How Low Can You Go? Forecast of Game Console Energy Consumption Based on Industry Trends

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Abstract

Each new generation of video game consoles brings with it previously unseen graphical realism and dazzling interactive features. The increased processing power of a latest-generation console also requires greater energy consumption compared to the most recent models of preceding generations. For example, the latest 8th-generation Microsoft Xbox One and Sony PlayStation 4 consoles provide full high definition (1080p) video output, video and sound input, and Internet connectivity, all enabled by an accelerated processing unit (APU) with 5 billion transistors, compared to 372 million transistors for the previous (7th)-generation consoles. This all comes at a cost: one report has calculated a cumulative energy consumption in excess of 10 TWh/year in the United States alone. How will this new load evolve over time?

Previous generations of high performance game consoles have exhibited decreasing energy consumption, as manufacturers have iteratively improved the components within each generation without changing the fundamental design. The likely primary driver of these intra-generational decreases has been "functional scaling", a semiconductor industry trend that has taken the place of geometric or Dennard scaling as a means of increasing processor performance and continuing Moore's Law. This trend is expected to continue, and together with power management, provides two paths for reducing energy consumption of current-generation game consoles over the next five years.

Projections based on these historical trends and semiconductor-industry roadmaps show that Gameplay Mode power draw will decrease by almost a third by 2017 and almost a half by 2020, compared to the 2013 launch models. This can be expected to decrease the annual energy consumption to 58 kWh/yr for Xbox One and 68 kWh/yr for PlayStation 4 by 2020. We also validate the forecast model against historical trends showing 14% average error for Xbox 360 and 15% for PlayStation 3. Finally, we present a high-improvement scenario based on efficient designs of other information and communications technology (ICT) products that show a potential pathway to approximately 85% energy savings by 2020.

Introduction and Background

This paper forecasts the power draw and energy consumption of current (8th)-generation high-performance game consoles[1] based on measurements conducted in 2013 [1] and 2014 [2], semiconductor industry roadmaps and forthcoming European Union (EU) connected standby regulations. We also validate the forecast model by backcasting and comparing the results to historical power draw of previous (7th)-generation game consoles[2]. Finally, although we anticipate significant reductions in power draw and energy consumption within the current generation of game consoles, the paper discusses potential measures for reducing energy consumption even further, while also locking in some of the savings into a potential, future 9th generation of game consoles, which could re-use some of these energy saving features even when the processor and other major components are updated.

[1] Microsoft Xbox One and Sony PlayStation 4. The Nintendo Wii U is another 8th generation console, but this study focuses on the Xbox and PlayStation due to their higher power draw and energy consumption.

[2] Microsoft Xbox 360, Sony PlayStation 3, and Nintendo Wii.

Game Console Energy Consumption

Game consoles consume energy in a number of modes, which previous work ([3],[4],[5]), has broadly divided into On (subdivided into Active and Inactive or Idle) and Standby (also Connected Standby or Rest Mode), based on whether the user is interacting with the console. Game consoles draw the least power in Standby Mode and the most in Active On Modes; however, the impact on annual unit energy consumption can be the opposite, due to the large portions of time spent in Standby Mode and the Inactive On Modes.

Furthermore, as the power draw in each mode can also vary based on the processor load and functions enabled, the U.S. Environmental Protection Agency (EPA), game console manufacturers, and other stakeholders developed a test method [6], ensuring there is no ambiguity. In this paper, we focused on the following modes, as defined in the EPA recognition criteria [7] and associated test method [6], which tend to have the largest impact on energy consumption.

1. Game Play Mode, where "a game is actively being played and the Game Console is receiving user input."

2. Video Stream Play, where "a game console is playing a video stream through a network connection" (and also approximates playback of video from local sources such as optical disc or hard drive),

3. Video Pause Mode, where "the video player is paused during active streaming of the video",

4. Navigation Mode, which "includes screen(s) initially displayed for user navigation", and

5. Standby Mode, where the game console is "is plugged into a power source but is not providing any primary or secondary function and has no saved hardware state. The Game Console has no active network link although may be capable of charging devices in this mode." [7] (However, 8th-generation high-power game consoles will maintain their network link when not providing other functions, remaining in a "Connected Standby" Mode, and it is this Connected Standby Mode that is used in the rest of the paper).

In addition, there are a number of other modes, from System Maintenance and Download Mode and Game Play Pause Mode [7], to TV Mode (pass-through and control of TV signals) [1] and Off Mode (completely turned off or unplugged, drawing 0 watts) [5]. These modes are not associated with primary functions but can impact annual energy consumption. A recent metering study found that game consoles spent 30% of the time in Off Mode [8], while another reported 34%, with 20% of units drawing 0 watts during the entire study period [5].[3] On the other hand another 10% were left on permanently in an Idle Mode, thereby increasing the average time in On Mode across the sample by a factor of three [5].

Figure 1, below, shows the power draw in three of the modes as measured through the years by Natural Resources Defense Council (NRDC). The data show that power in each mode increases at the beginning of a generation of game consoles as a more capable and therefore higher power consuming product is first released (e.g., PlayStation 3 compared to PlayStation 2). Subsequently, the power draw falls with each iteration within the same generation (e.g., PlayStation 3 2006 to PlayStation 3 2007).

[3] Although the study participants were recruited by energy efficiency organizations and may be more likely to unplug their game consoles or use a power strip to disconnect from mains, these findings will be used to develop usage profiles in the absence of other data.

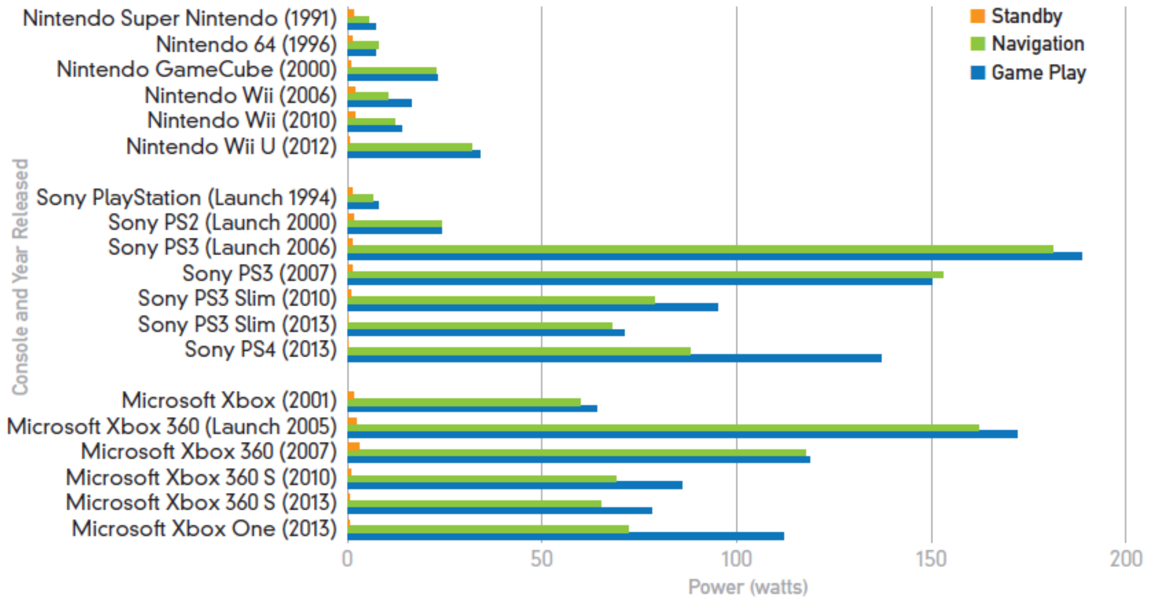

Figure 1. History of video game console power [1].

