A Quantitative Comparison of High Efficiency AC vs. DC Power Distribution for Data Centers

White Paper 127

Revision 4

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> Executive summary

This paper presents a detailed quantitative efficiency comparison between the most efficient DC and AC power distribution methods, including an analysis of the effects of power distribution efficiency on the cooling power requirement and on total electrical consumption. The latest high efficiency AC and DC power distribution architectures are shown to have virtually the same efficiency, suggesting that a move to a DC-based architecture is unwarranted on the basis of efficiency.

Introduction

The quest for improved efficiency of data centers has encouraged a climate of innovation in data center power and cooling technologies. One widely discussed energy efficiency proposal is the conversion of the data center power architecture to DC from the existing AC. Numerous articles in the popular press and technical magazines have made claims for the advantages of DC power distribution, and companies such as Intel, Schneider Electric, and Sun Microsystems have participated in technology demonstration projects.

There are five methods of power distribution that can be realistically used in data centers, including two basic types of alternating current (AC) power distribution and three basic types of direct current (DC) power distribution. These five types are explained and analyzed in the related White Paper 63, *AC vs. DC Power Distribution for Data Centers*. A key finding in that paper, which is generally supported in the published literature, is that two of the five distribution methods, one AC and one DC, offer superior electrical efficiency. This paper focuses on comparing only those two highest efficiency distribution methods. **Unless there is a major change in data center power technology, one of these two methods is very likely to become the preferred method for distributing power in future data centers down to the pod or rack level**. It is possible that both methods would exist within the pod or rack level.

The efficiency performance values for the AC power distribution system described in this paper are readily available numbers based on actual equipment that can be purchased today. Commercial 380V DC power distribution systems are not widely available today, so the efficiency values for the DC power distribution system are based on preliminary manufacturers' data, estimates, and calculations available. Citations and references are provided for all efficiency values used in this paper, so that the findings can be independently tested and verified.

Changes in power distribution efficiency affect the total electrical power consumption of the data center. However, the impact is mathematically complex because of two factors:

1. Variations in electrical power distribution efficiency affect the heating load and consequently the air conditioning power consumption.
2. There are significant power loads in the data center that do not receive power through the power distribution system under study.

This paper explains these effects in detail and shows how improvements in electrical power distribution efficiency quantitatively translate into reductions in total electrical consumption.

Background

It is true today that there are existing data center installations with poor designs and older power distribution technology that are operating at very low efficiencies. Schneider Electric has observed power system efficiencies of 30% and even less in operating data centers (exclusive of the cooling system). This represents a tremendous waste of electrical energy since much of this inefficiency is avoidable. The observed inefficiencies are primarily due to the following factors:

- Inefficient IT device power supplies
- Inefficient transformer-based power distribution units (PDUs)
- Inefficient UPS systems
- Operation at loads well below the design rating of the system, which amplifies all of the above losses

There have been great improvements in efficiency of IT device power supplies and UPS systems since 2007. This means that an AC distribution system installed today is typically much more efficient than installations prior to 2007. In addition, modular scalable UPS systems have made it simpler to right-size a UPS to the load, preventing the electrical inefficiency due to gross underutilization frequently seen in the past. Transformer-based PDUs remain a significant source of loss in many North American installations, but are not prevalent outside of North America. The AC system analyzed in this paper is based on the European standard of 400/230 V distribution. The application of 400/230 V AC power distribution in North America is discussed in detail in White Paper 128, *Increasing Data Center Efficiency by Using Improved High Density Power Distribution*.

DC distribution has been proposed as a way to achieve higher efficiency based on the following three premises:

1. It may be possible to build a DC UPS that is higher in efficiency than an AC UPS
2. The elimination of power distribution unit (PDU) transformers will reduce electrical losses
3. It may be possible to improve the efficiency of the IT equipment power supply itself, beyond the improvements possible in an AC input design

This paper examines and quantifies all of these concepts and reveals the following:

- The latest generation of AC UPS systems has as much as five times less loss than previous generations of AC UPSs, and there is no longer any evidence that a DC UPS of greater efficiency can be created
- Transformers in PDUs are a significant source of inefficiency, but don't exist outside of North America and are eliminated in new high efficiency AC power distribution architectures
- The efficiency improvements in the IT equipment power supply resulting from conversion to DC input are proving to be much lower in practice than was originally assumed

In many published articles, expected improvements of 10% to 30% in efficiency have been claimed for DC over AC. But, as you would not compare the performance of a new server technology to the performance of a server made ten years ago, it is similarly inappropriate to compare hypothetical DC power distribution efficiency to the efficiency of older legacy AC power distribution systems. The important comparison is not between past and future alternatives, but between current and future alternatives.

The data in this paper demonstrates that the best AC power distribution systems today already achieve essentially the same efficiency as DC systems, and that most of the quoted efficiency gains in the popular press are misleading, inaccurate, or false. And unlike virtually all other articles and papers on this subject, this paper includes citations and references for all of the quantitative data.

The two high efficiency power distribution options

The introduction explained that two alternative power distribution systems have emerged as candidates for building future high efficiency data centers. One system is based on the existing predominant 400/230 V AC distribution system currently used in virtually all data centers outside of North America and Japan. The other system is based on a conceptual 380 V DC distribution system supplying IT equipment that has been modified to accept DC power. These systems are diagrammed in **Figure 1** and **Figure 2**.

