Review of Four Studies Comparing Efficiency of AC and DC Distribution for Data Centers

White Paper 151

Revision 0

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> Executive summary

DC is proposed for use in data centers as an alternative to AC distribution primarily based on publicized claims of efficiency improvements and energy savings. This paper shows that the most widely cited values for quantitative improvements are wrong and grossly overstate the efficiency differences between AC and DC, and that the latest AC and DC systems provide effectively the same efficiency. This paper compares the results of four different publicized studies and explains the assumptions and mistakes that have led to erroneous but widely circulated beliefs about the efficiency benefits of DC power distribution.

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Introduction

Every data center uses power from an AC utility supply and ultimately consumes power for IT circuits as low voltage DC power. Therefore every data center is both AC and DC. As the power flows from the AC utility to the ultimate DC load, there are a variety of alternative points where the conversion from AC to DC can occur. In almost all data centers today, power is distributed to the IT equipment as AC, and converted within the IT device power supply to DC. Recently it has been proposed that power be converted to DC closer to the utility supply, and distributed around the data center as DC.

Due to the fact that there are many international safety and performance standards for AC power distribution, the universal availability of AC power distribution equipment, the wide-spread AC engineering and installation skills, and because virtually every IT device in production can operate from standard AC power, there needs to be a compelling advantage to DC distribution in order to cause a move of the industry from the AC standard. The primary justification for a shift to DC power is based on the assumption that large gains in energy efficiency are possible, large enough to overcome the transition barriers and costs associated with a change from AC to DC. This paper will focus on the efficiency benefits, and will specifically review, compare, analyze, and reconcile published claims about the efficiency of DC power distribution as compared to AC.

This paper considers the four studies of **Table 1**. The commonly cited conclusion about the quantitative gains for DC for data centers are shown in the table.

Table 1

The commonly cited efficiency gains from four studies of DC distribution in data centers

Study	DC Benefit Cited
Lawrence Berkley National Lab (LBNL)[1]	28%
Electric Power Research Institute (EPRI) study conducted at Duke Energy[2]	15%
The Green Grid[3]	1%
Schneider Electric[4]	0% – 1%

Note the huge variation, nearly a factor of 30, in the projected efficiency gains among the four studies. Since every 1% gain in energy efficiency translates to about $13,000 savings per year for a 1 MW IT load data center, it is very important for the industry to understand whether the actual improvements are at the low end or at the high end of the range.

[1] LBNL findings: http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReport.pdf

[2] EPRI findings:
http://www.emergealliance.org/imwp/download.asp?ContentID=20674&ei=rHwxT_CoJej2sQK-yrjYBg&usg=AFQjCNEyFsA7geYZ9ZofX4rkXBU8nA47bQ

http://greensvlg.org/wp-content/uploads/2011/11/3A-DC-Power-Symanski.pdf

[3] The Green Grid White Paper 16, *Quantitative Efficiency Analysis of Power Distribution Configurations for Data Centers*, http://www.thegreengrid.org/~/media/WhitePapers/White_Paper_16_-_Quantitative_Efficiency_Analysis_30DEC08.pdf?lang=en

[4] Schneider Electric White Paper 127, *A Quantitative Comparison of High Efficiency AC vs. DC Power Distribution for Data Centers*, http://www.apc.com/whitepaper/?wp=127

This paper will show that the cited values from the LBNL and EPRI studies do not represent reality for new data centers because they grossly overstate the losses of new AC systems. The actual power distribution efficiency gains available from DC are correctly described in The Green Grid and Schneider Electric studies. *In fact, some recent AC designs using Eco-mode are actually are more efficient than proposed DC designs*. The small size of the efficiency benefit reduces the incentive to convert the industry to DC and suggests that effort may be better directed to focus on server power management and cooling plant improvements as sources of efficiency gains in the future.