Semiconductor Industry Scaling Trends

This trend has been observed previously [3] and is mainly driven by updates to the integrated circuits (ICs, specifically logic and memory). The basic design of the ICs generally does not change within a particular generation of game consoles. The configuration and number of transistors is held constant, but the size of individual transistors decreases.

The same design with smaller transistors permit the ICs and the game console as a whole to use less power while ensuring compatibility with the same games. Throughout their lifetimes, Sony's PlayStation 3 (PS3) and Microsoft's Xbox 360 decreased the minimum feature size[4] of both the central processing unit (CPU) and graphics processing units (GPU) from 90 nm for both to 45 nm and 40 nm, respectively, as shown in Table 1. Similar trends occurred in memory ICs [9].

Table 1. Comparison of CPU and GPU technologies for game consoles. All data from references listed under Model unless referenced individually.

Model	Launch Year	Game-play Mode Power (W) [10]	CPU Line-width (nm)	Number of Transistors (million)	GPU Line-width (nm)	Power Supply Output Power (W)
PlayStation 2 [12]	2000	24.2	250	10.5	250	35 [13]
PlayStation 3 [14]	2006	188.6	90	234 [15]	90	380
PlayStation 3 [14]	2007	150.1	65	234 [15]	65	280
PlayStation 3 Slim [15]	2010	95.0	45	234 [15]	40	250

[4] The minimum feature size or linewidth is the smallest object that can be created in a semiconductor process and typically corresponds to the gate length of the transistor. This is the size of the gate as printed; nonidealities in the semiconductor process will reduce the gate to its "actual" or "physical" width. The minimum features size is also sometimes called the "technology node". [11]

Model	Launch Year	Game-play Mode Power (W) [10]	CPU Line-width (nm)	Number of Transistors (million)	GPU Line-width (nm)	Power Supply Output Power (W)
PlayStation 4	2013	136.5	28 [16]	N/A	N/A[a]	250 [17]
Xbox [18]	2001	64.0	180	21 [19]	150 [20]	100 [21]
Xbox 360 [22]	2005	172.0	90 [23]	165	90 [23]	150-203 [24]
Xbox 360 [25]	2007	118.8	65 [23]	165	90 [23]	150-203 [24]
Xbox 360S [26]	2010	86.0	45	372	N/A[a]	135 [24]
Xbox 360E [26]	2013	78.0	45	372	N/A[a]	120 [24]
Xbox One	2013	112.3	28 [25]	5,000 [27]	N/A[a]	135 [28]

[a] No GPU is listed as the CPU and GPU functions were combined in an accelerated processing unit (APU).

What drives this process is that smaller transistors permit smaller ICs. More of these smaller ICs can fit on a single wafer of silicon, so more can be produced in a given batch or per unit time. Furthermore, because there are now more chips on the wafer, proportionally fewer are right on the edge of the wafer, leading to fewer defects, and again lower costs [29]. Reducing the power of the processors also allows game console manufacturers to decrease the size of other components, such as power supplies, heatsinks, cooling fans, enclosures, and wiring, which saves additional money.

Traditionally, the shrinking of transistors in an IC permitted lower voltage and current. A shrink by a factor of k led to decrease in voltage by a factor of k as well as a decrease in current by a factor of k, which resulted in a decrease in switching power by a factor of k^2 [30]. In addition, there is also the leakage power that occurs when the transistors are not being switched.

Leakage power was small when Dennard proposed the scaling laws in 1974, but after 30 years of scaling, and corresponding reductions in the switching power, it became large enough to prevent further decreases in power through further Dennard, or “geometric”, scaling [31],[32]. Instead, designers have turned to “equivalent” or “functional” scaling, which is the use of new technologies, consisting of novel materials or geometric designs, to provide the same function but at a lower power and size. High dielectric constant (high-*k*) materials, transistors with multiple gates (FinFET) and other innovations have sustained progress in the industry. Although more gradual than geometric scaling, this trend is expected to continue as well as be augmented by new materials and processor designs better suited to particular applications [33],[35].

Power Draw Forecast for Current-generation Game Consoles (Xbox One and PlayStation 4)

The processors currently in use in both Xbox One and PlayStation 4 consoles are derivative of AMD’s Jaguar architecture, which is also used for personal computers (PCs) [36],[37]. Because of this overlap between game console and PC processors, we expect game consoles to be influenced by general computer industry trends. The scaling processes described above are expected to continue, leading to smaller, more efficient ICs in successive iterations of the Xbox One and PlayStation 4.

Power Use Model

To estimate the impacts of these industry trends on the power and energy consumption of game consoles, we developed a model of game console power draw that distributed the power draw in each mode among a handful of major components. The power draw of the components could then be varied with time based on industry forecasts to see the impact on total game console power draw and energy consumption.

The model is primarily top-down although it does include some bottom-up components such as power supply losses, and potential component savings. Including further bottom-up data, such as measured or theoretical power draw of components such as fans or processes such as video decoding could improve the realism of the model and we hope to include such granular data in the future. Even without these details the model tracks historical performance, as we will show toward the end of this paper.