Figure 1

High efficiency AC distribution (in common use outside North America)

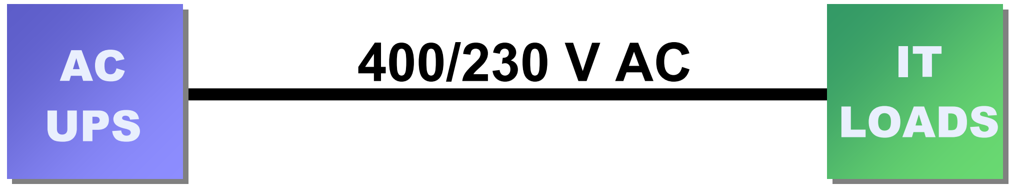


Figure 1 represents the first candidate. It is the common AC distribution system used outside of North America and Japan. Note that in today's standard North American power distribution system, the UPS voltage would be 480 V AC and there would be an additional block in the diagram representing a PDU transformer to convert 480 V to 208/120 V AC. In this figure the PDU transformer and the associated losses are eliminated because there is no need to step down the UPS output voltage before supplying it to IT loads at 230 V.

Figure 2

High efficiency DC distribution (hypothetical)

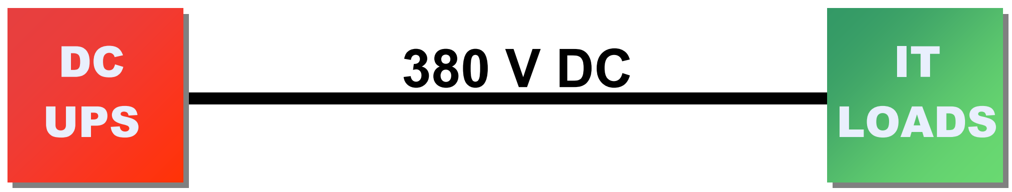


Figure 2 represents the second candidate use to distribute 380 V DC. IT devices designed to operate from 380 V DC power are required to allow this to work. This system has been proposed in the literature with a variety of different DC supply voltages, such as 300, 380, 400, and 575 V. However, a consensus in the literature has developed around 380 V as a preferred standard, and the analysis in this paper is based on this 380 V DC system. In the proposed international ETSI standard[1] for DC distribution for data centers, the 380V DC system is actually created with the midpoint at ground potential to keep the maximum system voltage to ground to within +/- 190 V.

Preview of analysis

In the sections that follow, it will be helpful to know the general structure of the model and the data that needs to be quantified to support the model.

The three power path segments

Figure 3 shows the basic power path in a typical data center when using high efficiency power distribution. Note the absence of PDUs, which are not needed in the two power distribution methods under consideration. The power path is divided into three segments:

- UPS
- Distribution wiring
- IT device power supplies (PSUs)

[1] 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

Efficiency data for the model

Subsequent sections of this paper will examine and quantify efficiency data for each of these three segments of the power path. The goal is to establish efficiency data as a function of load, which will result in an efficiency curve for each segment similar in shape to those at the bottom of **Figure 3**. This efficiency data will then be incorporated into a model that can be used to compare the efficiency of power configurations.

The 50% load point is marked on the efficiency curves because the baseline case in the model will use efficiency values at 50% load.

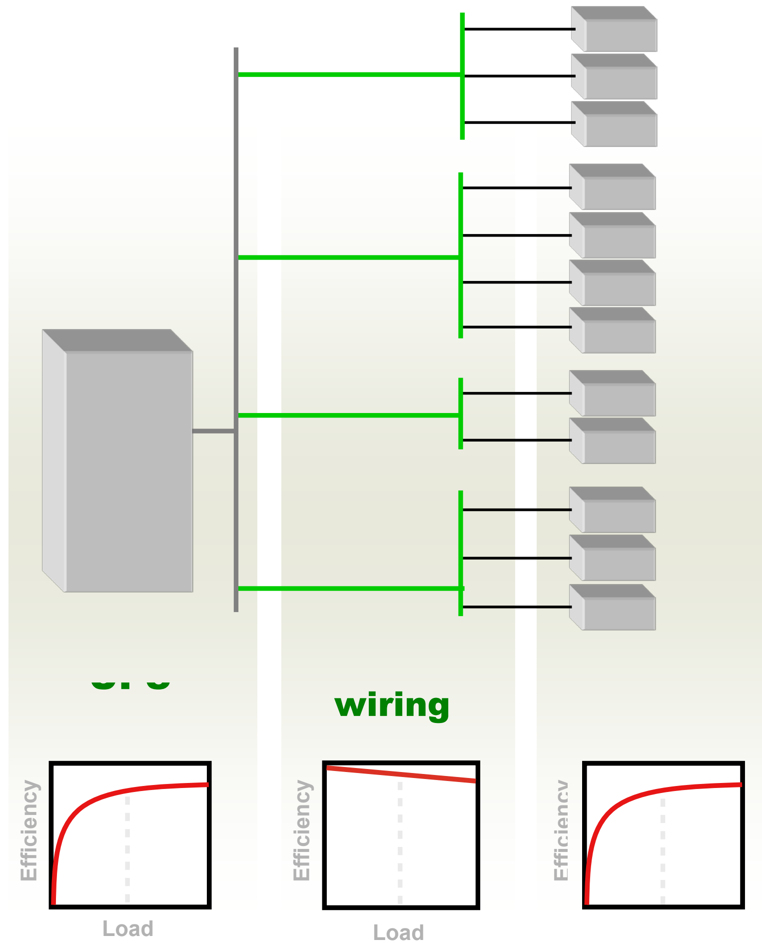


Figure 3

Data center power path: three segments, three efficiency curves

Baseline operating load for the model (50%)

The data clearly shows that the efficiencies of the devices in a power distribution system are not fixed numbers, but instead vary with the applied load – which is why efficiency is correctly represented as an *efficiency curve*, not a single number. Therefore, any calculation of power distribution efficiency is incomplete without considering the actual operating load for each segment of the power path.

Most of the prior work on the subject of power distribution efficiency does not provide information on the effect of load variation, which can be significant. In this paper, we will choose a baseline load that is representative of typical installations, and then explain how efficiency varies with load. Choosing a baseline operating load simplifies the initial discussion by providing a reference point for comparison of AC and DC, but it *does not constrain* *the actual model*, which comprehends that efficiency is a curve that varies with load – in real installations, the operating load (fraction of capacity) will be different for each of the three segments of the power path, and can be varied dynamically in the interactive model (see **Figure 8**).