Comparison of study data

Each of the four studies used both measurements and calculations to compare the projected energy efficiency differences between AC and DC distribution. The summary data for each study is shown in **Figure 1**:

Figure 1

Difference in losses of AC and DC distribution found in four studies

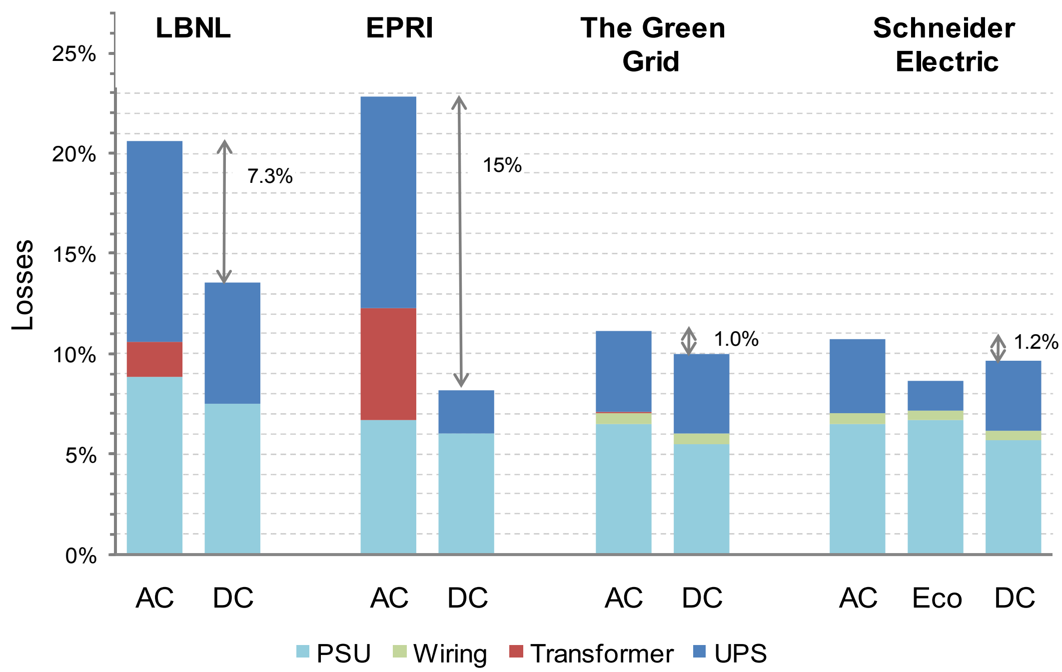

Figure 1 shows the contributors to the power system losses determined for both AC and DC for each study. The losses in **Figure 1** for all four studies share the following characteristics:

- DC rectifier output voltage is 380VDC
- Commercially available AC equipment was used
- All the studies considered the power path from utility AC power to the output of the IT equipment power supply

The loss values for The Green Grid and the Schneider Electric studies are at 50% load. The LBNL and EPRI studies operated different devices at different loads, which is a problem that accounts for some of the differences found in those studies and is discussed later in this paper. The efficiency differences for different systems can be directly read off the chart as the differences in the bars. Each bar shows the percent losses of the different parts of the distribution system that contribute to reducing efficiency from the ideal value of 100%.

A review of the chart provides the following key information:

- All of the studies found similar efficiency performance for the DC power distribution system
- The differences in the study conclusions are primarily due to different findings regarding the efficiency of AC power distribution systems
- Wiring losses are small and similar across the different systems and so are not contributing to differences between AC and DC systems.
- The major differences between the efficiency findings of the different systems are due to the differences between the losses of the AC UPS and the transformer

Note, **the actual value for the difference between AC and DC from the LBNL report is 7.3%, yet the commonly cited value by the popular press is 28%, which is taken from a poorly worded and misleading part of the report**. This misleading number, which was widely reported in the press, is responsible for an enormous amount of confusion in the market, and warrants more explanation. The reasons for this major discrepancy are explained in the **Appendix** titled “Misleading citations of the LBNL study”.