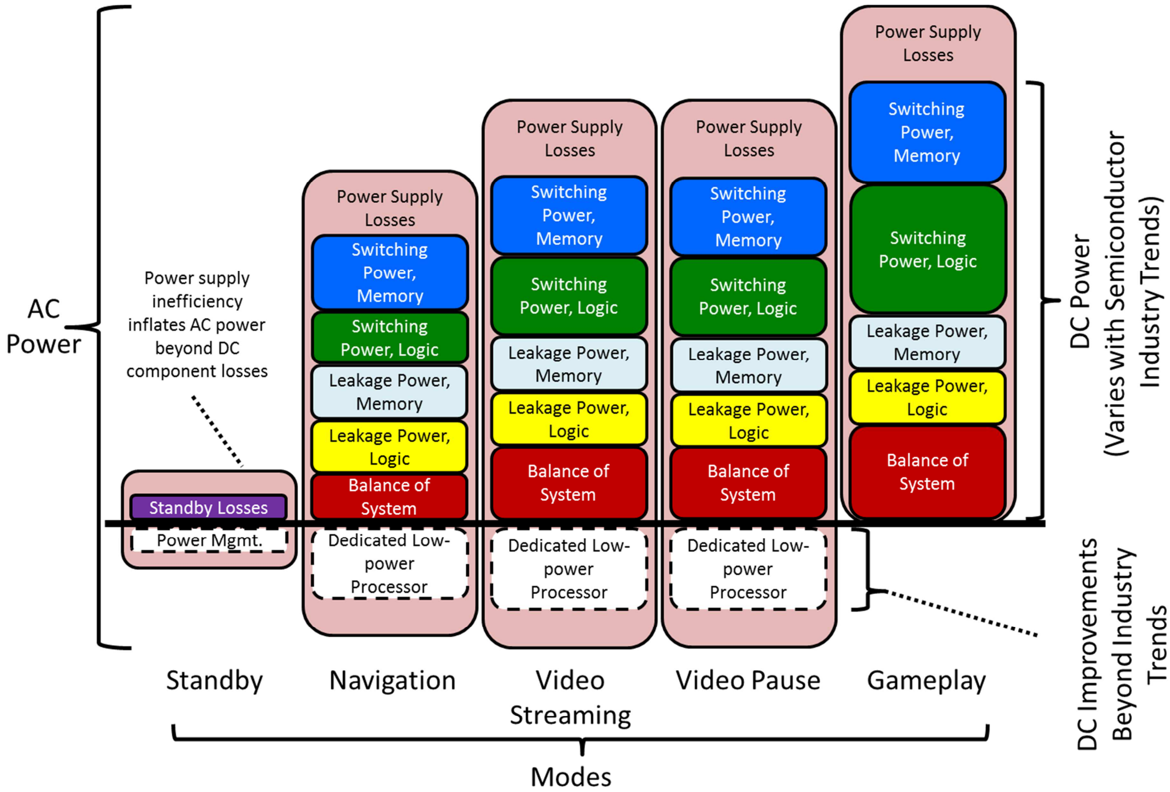

Figure 2. Illustration of the components of the model. Certain losses and improvements are held constant across modes, while others vary, such as switching and power supply losses. Not to scale.

As can be seen in Figure 2, above, we divided measured Standby power into a dc loss component, which includes all the functions powered in Standby (such as support for the Kinect component in the Xbox One), and a power supply loss component (ac-dc conversion). The On Mode allocations cover logic, memory, and other components of the system, which are operating in those modes.

The power supply losses are also different in the On Modes than in Standby due to the higher load on the power supply and therefore different efficiency. The losses were based on efficiency measurements of the 2014 Xbox One power supply with the game console in Gameplay, Navigation, and Standby Modes [2]. The Navigation Mode efficiency was assumed to apply to Video Stream Play and Pause Modes, and all these efficiency results were assumed to also apply to the PlayStation 4, for which power supply measurements were unavailable. The Kinect and total power draw in each mode were also based on test results (Gameplay: [10]; non-Gameplay: [2]).

The proportion of power attributable to logic and memory (switching and leakage) was based on forecasts in the 2011 edition of the International Technology Roadmap for Semiconductors (ITRS) [33], as described below. Finally, the power draw of the balance of components was estimated using data for a proxy PC with similar specifications as 8th-generation game consoles.[5]

[5] The proxy computer featured AMD's A10 6800K (Kaveri) APU, micro architecture motherboard, 1x8GB memory, 500GB hard drive, Blu-ray Disc optical drive, and cooling fan. The power draw for each of these components was estimated using [34] under full load (representative of Gameplay Mode), in idle (Navigation and Video Stream Pause), and an average of the two (Video Stream Play).

Semiconductor Roadmap Inputs

The ITRS estimates logic and memory performance based on the expected trends in transistor and interconnect performance and design complexity. Based on these micro-trends, the ITRS projects power draw over multiple years as shown in Figure 3, below. This trend is increasing and shows what the processor of a next-generation game console could draw upon release in a future year, though ITRS notes that these power draw values are not at acceptable limits and there is a pressing need to develop new solutions to reduce power.

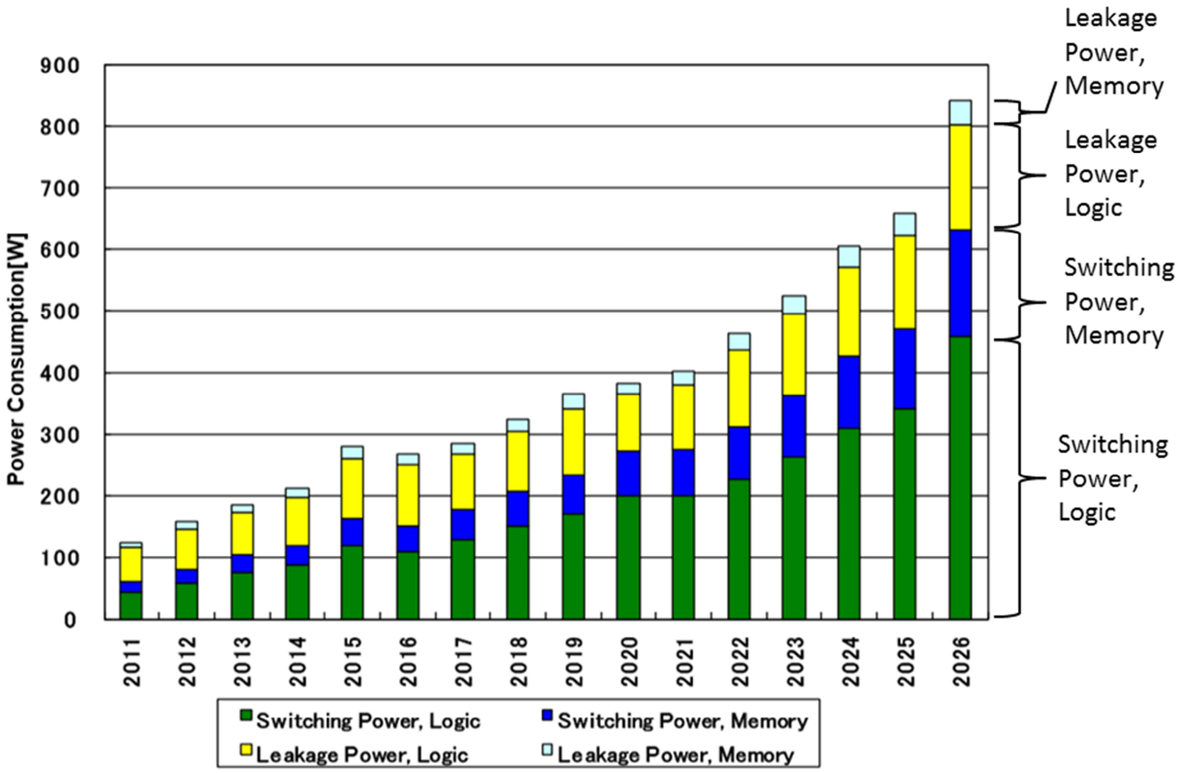

Figure 3. Switching and leakage power consumption trend for high-performance logic and memory, such as that in game consoles [38].