For the following presentation and comparison of AC and DC power distribution, the baseline load will be chosen as 50%. This is within the operating limits of all three segments of the data center (**Figure 3**). Here is how 50% load relates to each of the three data center segments:

- **UPS**
  For a non-redundant (1N) system, 50% is a typical operating point. For a redundant (2N) system, 50% represents the maximum operating point (i.e., full load shared across 2 UPSs).
- **Distribution wiring**
  Similar to UPS loading, 50% is a realistic operating load for non-redundant (1N) wiring. For a redundant, dual path, (2N) wiring system, 50% is the maximum you would see on either feed. (In fact, US electrical code restricts loading to 80%, which effectively limits the per-feed limit to 40%). In any case, it should be noted that the operating load on distribution wiring has little effect on overall efficiency because wiring efficiency is in the very narrow and high range of 99-100%.
- **IT power supplies**
  IT equipment has either one or two internal power supplies. With a single power supply, 50% operating load is in the middle of the range (and typical of “idle” loading, which is where a large portion of server time is spent), and for dual-power supply servers, 50% represents the maximum operating point (i.e., full load shared across 2 power supplies).

As will be shown later by the actual efficiency curves for these three segments, there is not a great difference in efficiency for operating loads in the neighborhood of the 50% mark, so the exact location of this point is not very significant.

Efficiency of the UPS

The AC distribution architecture starts with a UPS to create the AC distribution bus, and in the DC architecture, a DC UPS – sometimes referred to as a DC plant or rectifier – creates the DC distribution bus.

In the case of the AC UPS, products currently exist in the marketplace that have verifiable performance – either they have published efficiency specifications or their performance can be measured. Unfortunately, Schneider Electric has found many of the published specifications to be inaccurate and not representative of real-world performance. For purposes of this analysis, we will use the efficiency data from the only known UPSs with independent laboratory measured and certified efficiency ratings.

Figure 4 shows the efficiency of various commercially available AC UPS and DC UPS systems. For convenience, the graph is summarized in **Table 1**.

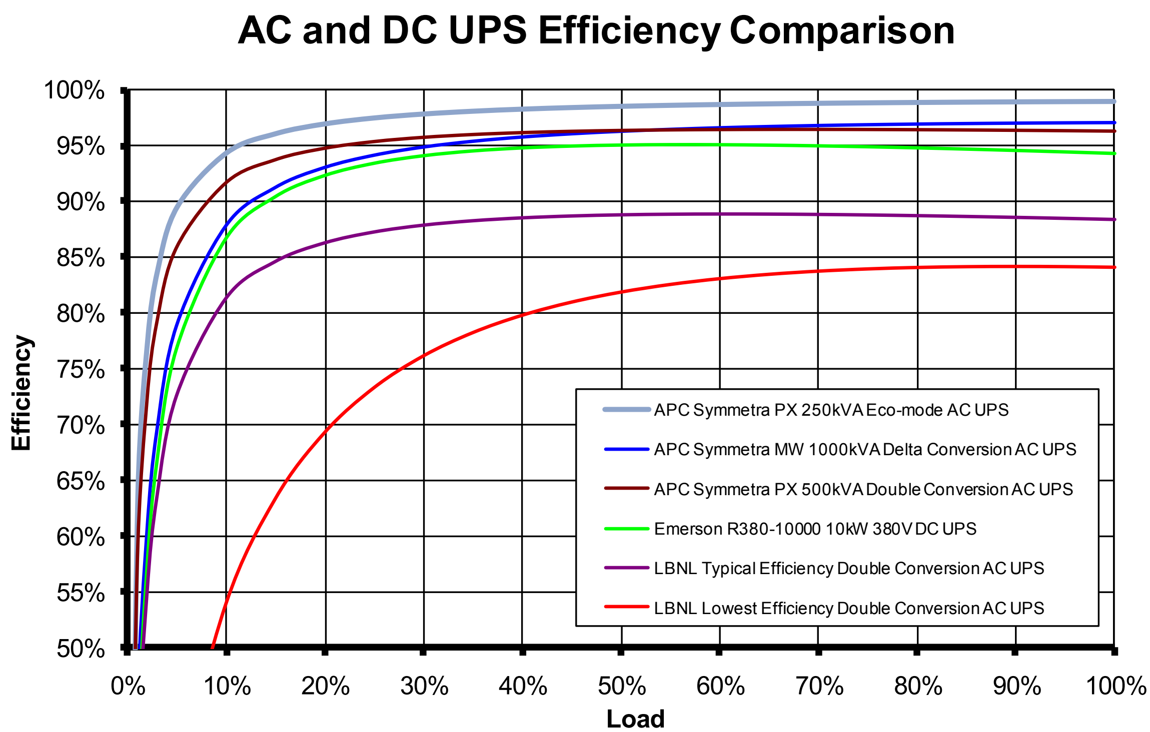


Figure 4

Efficiency of several commercially available AC and DC UPS systems

Table 1

*Summary of UPS efficiency data from **Figure 4***

UPS	Load			
	25%	50%	75%	100%
Symmetra MW (Delta conversion AC)	94.1%	96.2%	96.9%	97.0%
Symmetra PX (Double conversion AC)	95.5%	96.3%	96.4%	96.3%
Symmetra PX Eco-mode	97.4%	98.5%	98.8%	98.9%
Emerson R380 (DC UPS)	93.4%	95.1%	94.8%	94.2%
LBNL Typical Efficiency (Double conversion AC)	87.3%	88.8%	88.8%	88.4%
LBNL Lowest Efficiency (Double conversion AC)	73.3%	81.9%	84.0%	84.1%

AC UPS efficiency value for the model

The 1,000 kVA Symmetra MW delta-conversion UPS has an efficiency rating of 96.2% at 50% load, the 500 kVA Symmetra PX double-conversion UPS has an efficiency rating of 96.3% at 50% load – all certified by the testing laboratories of TÜV[2]. These ratings are not in an eco or bypass mode but are with the output regenerated and conditioned by the on-line

[2] Symmetra MW - TÜV Test Report Number 21113774_010, September 26, 2005. Symmetra PX - TÜV Test Report IS-EGN-MUC/ed, June 12, 2007.

output inverter. However, if a UPS using eco-mode is used, efficiency is greatly increased to 98.5% at 50% load. This analysis will use the Symmetra PX, with an AC efficiency of 96.3% at 50% load, and will also provide results for eco-mode.