To understand why and how these four studies came to different conclusions about the losses, the next sections of the paper consider and reconcile the quantitative performance of each major subsystem in turn: IT power supply, UPS, transformers, and wiring.

Comparison of power supply data

The IT device power supply must step down, isolate, and regulate the voltage to the IT circuits. These functions must be present whether the power supply operates from AC or DC, so the power supply is mostly unchanged. However, all modern AC power supplies have an additional power processing step, called the power factor corrector, which is used to control the input current and eliminate harmonics. The power factor corrector represents about 15% of the space taken by the power supply and contributes about 1.0 to 1.5% of loss to the system. The power factor corrector can be removed or bypassed for DC operation, allowing the power supply to be 1 to 1.5% more efficient.

The four studies all find the expected improvement in power supply efficiency when a DC supply is used instead of an AC supply, as shown in **Figure 2**.

All of the studies find similar efficiencies for AC and DC power supplies, with the improvement from DC ranging from 1% – 2%. As newer generation power supplies with lower losses are introduced, we can expect proportional reductions in the differences between AC and DC losses, pushing the difference nearer to the lower 1% value.

Note that an improvement of 1.5% is a much different result than found in the popular press. For example, numerous articles cite a paper presented at a recent APEC conference where the author is reported to have said: “Servers equipped with DC power supplies, instead of AC power supplies, operate with 20% to 40% less heat and reduce power consumption by up to 30%...[5]”. Clearly this is absurd because server power supplies are already on the order of 93% efficient making it mathematically impossible for servers to operate with 30% less power consumption.

Findings: the efficiency gain associated with conversion of an AC supply to DC is on the order of 1% – 2% as consistently reflected by all four studies. This number should come closer to 1% as the overall efficiency of power supplies improves. Claims of much greater improvements are not based on these studies, and may be impossible if they suggest DC power supply efficiency of greater than 100%.

[5] http://ecmweb.com/mag/electric_acdc_data_center/

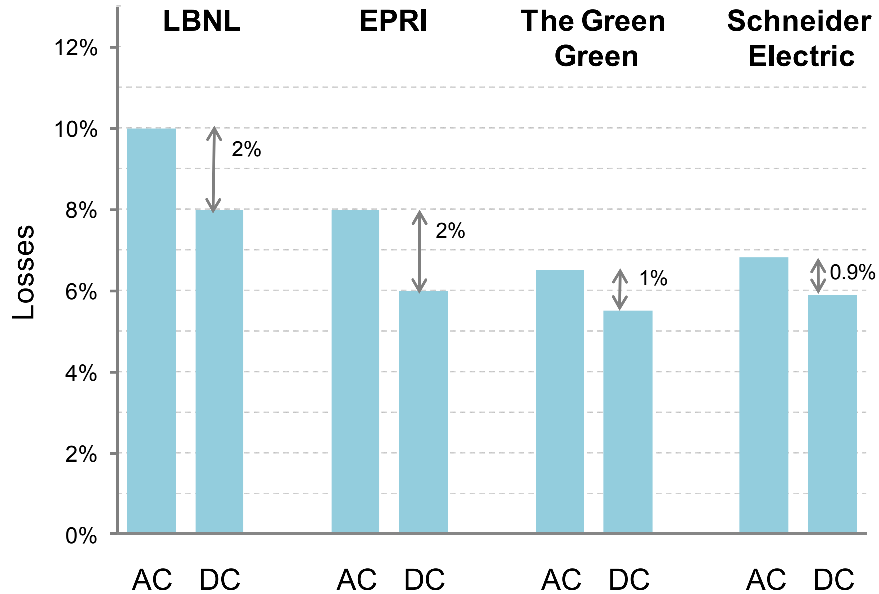

Figure 2

Difference in losses of IT power supplies for the four studies

Comparison of UPS data

Both the AC and DC systems have a UPS in the studies. The DC UPS takes in AC and puts out battery-backed DC, while the AC UPS takes in AC and puts out battery-backed AC. The study data for DC and AC UPS systems is shown in **Figure 3**. The studies vary considerably in their findings regarding the difference in losses between AC and DC UPS. This difference in UPS efficiency among the studies is a major reason for the differences in the summary conclusions.