Although the power rises rapidly in Figure 3, not shown is the even faster rise in the number of transistors per chip, from 1.5 billion in 2011 to 49 billion in 2026 [38][6]. Were the number of transistors to stay constant—as it is expected to do through the life of a game console generation—the per-transistor and total chip power would decrease.

To estimate this decrease, we normalized the switching and leakage contributions for both logic and memory, illustrated above, to the typical transistor count in 2013. Although the APUs in the current generation of game consoles were developed in 2012 ([39],[40]), they use a 28 nm process, which the ITRS dates to 2013. Therefore 2013 was the base year for all calculations, the results of which are shown in Table 2 for logic and Table 3 for memory.

[6] The complexity of the logic portion of game console processors is measured in number of transistors. The memory portion is measured in terms of gigabits, which are forecast to grow from 69 in 2011 to 1,100 in 2026.

Table 2. Logic process characteristics and power inputs to scaling model.

Model Parameter	Source	2013	2014	2015	2016	2017	2018	2019	2020
Linewidth (nm)	ORTC Tables, from [38]	28	25	22	19.8	17.7	15.7	14	12.5
Number of transistors (million)	Overall Tables, from [38]	3,092	3,092	3,092	6,184	6,184	6,184	12,368	12,368
Switching Power , Logic (W)	Figure 3	70.8	83.7	115.9	106.3	125.6	148.1	167.4	196.4
Leakage Power, Logic (W)	Figure 3	66.0	75.7	96.6	95.0	88.6	85.3	103.0	90.2
ITRS Switching Power , Logic Trend Normalized to 2013 Number of Transistors (W)	Calcula-tion	70.8	83.7	115.9	53.1	62.8	74.1	41.9	49.1
ITRS Leakage Power, Logic Trend Normalized to 2013 Number of Transistors (W)	Calcula-tion	66.0	75.7	96.6	47.5	44.3	42.7	25.8	22.5

Table 3. Memory process characteristics and power inputs to scaling model.

Model Parameter	Source	2013	2014	2015	2016	2017	2018	2019	2020
DRAM ½ Pitch (nm)	Overall Tables, from [38]	28	25	23	20	17.9	15.9	14.2	12.6
Functions per Chip (Gbits)	Overall Tables, from [38]	69	137	137	137	137	275	275	550
Switching Power, Memory (W)	Figure 3	31.9	30.3	43.1	41.5	47.9	55.9	65.4	73.4
Leakage Power, Memory (W)	Figure 3	14.4	12.8	20.7	17.6	16.0	19.1	22.3	19.1
ITRS Switching Power, Memory Trend Normalized to 2013 Functions per Chip (W)	Calcula-tion	31.9	15.2	21.5	20.7	23.9	14.0	16.4	9.2
ITRS Leakage Power, Memory Trend Normalized to 2013 Functions per Chip (W)	Calcula-tion	14.4	6.4	10.4	8.8	8.0	4.8	5.6	2.4

One challenge is that increases in transistor count and memory complexity only occur every two or three years [38]. Therefore, during the in-between years, per-transistor power is increasing, and the power of a chip with a fixed design would tend to go up. We controlled for this by keeping the previous chip power between shrinks. This is equivalent to assuming that game console manufacturers would keep using the same chip until there is one available that draws less power. Although manufacturers would benefit from the lower cost of a smaller chip, waiting for a more efficient one permits them to also make the cooling fan and power supply smaller. The resulting trend for the contribution of logic and memory to processor power, normalized to 2013, is shown in Figure 4.

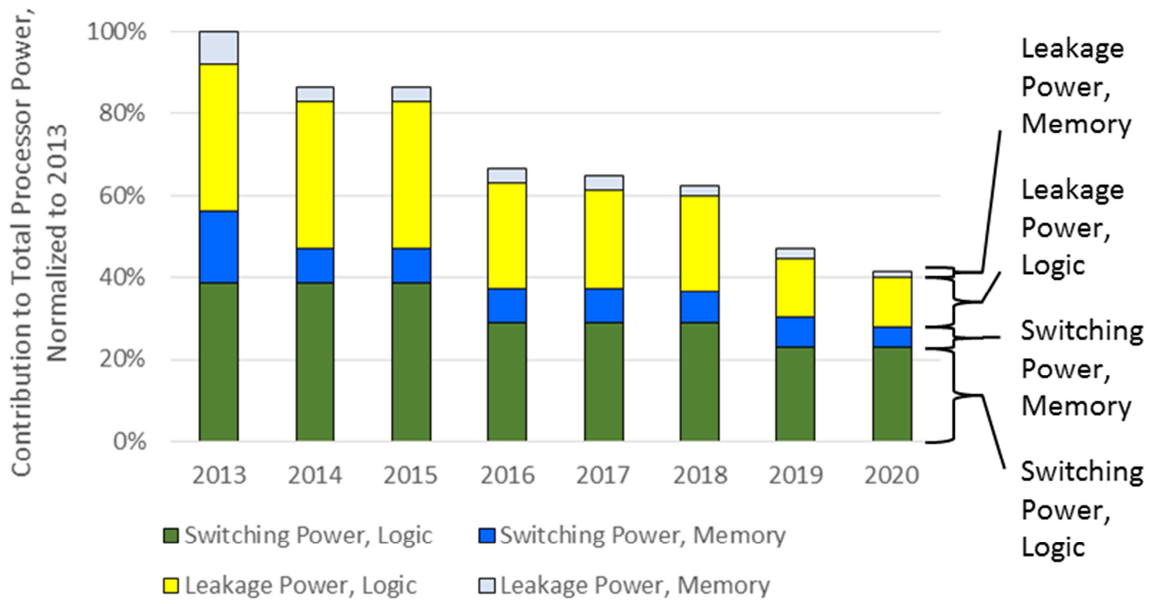

Figure 4. Relative switching and leakage power draw trend for logic devices and memory normalized to 2013 transistor and function counts.

It should be noted that although Dennard and functional scaling give a general idea of shrink and power draw at the transistor level, ICs will still vary in power draw even if they have the same number of transistors and feature size due to their design and operating conditions. For example, even though both the PlayStation 4 and Xbox One use similar APUs manufactured using the 28 nm process, they have different power draw in each mode. However, if each APU subsequently undergoes a shrink, equivalent decreases in power draw will be observed, and have been observed in the past (Figure 1). Figure 4 shows the expected decreases through 2020.

Model Results

After developing the normalized power draw trends for logic and memory leakage and switching power draw, we incorporated them into the game console model described earlier. We started with Gameplay Mode, where the processor is operating at a maximum and therefore where the ITRS data are most applicable.