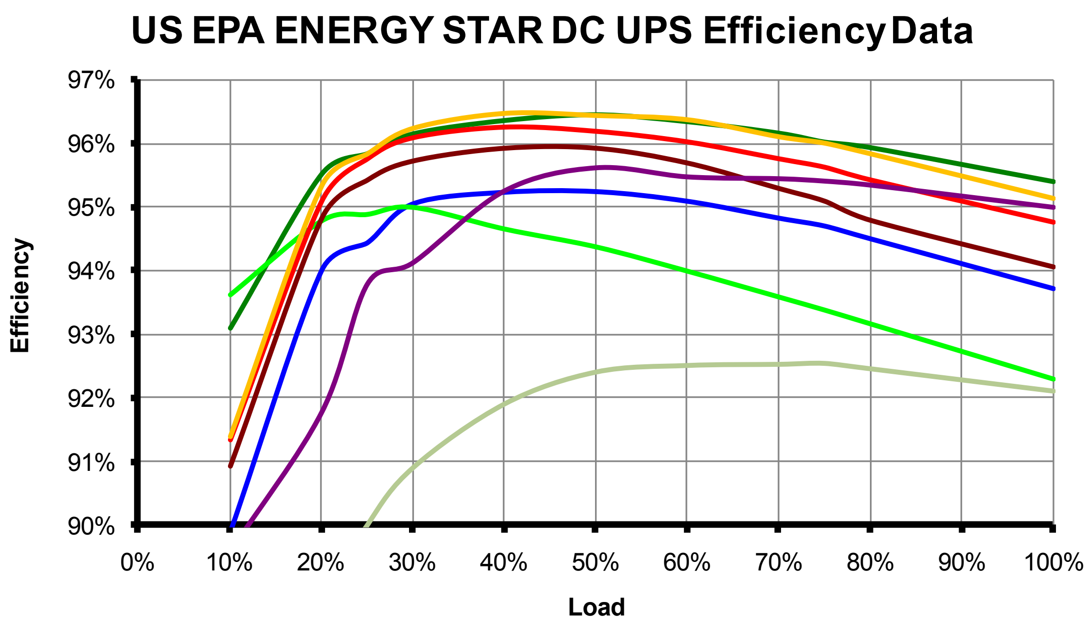
The remaining two curves show legacy-efficiency, double-conversion UPSs as measured by a 2005 LBNL study[3].

DC UPS efficiency value for the model

In the case of a DC UPS, commercial products with standard specifications are not widely available. Emerson provided data to The Green Grid which describes a DC UPS efficiency (at 50% load) as 95.1%, as shown in **Figure 4**. Delta Electronics has published an efficiency of 97.7% for a DC UPS, however this design does not meet the grounding requirements of the ETSI 300 international standard or any proposed DC standard[4]. The US EPA is developing an ENERGY STAR® standard for DC telecommunication rectifiers that will require an efficiency of 95.5% to qualify for the ENERGY STAR rating. In development of the ENERGY STAR standard, the EPA published data on the efficiency of DC telecom rectifiers as shown in **Figure 5**.

Figure 5

Efficiency of several commercially available DC Telecom plants (Vendor names not published by EPA)



The ENERGY STAR efficiency data from **Figure 5** is for DC rectifiers for 48 V telecom plants, which can be adapted for 380 V DC use. While these products cannot be directly used for 380 V DC, this data shows that there is potential to make DC UPS that are around 96.5% efficient, which is more efficient than the current first generation DC UPS systems such as the 95.1% example from **Figure 4**.

Reference values for UPS efficiency at 50% load	
AC UPS	96.3%
AC UPS (eco-mode)	98.5%
DC UPS	96.5%

[3] Lawrence Berkeley National Labs report: High Performance Buildings: Data Center – Uninterruptible Power Supplies (UPS) December 2005, Figure 17, http://hightech.lbl.gov/documents/ups/final_ups_report.pdf

[4] The international ETSI 300 standard will require midpoint ground reference for DC UPS. This paper will only consider data from DC UPS that meet the international safety standards.