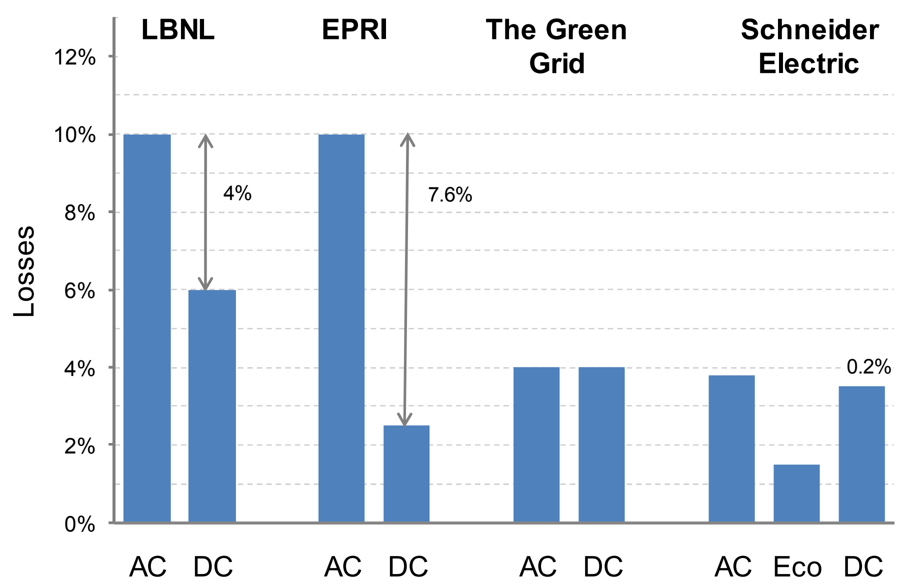

Figure 3

Difference in losses of UPS systems for the four studies

In all of the studies, the UPS efficiency data is based on actual measurements of UPS systems. An analysis of the data and the efficiency performance curves of the actual products used in the analysis shows that **the reported data in all four reports is accurate**. What is different between the reports is the performance of each UPS used and its operating conditions.

Differences between the AC UPSs

The Schneider Electric and The Green Grid studies used data from current generation UPS systems and had nearly identical findings. The LBNL and EPRI reports used UPS systems that were two generations older than current models. **The LBNL study used a UPS designed in 1992, while the EPRI study used a UPS based on a 1990 design.** Furthermore, the EPRI UPS was equipped with an optional input isolation transformer that was unnecessary and reduced the system efficiency. The LBNL study also used a 208V UPS, while all the other studies were based on a 480V or 415V UPS. Lower voltage UPS systems are typically 2-3% less efficient than higher voltage UPS.

Curiously, the LBNL study correctly identifies the availability of AC UPS products of 97% efficiency in the report, but then draws conclusions based on 90% efficient AC UPS which it describes as a “best in class” system. **This error alone accounts for all of the efficiency difference found by LBNL between AC and DC systems**.

There have been remarkable improvements in UPS efficiency, since 1992, that account for much of the difference in the findings of the studies. In 1992, best in class UPS efficiency was 90%. Today, best in class UPS efficiency is 97%. Again, this dramatic improvement has negated most of the efficiency advantages claimed for DC when compared with AC.

The Schneider Electric study also considers the use of AC UPS utilizing so call “Eco-mode” operation, in which the UPS operates in bypass operation when the AC power quality is acceptable[6]. UPS systems from Schneider Electric, Eaton, Emerson, GE, S&C, and others offer this capability. The efficiency of UPS operating in this mode for all vendors is approximately 98.6%. This performance is better than any known or proposed DC UPS.