In that mode, the measured power for the Xbox One, for example, was 112.3 W ac [1]. We subtracted out the power supply losses (17%) [2] and power attributable to other components such as motherboard, drives and cooling (45.4 W dc) to obtain 48.1 W dc. This is the portion of power draw that was ascribed to logic and memory and therefore subject to future scaling. We divided this portion between logic and memory and switching and leakage power using the 2013 proportions apparent in Figure 4: 39%, 36%, 17%, and 8%. In 2013, the proportions add up to 100%, as the contributions of each portion were normalized to 2013. However, as memory and processors improve with time, these proportions normalized to 2013 will decrease, and so will the total Gameplay Mode power.

For the power attributable to other components, it was assumed that the power draw will decrease at half the rate of the memory and logic. This was a compromise between holding it constant and scaling it per the ITRS, and reflects that transistors outperform most other components over time.

For other On Modes (Navigation, Video Stream Play, and Video Stream Pause), we subtracted out the power supply losses measured during Navigation Mode, the power attributable to other components, and the memory and logic leakage power calculated in Gameplay. The latter were assumed to remain the same between On Modes. Finally, we distributed the remainder among the logic and memory switching power, which would vary between On Modes.

This remainder ended up being a fraction of that in Gameplay Mode; however, the proportions between these fractional switching logic and memory proportions were assumed to be the same as in Gameplay Mode. For example, for the Xbox One the proportions in Navigation Mode in 2013 were estimated to be 17.3 W and 3.8 W for the logic and memory leakage power (same as for Gameplay Mode) and 1.1 W and 0.5 W for the logic and memory switching power (much less than in Gameplay, but the ratio between them remained at 2.2:1, same as in Gameplay).

We then multiplied the component power in 2013 by the proportions for each subsequent year shown in Figure 4 to project the effects of scaling through 2020, and summed the results to obtain the total power in each mode. Finally, a few additional improvements were added to the model manually:

1. A decrease in Standby Mode power to meet the following forthcoming requirements in Europe: 6 W by 2015, 3 W by 2017, and 2 W by 2019.

2. A decrease in Standby Mode power for the PlayStation 4 to reflect a 2014 firmware change that would stop charging controllers after a preselected time.

3. An increase in power supply efficiency to 60% in Standby, 84% in Navigation, and 86% in Gameplay to meet forthcoming U.S. DOE external power supply requirements (this was only applied to the Xbox One, as the PlayStation 4 has an internal power supply not subject to DOE requirements).

The results of these forecasts can be seen in Figure 5, which also shows the total annual energy consumption based on usage profiles for 7th generation game consoles. These are shown in Table 4, below. Until specific usage data can be developed for the Xbox One and PlayStation 4, these should be considered illustrative.

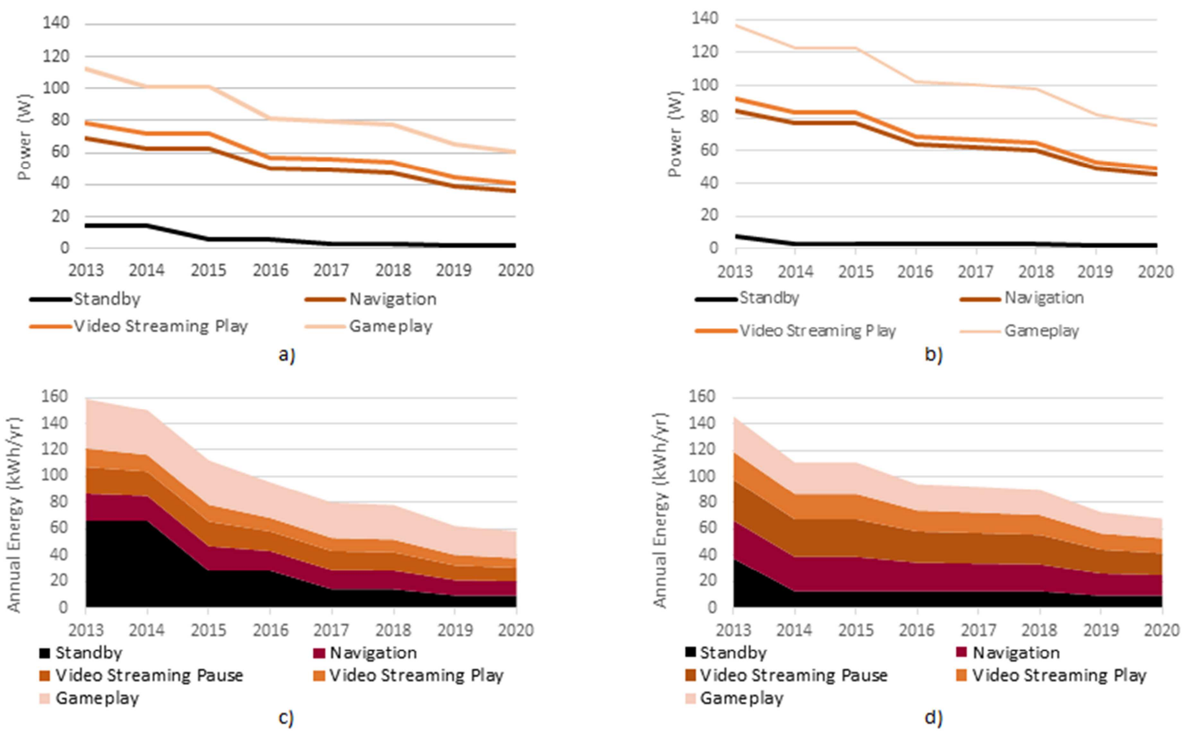

Figure 5. Forecasts of a) power for the Xbox One, b) power for the PlayStation 4, c) total annual energy consumption for the Xbox One, and d) total annual energy consumption for the PlayStation 4.

Note: Video Streaming Pause power is equal to Video Streaming Play power in the Xbox One and Navigation Mode power in the PlayStation 4, so it does not appear on the power graphs (a) and b)).

Table 4. Usage profiles for calculating annual energy consumption.

	Xbox Usage (h/wk)	PlayStation Usage (h/wk)	Source
Standby	90.1	90	Average Standby usage (Table 5 in [5])
Navigation	5.8	6.6	Half of Idle Time (Average usage per Table 3 in [5] minus active usage per Table 3 in [3])
Video Streaming Play	3.4	4.4	Proportion of time spent on all other activity per [39] times active usage per Table 3 in [3]
Video Streaming Pause	5.8	6.6	Remaining half of Idle Time
Gameplay	6.5	3.8	Proportion of time spent in Gameplay Mode per [39] times active usage per Table 3 in [3]
Total	**111.5**	**111.4**	Total does not sum to 168 due to Off/Unplugged Mode at 0 W (Table 5 in [5])

Validating the Model through Backcasting

As described in the previous section, our model of game console power and energy use relies on semiconductor industry forecasts for high-performance processors to forecast future consumption. Although the APU is the primary driver of power draw, there are many other components that contribute to the energy consumption, and which, in totality, can be significant. Using measurements, rather than the PC proxy, to model the current power draw and likely trends of cooling fans, HDMI driver, video decoder etc. would improve accuracy.

