, requires the collection of more market data. In the future, finer-grain data on equipment stocks, energy using characteristics, and user behavior will allow for more precise and disaggregated energy-use estimates (e.g., in homes versus workplaces, the latter of which is not incorporated in our analysis). The additional gaming-related energy use of general-purpose computing devices also remains to be estimated. To enable improved energy analyses as well as better consumer decision making, standardized methodologies should be developed to more rigorously and consistently benchmark and normalize energy use and peak power demand of computers as well as that for specific games.

The mainstream gaming computer industry does not emphasize energy use or efficiency, consumers do not have ready access to the information needed in order to make informed decisions, and energy analysts and policy makers have only begun to identify the importance of this particular energy end use. Policies proposed for addressing other types of household electronics (OECD/IEA 2009) and game consoles in particular (Webb et al. 2013) could be beneficially applied to gaming computers as well. More vigorous energy programs and policies are needed to mitigate the energy consequences of the very fast-growing worldwide market for gaming computers.

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