Finding: Since any DC UPS is a new system, it is unreasonable to compare its performance to obsolete AC UPS systems. The correct alternative to a DC UPS is a current-generation AC UPS. If this comparison had been made, the findings of the LBNL and EPRI studies regarding AC UPS efficiency would have been consistent with The Green Grid and Schneider Electric studies. Furthermore, if the use of an eco-mode AC UPS is considered, AC UPSs actually become more efficient than DC UPSs.

Differences between the DC UPSs

The Schneider Electric and The Green Grid studies reached have nearly identical findings regarding DC UPS efficiency. The LBNL study had a 1% higher loss, which can be attributed to the fact that it is now approximately 5 years old and DC UPS efficiency has advanced about 1% in that time. The EPRI report found a DC UPS loss lower than any of the other studies. The DC UPS used in that study was a model from Delta Electronics that is non-isolated and does not provide a mid-point ground referenced 380V supply. That type of DC UPS is inherently capable of higher efficiency as EPRI found, but cannot realistically be considered an option because it is incompatible with the emerging DC UPS safety standards[7].

Findings: The differences in DC UPS efficiency between the four studies was small and does not account for the differences in the quantitative findings. The EPRI study did identify a type of DC UPS that is approximately 1% more efficient than the DC UPS in the other studies, but

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[6] Considerations for the use of ECO mode are described in detail in Schneider Electric white paper 157, *Eco-mode: Benefits and Risks of Energy-saving Modes of UPS Operation,* http://www.apc.com/whitepaper/?wp=157

[7] ETSI EN 300 132-3-1 v2.1.1 (2011-10), European Standard (EN) by ETSI: Operated by rectified current source, alternating current source or direct current source up to 400 V; Sub-part 1: Direct current source up to 400 V

that UPS cannot be considered representative because it violates proposed DC UPS safety standards to achieve its efficiency advantage.

The major differences in UPS performance between the studies are due to differences in the reported performance of the AC UPS systems. The LBNL and EPRI studies used older generation less efficient UPS systems operated at unfavorable light loads. This completely accounts for the greatly increased AC UPS losses found in those studies. **If LBNL and EPRI had used current generation UPS, they would have found the same losses as The Green Grid and Schneider Electric studies, which would have dramatically altered their quantitative findings.**

Comparison of transformer data

The studies all assumed that there was no AC power transformer in the DC distribution system, but the studies varied in their use of transformers in the AC system. Any power distribution system must provide some isolation between the high power system and the IT logic circuits. In all cases studied, this isolation is achieved within the IT device power supply. This means that any transformers used provide redundant and unnecessary isolation. However, in an AC system there can be differences between the utility supply voltage and the utilization voltage by the IT device, which requires voltage step-down transformation. The different studies made different assumptions about the number of transformers in the AC distribution system, and they found different efficiencies for the transformers. The result is that the transformer losses varied as shown in **Figure 4**.

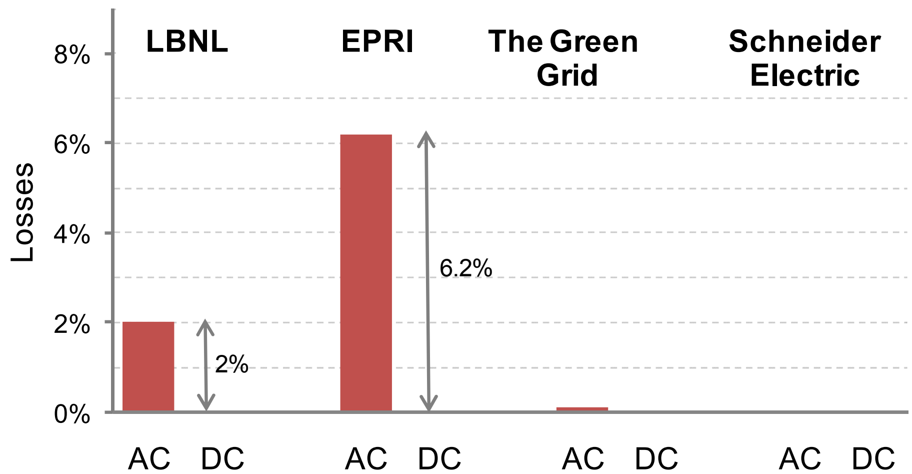

Figure 4

Difference in losses of transformers for the four studies

In the figure, we see that transformer losses are zero for all the DC systems, but for the AC system the losses vary from zero to 6.2% across the studies. This is a major contributor to the variation in quantitative findings of the studies and must be examined.