Similarly, although we do not expect the fundamental design of the game consoles and their APUs to change within the next five years, additional functions may be added, impacting the power draw beyond what can be forecast today. For example, the Kinect was introduced as an optional accessory with the Xbox 360, and was subsequently included with the Xbox One, affecting its power draw [2]. Similarly, Ultra High Definition video output or virtual reality headsets could increase power draw. Alternatively, accessories could add new modes which would not affect the power forecast in the existing modes, but could result in a real-world energy consumption significantly different from that forecast by the model. For example, encoding and uploading video during gameplay is not currently tested or included in the model, but is a popular activity and could become even more so in the future.

Given these limitations, can the model be trusted to provide reasonable forecasts of future power and energy consumption? To help answer this question, we put in logic and memory performance data from the 2005 and 2007 ITRS [9], and projected the impacts scaling trends predicted in 2007 would have on power in Navigation and Gameplay modes. We also factored in the Xbox 360 power supply efficiency [42]. We then compared the results of this backcast over 2005[7] through 2013 to contemporaneous measurements of 7th generation consoles performed by NRDC.

As now, it was not clear in 2007 whether the scaling trends would hold over multiple years or whether the game consoles themselves would not be redesigned to add functionality. As mentioned above, the Kinect was added, but as a separate accessory; meanwhile, one of the Universal Serial Bus (USB) ports on the Xbox 360 was removed in 2013, likely saving some power in all the modes [43]. Nonetheless, the backcast remained reasonably true to the historical power draw in Navigation and Gameplay Modes, as shown in Figure 6. The average error for these two modes across the three years when measurements were conducted was 14% for the Xbox 360 and 15% for the PlayStation 3, as indicated in Table 5.

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[7] The Xbox 360 launched in 2005. Although the PlayStation 3 launched in 2006, it used a 90 nm processor, which the ITRS dates to 2005.

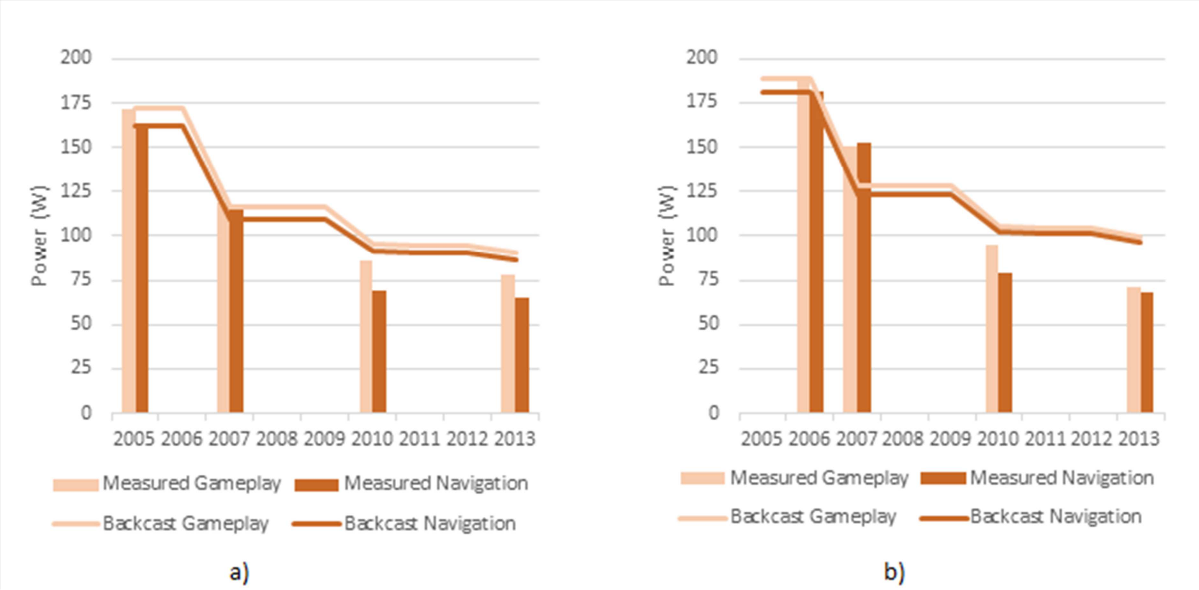

Figure 6. Backcast results compared to historical measurements for a) Xbox 360 and b) PlayStation 3. (Historical measurements from [10])

Table 5. Error between backcast results and historical measurements

	2007	2010	2013	Average
Xbox 360 Navigation Error	-7%	32%	33%	**19%**
Xbox 360 Gameplay Error	-2%	11%	16%	**9%**
Xbox 360 Average Error	**-4%**	**22%**	**24%**	**14%**
PlayStation 3 Navigation Error	-20%	29%	42%	**17%**
PlayStation 3 Gameplay Error	-15%	10%	40%	**12%**
PlayStation 3 Average Error	**-11%**	**20%**	**41%**	**15%**

Options for Further Efficiency

The previous two sections have shown large historical reductions in power draw and energy consumption within a generation of game consoles, and semiconductor industry trends that foreshadow a similar reduction in the current generation. However, even greater reductions may be possible using currently available technologies.

To estimate further energy reductions beyond the business-as-usual forecast (almost 50% reductions in Gameplay and other modes by 2020), we added the following improvements to the model:

1. Power supply efficiency: An 80PLUS Titanium power supply will be used, providing >90% efficiency in all modes, though this would be a costly upgrade;

2. Power supply output power reduction: As the console power draw decreases, so should the rated output power of the power supply, meaning that the power supply will be closer to its design optimum during normal operation;

3. All user-available energy saving settings are implemented by default, reducing power to less than 0.5 W in Standby Mode;

4. Xbox One Kinect is augmented with an occupancy sensor, reducing its power to 0.1 W in Standby Mode; and

5. A dedicated low-power secondary processor, similar to ones used in commercially available over-the-top set-top boxes is implemented to reduce power in Navigation, Video Streaming

Play, and Video Streaming Pause Modes to 5 W.

This may require a significant redesign in the case of the Xbox One. However, a secondary processor is already present in the PlayStation 4 and carries out many background tasks. Unfortunately, the APU remains active during video streaming to download the large files, resulting in high power draw [44]. However, if secondary processors are used for downloads as well as to perform all tasks that do not require graphics processing (i.e., all modes except Gameplay), lower power draws should be achievable.

We assumed that software changes could go into effect in 2015. However, hardware improvements could not be implemented until at least 2016. With the exception of the power supply, which is a factor applied to the total dc consumption within each mode, the improvements were modeled as a dc power subtracted from the dc draw occurring in that mode, resulting in a power savings. The effects of the improvements are shown for the Xbox One in Figure 7 and the PlayStation 4 in Figure 8, below.