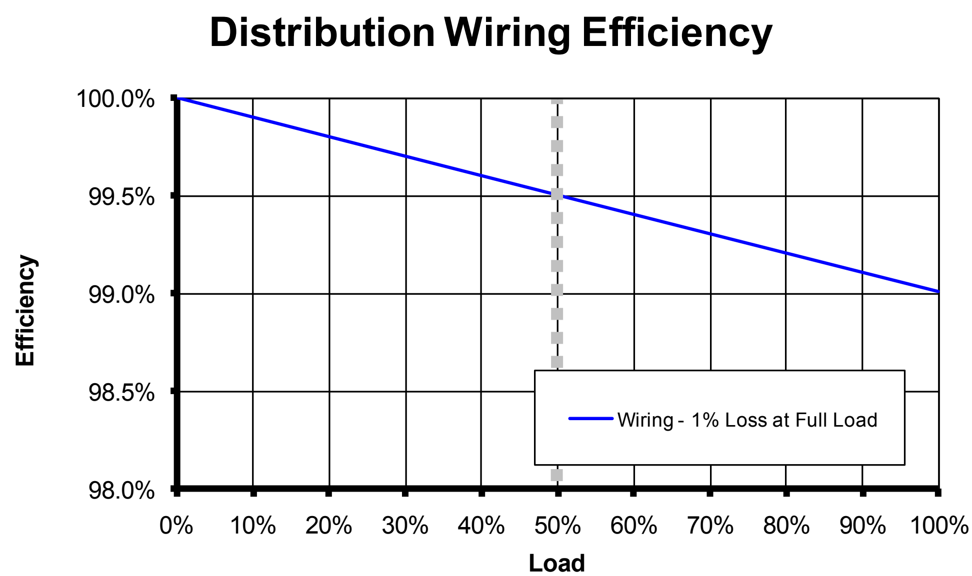
Although the best available 380V DC plants that meet international standards are currently 95.0% efficient, for this paper we will assume that it is possible to make DC UPSs that match the 96.5% efficiency of the best ENERGY STAR telecom rectifiers.

Efficiency of the distribution wiring

The wiring between the AC or DC UPS and the IT loads has electrical loss. The losses depend on the operating current, the size of the wiring, and the length of wire. A data center hosts hundreds or even thousands of different wires, and the losses of each wire must be added to compute the total loss. **Figure 6** illustrates the distribution wiring efficiency as a function of load.

Figure 6

Distribution wiring efficiency



It is possible to estimate the wiring loss for a typical installation. Wire sizes are dictated by circuit capacity ratings, and the average wire length is typically known. A common design value for wiring loss is 1% of the load power at full load. The losses in the distribution wiring vary with the square of the load. Each time the load is halved, the wiring losses fall by a factor of four. For a 50% load data center, the wiring efficiency would be 99.5%. For this reason, wiring losses are negligible in most data centers.

Reference values for wiring Efficiency at 50% load	
AC distribution wiring	99.5%
DC distribution wiring	99.5%

Note that the wiring loss is the same for a DC or an AC installation. A slight difference may exist in the amount of copper used, but the efficiency is the same. The wiring loss does not give rise to any differences of efficiency between AC and DC systems.

Efficiency of the IT power supply

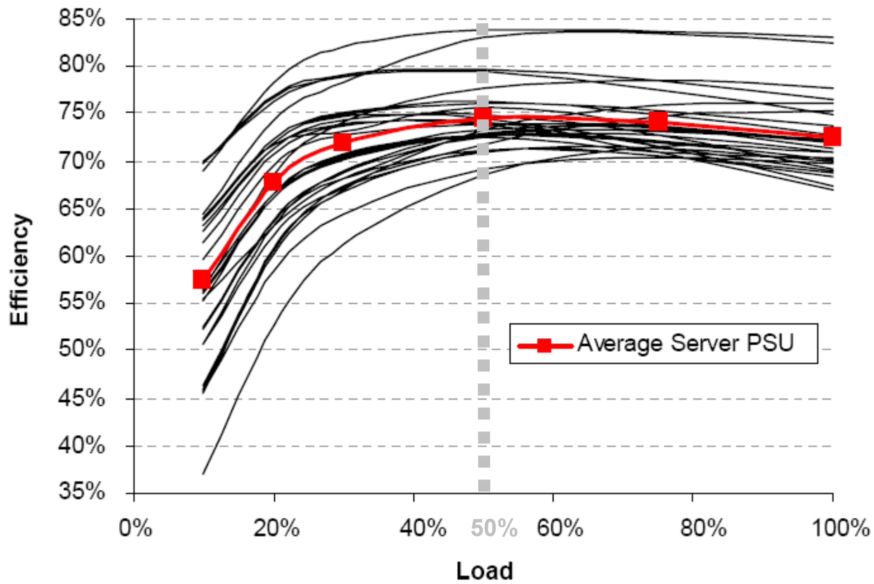
Modern IT equipment has one or more internal power supply units (PSUs) that convert incoming AC power to a 12 V DC bus, which supplies the individual cards or subsystems in the chassis[5]. These PSUs represent an opportunity for efficiency improvement.

[5] In this "distributed power system architecture," the individual cards or subsystems generate their specific local power requirements (e.g., 1.1V, 3.3V, 5V) from the 12V bus, using on-board power converters. The PSU is often a user-replaceable module plugged into the chassis.

In past generations of servers, the efficiency of PSUs was approximately 75% at 50% load (see **Figure 7**)[6].

Figure 7

Lawrence Berkeley National Laboratory efficiency of past generation server PSUs



The low efficiency of these older power supplies suggested that large gains might be possible if high voltage DC input operation were developed. However, the most recent AC designs are now routinely 92% efficient or greater over a broad range of operating loads, according to published power supply efficiency data from various manufacturers. One of the world's largest power supply manufacturers, Delta Electronics, has published the power supply efficiency data of **Table 2**[7].

Table 2

Difference between AC and DC power supply efficiencies (Delta Electronics)

Power Supply	Load 20%	50%	80%	100%
AC (208V)	85.0%	93.2%	93.7%	93.6%
DC (400V)	85.5%	94.1%	94.8%	94.5%
Difference	0.5%	0.9%	1.1%	0.9%

Note that the improvement in efficiency gained by DC operation is 0.9% at 50% load, and even less at the lighter loads where many IT power supplies operate. For this analysis, we will use the Delta Electronics data at 50% load.

Reference values for power supply Efficiency at 50% load	
AC IT power supply	93.2%
DC IT power supply	94.1%

[6] Lawrence Berkeley National Laboratory: "High Performance Buildings: Data Centers – Server Power Supplies" December, 2005 http://hightech.lbl.gov/documents/PS/Final_PS_Report.pdf.