Differences in number of transformers in the AC system

In both the LBNL and EPRI studies, it was assumed that the utility supply voltage was 480 VAC, and that the IT utilization voltage was 120/208 VAC. Therefore, these systems required a step-down transformer. In the EPRI study, the step-down transformer was placed after a 480 VAC UPS. In the LBNL study, the transformer was placed before the UPS.

In the EPRI study, there are actually **three** transformers in series in the AC power distribution system. There is an optional UPS input transformer, a UPS output transformer, and a PDU transformer. Two of these transformers are actually contained within the UPS, and their losses are accounted for in the UPS losses; this partially accounts for the high UPS loss of that system. Only the PDU transformer contributes to the transformer loss of the EPRI AC system shown in **Figure 4**.

In the Schneider Electric and The Green Grid studies[8], it was assumed that the distribution voltage was 415/240 VAC, using a typical international system design. This system has the major advantage that there is no need for step-down transformers in the power path. This system is currently being deployed in newer North American data centers because it:

- does not require PDU transformers
- eliminates a power conversion step
- uses less copper
- causes the IT loads to operate more efficiently[9]

Link to resource
White Paper 128
Increasing Data Center Efficiency by Using Improved High Density Power Distribution

This approach is described in more detail in White Paper 128, *Increasing Data Center Efficiency by Using Improved High Density Power Distribution*.

Differences in performance of transformers

The LBNL and EPRI studies both assumed the existence of unnecessary transformers, and found significant differences between transformer efficiency.

In the USA, transformer efficiency is established by Federal regulations. For a data center transformer rated in the range of 500 kW, the regulation requires an efficiency of better than 98.7% at 35% load. Transformers with the efficiencies found in the LBNL and EPRI studies would not be compliant with current Federal regulations.

Findings: The LBNL and EPRI studies used transformer-based low-voltage AC architectures which are known to be less efficient than best practice. Furthermore, they used sub-optimal transformer configurations that exaggerated the transformer losses compared to a typical data center. If those studies had used the 415/240 VAC distribution architecture recommended for new designs, the transformer losses would have been eliminated, and the overall results would be more in line with The Green Grid and Schneider Electric studies.

Comparison of wiring data

Wiring losses did not significantly contribute to any reported differences in efficiency between AC and DC systems in the four studies. In general, data center circuits are designed for losses on the order of 1% at full load but, due to load diversity, are operated well below full load, resulting in much lower than 1% wiring losses. There is no fundamental reason why these losses would be significantly different between AC and DC systems.

Findings: Wiring losses are not a significant factor in comparing DC and AC efficiencies in any of the four studies.

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[8] In The Green Grid study, utility voltage of 480V was assumed, which was converted to 415V by the AC UPS. A 480-415 autotransformer was included in the UPS bypass. This transformer is not normally in line with the load and therefore did not contribute significant loss in that study.

[9] The IT load power supplies operate more efficiently at 230V than they do at either 120V or 208V. This widely reported effect is on the order of 1 - 2%.

Determining total energy savings

The above analysis of the four reports is focused on the **efficiency** of the power distribution systems **only**. Another factor discussed in most of these reports is how changes in power distribution efficiency translate to **total energy savings for the data center.** To compute total data center energy savings (the amount saved on the utility bill), any reductions in energy losses are summed across all data center systems, including those like the cooling system that are not powered from the IT load power distribution system.