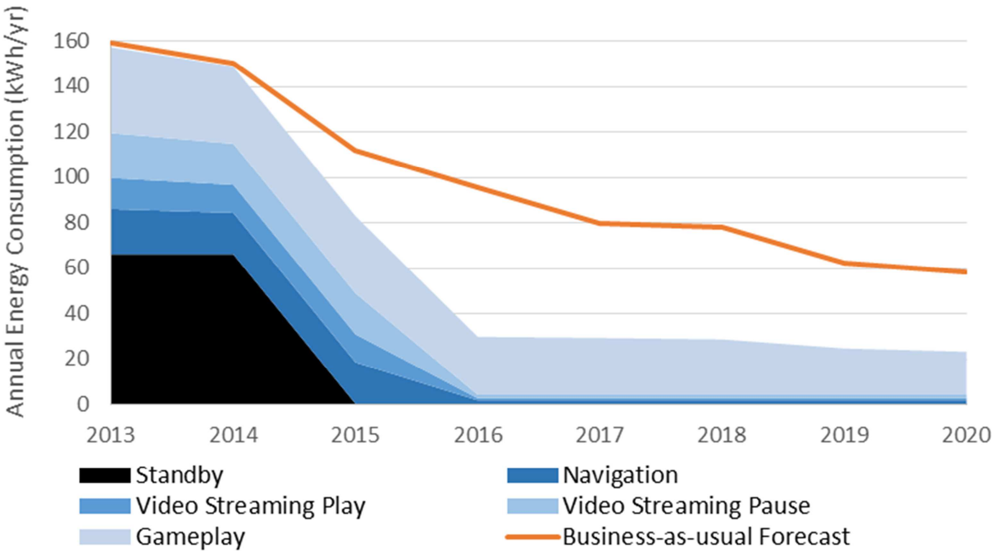

Figure 7. Forecast of annual energy consumption contributions of each mode following additional improvements, compared to business-as-usual, for the Xbox One.

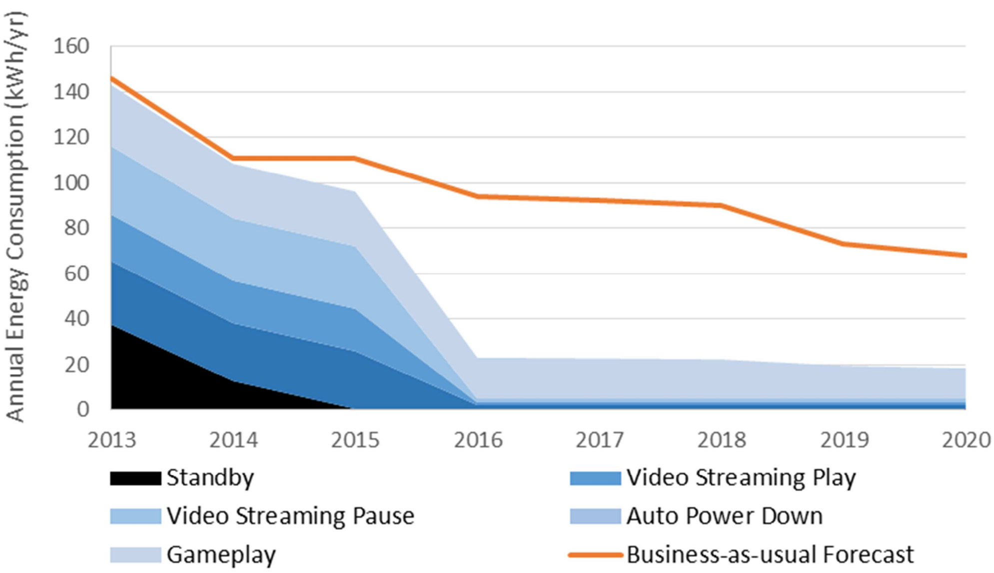

Figure 8. Forecast of annual energy consumption contributions of each mode following additional improvements, compared to business-as-usual, for the PlayStation 4.

As can be seen in the figures above, significant savings beyond business-as-usual could be achieved in the non-Gameplay modes by increasing power supply efficiency, implementing currently available energy saving settings, and providing dedicated hardware for video playback, comparable to over-the-top Internet Protocol set-top boxes. Total energy consumption could decrease approximately 90% by 2020, to 23 kWh/yr for the Xbox One and 18 kWh/yr for the PlayStation 4.

Conclusion

In this paper, we forecast a reduction in power and energy consumption for current (8^{th})-generation high-power game consoles: a 46% reduction in Gameplay Mode power and 63% reduction in annual energy for the Microsoft Xbox One and a 44% reduction in Gameplay Mode power and 53% reduction in annual energy Sony PlayStation 4, by 2020. The reduction is due to updated processors in subsequent iterations of these game consoles, and the expected hardware improvements is based on semiconductor industry trends that underlie performance improvements in in all areas of computing and are expected to continue into the future. Moreover, we showed that these trends also help explain the improvement in previous (7^{th})-generation high power game consoles, the Xbox 360 and PlayStation 3. Finally, we evaluated a series of improvements that could further reduce power draw in non-Gameplay modes, such as lower-power Standby and a dedicated processor for video playback, resulting in an annual energy reduction of 85% for the Xbox One and 87% for the PlayStation 4 by 2020.

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References

[1] Delforge P. and Horowitz N. *The Latest-Generation Video Game Consoles. How Much Energy Do They Waste When You're Not Playing?* 2014. NRDC Issue Paper. May 2014. http://www.nrdc.org/energy/game-consoles/files/video-game-consoles-IP.pdf.

[2] ICF International. *Game Console User Guide Mockups*. Report and test results presented to the U.S. Environmental Protection Agency (EPA). September 30, 2014.

[3] Hittinger, E., Mullins K. A., and Azevedo, I. L. *Electricity consumption and energy savings potential of video game consoles in the United States*, Energy Efficiency Journal, March 2011.

[4] Webb A., Mayers K., France C., Koomey J. *Estimating the energy use of high definition game consoles.* Energy Policy Journal. 61. 2013. pp 1412–1421.

[5] Desroches L.-B., Greenblatt J. B., Pratt S., Willem H., Claybaugh E., Beraki B., Nagaraju M., Price S. K., Young S. J., Donovan, S. M. Ganeshalingam, M. *Video game console usage and US national energy consumption: Results from a field-metering study*. Energy Efficiency Journal. Published online October 23, 2014.

[6] U.S. Environmental Protection Agency (EPA). *Recognition Program for Game Consoles: Test Method.* March 2013. http://www.energystar.gov/sites/default/files/specs//Final%20Version%201%200%20EPA%20Voluntary%20Criteria%20for%20Energy%20Efficient%20Game%20Consoles.pdf.

[7] EPA. *Recognition Program for Game Consoles: Performance Requirements Version 1.0*. March 5, 2013. http://www.energystar.gov/sites/default/files/specs//Final%20Version%201%200%20EPA%20Voluntary%20Criteria%20for%20Energy%20Efficient%20Game%20Consoles.pdf.