[7] http://www-03.ibm.com/procurement/proweb.nsf/objectdocswebview/file7+-+delta+-+lai+-+380vdc+data+center+ibm+symposium/$file/7-delta-lai-380vdc+data+center+ibm+symposium.pdf, accessed February 13, 2012

Overall power path efficiency comparison

The overall efficiency of the power path is the product of the efficiencies of the UPS, the distribution wiring, and the IT power supply given above. This is a simple calculation, as shown in **Table 3**.

Table 3

Overall power distribution efficiency calculation at 50% load comparing high efficiency AC and 380 V DC distribution methods

	UPS		Distribution wiring		IT power supply		Overall efficiency
DC	96.5%	X	99.5%	X	94.1%	=	90.35%
AC	96.3%	X	99.5%	X	93.2%	=	89.30%
AC (eco-mode)	98.5%	X	99.5%	X	93.2%	=	91.34%

Therefore, the high efficiency DC system has a 1.05% efficiency advantage in power distribution efficiency over the high efficiency AC system. However, when the AC UPS is operated in eco-mode, **the DC system is actually less efficient by 0.99%**. This analysis is for 50% operating load on all segments of the power path. As can be seen from the relatively flat shape of the efficiency curves at 50% load, there is not a great variation in efficiency in the load range surrounding 50%.

The results of this analysis are sensitive to the assumptions and data previously described in this paper. The confidence in those assumptions and data and the potential range of outcomes that might result from future technology improvements are described in the **Appendix** of this paper, titled “Confidence in the results”.

This efficiency difference is only for the power distribution system – the impact on overall data center power consumption requires further analysis as explained in the next section.

Overall data center power consumption impact

Any percentage efficiency gains in the power distribution system do not directly translate to an equal percentage gain in overall data center power savings. Any savings in power distribution losses reduces the heat in the data center which reduces the cooling load. Therefore a watt saved in power distribution will actually save more than a watt of the overall data center demand. **However, a 1% gain in power distribution efficiency does NOT translate to more than a 1% gain in total data center efficiency**. In fact, a 1% gain in power distribution efficiency actually leads to *less* than a 1% reduction in total data center energy use.

The actual computation for the reduction in electrical consumption resulting from a change in power distribution efficiency is as follows:

$$\Delta P = P - P'$$
$$\Delta P = 1 - [(1 - \Delta\eta_{PD}) \times (IT_P + PD_P + ACP_P) + L_P + ACF_P]$$

Where **P** is the baseline AC system power consumption, referenced to 1, and **P'** is the power consumption after a change in power distribution efficiency. The other values in the equation are defined in **Table 4**, along with their values for a typical data center with a PUE of 1.47.

Table 4

Variables used for computation of electrical load reduction

Variable	Description	Typical value for PUE of 1.47
$\Delta\eta_{PD}$	Change in power distribution efficiency	Input variable
IT_P	% of total data center power consumed by IT load	68%
PD_P	% of total data center power consumed by baseline power distribution	5%
ACP_P	% of total data center power consumed by air conditioner losses that vary with load	13%
L_P	% of total data center power consumed by lighting load	2%
ACF_P	% of total data center power consumed by fixed air conditioner losses	12%

When these values are entered into the overall data center power reduction equation above, the resulting change in overall consumption from a 1% change in the power distribution efficiency is 0.86%. **The overall change in data center energy consumption is *less* than the change in power distribution efficiency**. This finding should not be surprising when it is understood that a significant part of the data center power consumption (in particular, the cooling system) does not pass through the power distribution system, and when it is understood that reducing the power distribution losses does not affect the fixed component of the cooling losses, it only affects the proportional component of the cooling losses (losses that vary with cooling load).

When this calculation is applied to the AC and DC power distribution efficiency result of the previous section, we find that the power distribution efficiency improvement by converting from AC to DC of 1.05% will cause a reduction of overall electrical consumption of 0.90%.

Use of DC instead of AC causes a reduction in total energy consumption of less than 1%. If the UPS uses eco-mode, use of DC actually increases total energy consumption.

Note that this finding directly contradicts published information in other studies. Many superficial analyses suggest that a watt of power saved by conversion to 380 V DC leads to "double or quadruple the impact" on the overall data center power consumption[8]. In fact, the only power saved beyond the distribution power is the proportional fraction of the air conditioning losses that vary with load (proportional loss). For a well designed modern data center[9], these variable losses are on the order of 13% of the IT load, so **a watt saved in power distribution saves only 1.13 watts of overall data center power.**

[8] Guy Ailee, Milan Milenkovic, and James Song, Data Center Energy Efficiency Research @ Intel Day , June 2007. http://download.intel.com/pressroom/kits/research/poster_Data_Center_Energy_Efficiency.pdf

[9] Doug Garday and Daniel Costello, Intel white paper, *Air-Cooled High-Performance Data Centers: Case Studies and Best Methods*, November 2006. http://www.intel.com/content/dam/www/public/us/en/documents/white-papers/date-center-efficiency-air-cooled-bkms-paper.pdf

AC vs. DC efficiency calculator

The interactive TradeOff Tool™ in **Figure 8** determines the power path efficiency and the overall input power percentage reduction for four different scenarios. The effect of changing the efficiencies of the various power path components on the power path efficiency and on the overall input power loss reduction can be investigated using this tool.

The baseline or **Legacy AC** case represents an older data center with typical efficiency values for AC UPS, PDU, and IT power supply, and assumes IT power supplies operating at 208 V AC. The **Modern AC** case represents a new data center with the latest generation of high efficiency AC UPS, PDUs and IT power supplies. The **415 V AC** case uses the same modern components as best practice AC, but it eliminates the PDUs (and their associated transformer losses), and assumes IT power supplies operating at 230 V AC with an efficiency benefit of 0.5% over 208 V AC. The **380 V DC** case uses a DC UPS, no PDUs, and IT power supplies having a slight efficiency benefit over 208 V AC as shown in **Table 2**. All cases assume the same distribution wiring efficiency.