If a data center were to have only the power distribution and IT load (no cooling energy use or other loads), then any percent improvements to the power distribution system would directly translate to the same improvement in total data center energy. In that case, a 1% improvement in the power distribution system would translate to a 1% reduction in total data center energy use.

However, a real data center includes other loads like cooling, controls, lighting, and diesel standby generator heaters. In this case the energy saved in power distribution reduces heat generated and therefore also can reduce cooling energy requirements. To determine the magnitude of this effect on total data center energy use, it is necessary to understand how the energy use of the cooling system varies with thermal load.

In a typical new data center with a PUE of 1.47 operating at 50% IT load, the cooling system represents about 25% of total energy use. Of the cooling energy use, typically slightly more than half represents proportional losses that vary with the thermal load, the remainder being fixed losses that do not vary with the thermal load. Therefore, typically about 13% of the total energy use is cooling load that is proportional to the thermal load.

If we assume the PUE of a new data center is approximately 1.47, then a 1% savings in the power distribution system gives rise to a reduction of only a 0.86% in total data center energy use[10]. The percent improvement in total data center energy use is **less** than the improvement in the power system, because some of the data center subsystems, like lighting, generator heaters, controls, and humidifiers still draw the same amount of energy even if the power system draws less energy, effectively diluting the effect of the power system savings on total energy use.

In summary, for a typical data center, each watt saved in the power system translates to 1.14 watts in total energy saved, but a 1% improvement in power system efficiency translates to only a 0.86% reduction in total data center energy use. **The percent reduction of total system energy must always be *less* than the change in power system efficiency.**

To show how badly this concept has been reported by the popular press, consider the following typical quote[11]:

"It is expected that the Duke Energy (EPRI study) data center should yield anywhere from 7 to 20 percent energy savings, and those figures can be doubled when the added energy savings realized by the decrease in cooling load are taken into account."

This misleading quote, similar to many other quotes found in the press, suggests that the percent total energy savings will be much more than 7-20%, even doubled (presumably to 14-40%), when the cooling load is taken into account. This "multiplier effect" on percentage

[10] For details on the supporting formulas and calculations, see the section "Overall data center power consumption impact" in White Paper 127, *A Quantitative Comparison of High Efficiency AC vs. DC Power Distribution for Data Centers,* http://www.apc.com/whitepaper/?wp=127

[11] "Utility data centers and DC power", Intelligent utility Dec 15, 2010, http://www.intelligentutility.com/article/10/12/utility-data-centers-and-dc-power

improvements is nonsense, as we have just demonstrated that the percent savings of total energy must always be **less** than the percent improvement in power system efficiency.

Conclusion

The EPRI and LBNL studies that claimed significant efficiency improvements for DC were not using current best practice AC systems for quantitative comparisons.

When those studies are adjusted taking into account newer AC system equipment and architectures, the results closely match the findings of The Green Grid and Schneider Electric studies, which found a very small efficiency benefit for DC.

Curiously, the LBNL study correctly identifies the availability of AC UPS products of 97% efficiency in the report, but then draws conclusions based on 90% efficient AC UPS which it describes as a “best in class” system. This error alone negates all of the 7% efficiency gain for DC found in that study. The widely cited value from the LBNL study of 28% efficiency improvement for DC **is not actually even a finding of that study**, and its origins are explained in the **Appendix**.

The EPRI report used an AC architecture that had three isolation transformers configured in series, as well as an older UPS designed in 1990, which together grossly reduced the efficiency of the AC power system and accounts for the findings of that report. When these factors are accounted for, the widely cited 15% improvement for DC from the EPRI study is reduced to 1%.

The Green Grid and Schneider Electric studies generally agree and find that with new AC equipment the efficiency gain of using a DC system is around 1%. The corresponding reduction in total data center energy use must always be lower than this number, and is typically on the order of 0.86%

The highest efficiency power system for data centers today is an AC 415/240V system with a UPS in Eco-mode. This is actually more efficient than any known DC system.