[8] Larson, B., Gilman, L., Davis, R., Logsdon,M., Uslan, J., Hannas, B., Baylon, D., Storm, P., Mugford, V., & Kvaltine, N. April 28, 2014. Residential building stock assessment: Metering study. Seattle: Northwest Energy Efficiency Alliance. p 85.

[9] ITRS. *International Technology Roadmap for Semiconductors 2007 Edition: System Drivers*. http://www.itrs.net/links/2007itrs/2007Chapters/2007SysDrivers.pdf.

[10] Delforge P. *NRDC Report Charts and Numbers.* Excel spreadsheet provided through personal communication. September 9, 2014.

[11] Pangrle B. A Node by Any Other Name. Semiconductor Engineering. May 12, 2014. http://semiengineering.com/a-node-by-any-other-name/

[12] Diefendorff, K. *Sony's Emotionally Charged Chip*. http://docencia.ac.upc.edu/ETSETB/SEGPAR/microprocessors/emotionengine%20(mpr).pdf.

[13] Sony. *PlayStation 2 computer entertainment system Tech Specs*. http://us.playstation.com/ps2/techspecs/ps2black.html.

[14] Edepot. *PlayStation 3 Secrets*. http://www.edepot.com/playstation3.html.

[15] Anandtech. *Understanding the Cell Microprocessor*. http://www.anandtech.com/show/1647/9.

[16] AMD. *AMD and the Sony PS4. Allow Me To Elaborate.* http://community.amd.com/community/amd-blogs/amd-gaming/blog/2013/02/21/amd-and-the-Sony-ps4-allow-me-to-elaborate.

[17] Famitsu. *PS4 is the culmination of expertise gained in PS3*. http://www.famitsu.com/news/201401/17046618.html [Translated from Japanese using Google Chrome's Translate feature].

[18] Anandtech. *Hardware Behind the Consoles – Part I: Microsoft's XBOX*. http://www.anandtech.com/show/853/2.

[19] Anandtech. *Intel Pentium III 1GHz*. http://www.anandtech.com/show/500/2.

[20] Techpowerup. *NVIDIA XXGPU-B*. http://www.techpowerup.com/gpudb/1867/xgpu-b.html.

[21] CNET. *Microsoft Xbox specifications*. http://www.cnet.com/products/microsoft-xbox/specs/.

[22] IBM. *Application-customized CPU Design. The Microsoft Xbox 360 CPU story*. http://www.ibm.com/developerworks/power/library/pa-fpfxbox/.

[23] Anandtech. *Welcome to Valhalla: Inside the New 250GB Xbox 360 Slim*. http://www.anandtech.com/show/3774/welcome-to-valhalla-inside-the-new-250gb-xbox-360-slim.

[24] XBOX. *Xbox 360 power supply*. http://support.xbox.com/en-US/xbox-360/system/power-supply.

[25] Anandtech. *Microsoft's Xbox 360 goes 65nm: Falcon Dissection and Power Consumption*. http://www.anandtech.com/show/2377.

[26] Arstechnia. *Inside the Xbox 360, Part II: the Xenon CPU*. http://arstechnica.com/features/2005/06/xbox360-2/

[27] XBOX. *Marc Whitten and Major Nelson Discuss Xbox One Architecture*. http://news.xbox.com/2013/05/marc-whitten-and-major-nelson-discuss-xbox-one-architecture.

[28] Bestbuy. *AC Adapter Power Supply Charger for Microsoft XBOX one Console*. http://www.bestbuy.com/site/agptek-ac-adapter-power-supply-charger-for-microsoft-xbox-one-console-12v-10-83a-black-

black/1309980017.p?id=mp1309980017&skuId=1309980017&st=categoryid$pcmcat303700050011&cp=2&lp=12#tab=buyingOptions.

[29] Zant, Peter Van. *Microchip Fabrication. A Practical Guide to Semiconductor Processing*. Second Edition, McGraw Hill Publishing, 1990. pp. 111-117. ISBN 0-07-067194-X.

[30] Dennard, R. H., Gaensslen, F.H., Rideout, V.L., Bassous, E. *Design of ion-implanted MOSFET's with very small physical dimensions*. Solid-State Circuits, IEEE Journal of, Vol 9, Issue 5, Oct 1974, pp. 256-268.

[31] Bohr, M. *A 30 Year Retrospective on Dennard's MOSFET Scaling Paper*. Solid-State Circuits Society, Volume 12, Issue 1, 2007, pp. 11-13.

[32] McMenamin, A. *The End of Dennard Scaling*. http://cartesianproduct.wordpress.com/2013/04/15/the-end-of-dennard-scaling/.

[33] ITRS. *International Technology Roadmap for Semiconductors 2011 Edition: Emerging Research Devices*. http://www.itrs.net/links/2011itrs/2011Chapters/2011ERD.pdf.

[34] Power Supply Calculator. http://powersupplycalculator.net/.

[35] Kahng, A.B. *The ITRS design technology and system drivers roadmap: Process and status*. Design Automation Conference (DAC), 2013 50th ACM / EDAC / IEEE. May 29, 2013-June 7, 2013. pp.1,6.

[36] Parrish, Kevin. *AMD Elaborates on PS4's Custom 'Jaguar' APU.* Tom's Hardware. February 21, 2013. http://www.tomshardware.com/news/APU-Jaguar-PlayStation-Kabini-Temash,21229.html.

[37] Yam, Marcus. *Xbox One Review: Unifying Your Living Room Experience*. Tom's Hardware. November 20, 2013. p 3. http://www.tomshardware.com/reviews/microsoft-xbox-one-console-review,3681-3.html.

[38] ITRS. *International Technology Roadmap for Semiconductors 2011 Edition: System Drivers*. http://www.itrs.net/links/2011itrs/2011Chapters/2011SysDrivers.pdf.

[39] Chipworks. *Inside the XBOX One.* November 26, 2013 http://www.chipworks.com/about-chipworks/overview/blog/inside-xbox-one.

[40] Chipworks. *Inside the Sony PS4*. November 15, 2013. http://www.chipworks.com/about-chipworks/overview/blog/inside-sony-ps4.

[41] Nielsen. *U.S. Gaming, A 360° Review*. March 14, 2013.

[42] DOE. *2009 DOE Non-Class A EPS Determination Analysis Technical Support Document*. http://www.regulations.gov/#!documentDetail;D=EERE-2009-BT-DET-0005-0004, p. 3-43

[43] Brunner G. *What will the PS4 and Xbox One redesigns look like?* ExtremeTech. December 25, 2013. http://www.extremetech.com/gaming/173329-what-will-the-ps4-and-xbox-one-redesigns-l.

[44] Nextpowerup. *Sony PlayStation 4 Torn Down, Reveals Secondary ARM Processor and 2 GB RAM Chip.* http://www.nextpowerup.com/news/5390/sony-playstation-4-torn-down-reveals-secondary-arm-processor-and-2-gb-ram-chip/.