> **> Using the AC vs. DC efficiency calculator**
>
> **This is an interactive calculator referenced in this white paper**
>
> Flash Player version 9 or later is required -- click here to find out what version you have
>
> To download Flash Player, click here
>
> Click to access to the Data Center AC vs. DC Calculator

In this efficiency calculator, all the key variables affecting the efficiency are adjustable by dragging the sliders. The tool starts with baseline default values for all variables, as described in this paper, based on a 50% load.

The default "Cooling Losses per Unit Heat Load" values provided in the calculator tool are typical values for a 50% IT load. When modeling operating loads near 100% IT load, the user should manually adjust "Cooling Losses per Unit Heat Load" downward, to reflect an increase in cooling efficiency at full load. The model includes an input for lighting load (2% for traditional, 0.5% for high efficiency) for the input power reduction calculation. If there are additional fixed loads such as a network operations center, the percent input power loss reductions will be reduced for all the scenarios.

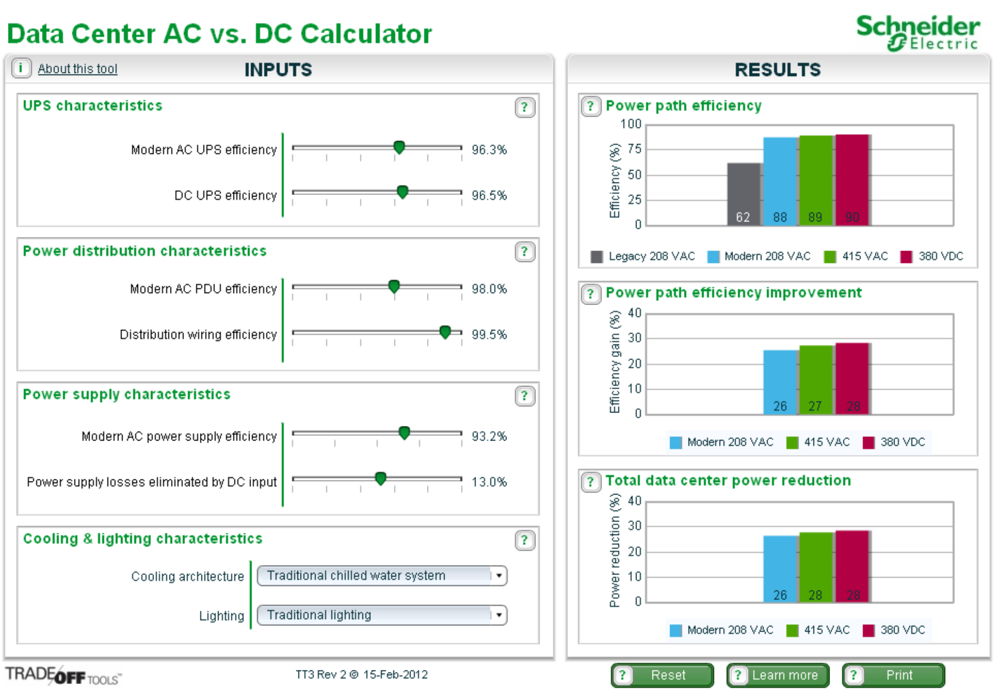


Figure 8

AC vs. DC Calculator Tool for comparison of power distribution architectures

Special consideration for North America

In general, North American data center power distribution efficiencies are lower than the rest of the world due to the historic use of transformer-based power distribution units (PDUs). In North America, UPS power commonly operates on three-phase 480/277 V AC, which is stepped down by PDU transformers to three-phase 208/120 V AC for distribution to the IT loads. By contrast, most regions outside of North America use three-phase 400/230 V UPS power, which is supplied directly to the loads without any step-down transformer. The step-down transformer represents a substantial loss in most designs, especially because the sum total of the installed step-down transformer ratings is typically much larger than the UPS rating, which means that the transformers are underutilized. Furthermore, in a high density data center, the transformers consume significant floor space and constitute a significant floor weight load. For a detailed discussion of this problem and how the 400/230 V distribution system can be used in North America, see White Paper 128, *Increasing Data Center Efficiency by Using Improved High Density Power Distribution*.

In some North American installations, it may be necessary to install an auto-transformer to adapt existing 480/277 V power to the 400/230 V standard. The use of an auto-transformer means that the transformer kVA rating is only 17% of the system power rating, which allows the transformer to operate at high efficiency. For systems in North America where an auto-transformer is needed, the efficiency of the power distribution system will be reduced due to the auto-transformer losses. This will reduce the efficiency for some AC distribution systems in North America by approximately 1%. However, there is a proposal among the OEM manufacturers to widen the input range of power supplies to include 277 V AC that is already present in North American 480/277 V system. If this is accomplished, not only will the need for an auto-transformer be eliminated, but there is a significant improvement in the efficiency of the power supply that would result in the AC distribution system having about the same or slightly better overall efficiency than the 400/230 VAC system used in this study.

Hybrid AC-DC power distribution

This analysis has compared AC and DC distribution as alternative systems. However, it is possible to consider hybrid systems where distribution is AC for part of the path and then converts to DC for the remainder of the path. In particular, supplying unprotected AC down to the pod or row or rack level in a data center and converting to DC for the final distribution to the IT equipment is an approach that has been used in some published designs such as the Open Compute design by Facebook. In such a hybrid design the UPS can be placed in either the AC part of the path or the DC part of the path. The principles for efficiency analysis used in this paper can be readily applied to such systems.

It can be shown that such hybrid systems have an efficiency which is essentially equal to the DC efficiency found in this paper if the hybrid system uses a DC UPS. However, if a hybrid system uses an AC UPS, then it still would require an AC/DC rectifier plant in series which would lead to an efficiency worse than either the AC or DC efficiency found in this paper. Therefore, we expect any hybrid systems to utilize a DC UPS.