About the author

Neil Rasmussen is a Senior VP of Innovation for Schneider Electric. He establishes the technology direction for the world’s largest R&D budget devoted to power, cooling, and rack infrastructure for data centers.

Neil holds 25 patents related to high-efficiency and high-density data center power and cooling infrastructure, and has published over 50 white papers related to power and cooling systems, many published in more than 10 languages, most recently with a focus on the improvement of energy efficiency. He is an internationally recognized keynote speaker on the subject of high-efficiency data centers. Neil is currently working to advance the science of high-efficiency, high-density, scalable data center infrastructure solutions and is a principal architect of the APC InfraStruXure system.

After founding APC in 1981, Neil served as Senior VP of Engineering and CTO for 26 years, assuming his current role after APC joined Schneider Electric in 2007. He received his bachelors and masters degrees from MIT in electrical engineering, where he did his thesis on the analysis of a 200MW power supply for a tokamak fusion reactor. From 1979 to 1981 he worked at the MIT Lincoln Laboratory on flywheel energy storage systems and solar electric power systems.

Appendix: Misleading citations of the LBNL study

One of the most widely cited quantitative claims regarding the efficiency differences between DC and AC power distribution systems for data centers is that "LBNL finds that DC is 28% more efficient than AC". This number comes from the following misleading section of the LBNL report:

"*In this case, an improvement of over 28% is possible in an average data center. This means the DC distribution system, as demonstrated, will have the potential of using 28% less energy than the typical AC system found in today's data centers. Since data center HVAC loads are typically about the same as the IT load, this means that a 28% improvement in distribution and conversion also means a 28% overall facility level efficiency improvement*."[12]

This particular part of the report is at odds with the measured and calculated data of 7.3% from the report as shown in **Table ES1 of that report**[13]. This section of the report does not actually refer to measured or calculated data, but is based on speculative and unreasonable assumptions such as the supposition that a DC powered server would be 19% more efficient than an AC powered server, when in fact all of the studies found that this difference is more in the range of 1 to 1.5%. In fact, modern server power supplies are routinely achieving 95% overall efficiency, so a 19% improvement is an absurd and impossible gain which would make the power supply well over 100% efficient.

A reading of the LBNL report suggests that the 28% percent figure was intended to represent the comparison of a new DC system to an older AC system with performance representative of the 1980's. Their description of "the typical AC system found in today's data centers" in the above quotation is a reference to a much older hypothetical AC system that might still be in service, and not to a new and more efficient AC system. A review by Schneider Electric of the efficiency of equipment from the 1980's does suggest it is possible that a typical power system was over 20% less efficient than today's equipment, particularly due to inefficiency of IT power supplies of that era. However, virtually none of that equipment is in service today. The correct alternative to a proposed DC power system is a best-practice **current generation** AC system, which, as this paper has shown, has nearly the same efficiency as proposed DC systems.

The above referenced quote is also wrong about how energy saved in the power system affects overall facility level energy use. First, new data centers do not have HVAC loads "about the same as the IT load"; the HVAC load is much less than the IT load in a new data center, ranging from 10% to 35% of the IT load. Second, savings in the power distribution system do not directly translate to proportional savings in the HVAC load. Only the fraction of the HVAC energy consumption that is proportional to the heat load will vary. Most cooling systems have fans, humidifiers, and other components that consume the same amount of power regardless of the heat load on the system. Furthermore, some of the power plant may be outside of the cooling envelope and is therefore not cooled by the HVAC system. **Contrary to the statement in the above quote, the total percent energy improvement will always be significantly less than the percent power distribution efficiency improvement.**

The unfortunate and misleading 28% value which is widely cited as the conclusion of that report has caused much confusion in the market and repeated citation of that value must be viewed as misinformation and even as disinformation; LBNL should issue a corrective clarification retracting that misleading part of the report.

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[12] http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReport.pdf#page=8
[13] http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReport.pdf#page=7

Resources

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