Conclusion

There are significant losses in the power distribution systems of existing data centers, and it is in the interest of all data center operators to reduce these losses in new data centers, and, if possible, in existing data centers.

Most data center operators can and should specify high efficiency into their new AC designs, and solutions are available today to achieve very high power distribution efficiency. 380V DC adoption will become a viable alternative as safety regulations are created and DC power distribution devices and standard 380 V DC input IT products become widely available.

For the future, customers and suppliers should consider if DC will become a realistic alternative to AC. Because the efficiency of the most recent generation of correctly-designed high efficiency AC power distribution systems are so high to begin with, there is simply very little room for a DC alternative to provide a meaningful improvement. Using the available data, **the most efficient AC systems using eco-mode are actually 0.99% *more* efficient than DC systems.** Even if eco-mode is not used, the efficiency advantage of DC is only 1.05% (see **Table 3**), corresponding to a data center facility energy savings of only 0.90%.

Any and every gain in efficiency is worthwhile. **However, on the basis of efficiency alone, it does not appear justified to make massive changes to the IT, engineering, installation, and power industries over a course of 10 years for a gain of less than 1%, particularly when much larger gains are quite feasible by focusing on improvements to the cooling systems of data centers[10].** In fact, very minor adjustments in cooling system design or operating settings result in changes in data center power consumption that dwarf those possible by changing data centers from AC to DC.

It is true that there are many data centers operating today – and even under construction today – that have overall power distribution efficiency that has not been optimized, which will result in the waste of as much as 10% of all the power used by those data centers. DC distribution has been proposed to save this energy, but could take years to implement. However, **there are newer AC approaches that achieve virtually the same efficiency gains but can be implemented now**.

Why do other studies on DC power report significantly different results?

The findings of this study are dramatically different from the claims made in many published articles. Journalists have written hundreds of articles suggesting that studies have shown improvements of 7%, 10%, 15%, 28% and even 40% in efficiency through the use of DC. However, the findings of this paper are in substantial agreement with the findings of a similar study by The Green Grid[11]. One clear finding is that there are mathematical limits to the improvement possible, and that claims of 15% or larger improvements are simply not theoretically possible.

There are two published studies, by Lawrence Berkeley National Laboratory[12] and the Electric Power Research Institute (EPRI)[13], that are reported as finding efficiency improve-

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[10] ROI of Cooling Energy Efficiency Upgrades http://www.thegreengrid.org/~/media/Presentations/2011EMEATechForum_ROIofCoolingEnergyEfficiencyUpgrades.pdf?lang=en, accessed on February 15, 2012

[11] 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

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

ments from DC of 28% and 15%, respectively. (The widely publicized 28% figure is misleading because the report actually only found a 7.3% improvement.) These two studies incorrectly represent the performance comparison for new data centers because the AC system used was of an inefficient design from the 1990 timeframe. If newer designs were used, these reports would have reported efficiencies close to those found in this report and in The Green Grid report.

Due to the controversy and misinformation about the findings of different studies regarding efficiency of DC power distribution, Schneider Electric has written a detailed report comparing the four best-known studies on this subject in White Paper 151, *Review of Four Studies Comparing Efficiency of AC and DC Distribution for Data Centers*. In that paper, we identify the mistakes and assumptions that have led to inflated claims for efficiency improvements from DC, and cross check and validate the findings of this paper with the findings of other published papers.

About the authors

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.

James Spitaels is a Consulting Engineer for Schneider Electric. He has Bachelors and Masters Degrees in Electrical Engineering from Worcester Polytechnic Institute. Since joining the company in 1991, he has developed UPSs, communications products, architectures and protocols, equipment enclosures, and power distribution products and has managed multiple product development teams. He holds over 20 US and international patents related to UPSs, enclosures, power and cooling systems.

[13] 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

Appendix: Confidence in the findings

The mathematics of the calculations used to establish the efficiency of the DC and AC power distribution systems are indisputable. It is also indisputable that none of the power distribution devices can have an efficiency of over 100%. This immediately bounds the theoretically possible efficiency benefits of a DC architecture to numbers well below the numbers that have been circulated in the press.

This paper shows that there are only four key parameters that have a significant effect on the efficiency analysis, which are:

1. The efficiency of AC UPS systems
2. The efficiency of DC UPS systems
3. The efficiency improvement possible by converting IT power supplies (PSUs) to DC operation
4. The effect of the choice of operating load on efficiency

Uncertainty in these values affects the conclusions of the efficiency comparison – it is therefore worthwhile to consider whether these values are likely to change significantly as a result of further research or new technology.

AC UPS efficiency

With regard to the efficiency of the AC UPS, the value used in this paper is based on a real product, available today, with efficiency performance certified by a third party. At Schneider Electric, we are aware of other products that will soon be on the market which are likely to achieve similar – or slightly better – performance. There are certainly many older AC UPS products still on the market that have much lower efficiency, so any attempt to build a high efficiency data center should ensure that a high efficiency UPS is used. At this time, we do not expect dramatic improvements over the current 96.3% (at 50% load) best-of-class double conversion AC UPS efficiency in the next few years.

DC UPS efficiency

With regard to the efficiency of the DC UPS, the values used in this paper were based on the highest performance data submitted to the EPA, and there is no known galvanically isolated DC UPS for data center power distribution of higher efficiency. However, it is worth considering whether DC UPS systems of higher efficiency are possible. A DC UPS must convert AC to DC, it must provide a regulated output, and it must present a power-factor corrected input to the utility mains. Within these constraints, it is conceivable that DC UPS systems greater than 96% are possible, but none have been demonstrated. Currently, the best example of actual commercial devices that are similar to a DC UPS are photovoltaic utility-interactive inverters, which are optimized for efficiency and are technically a DC UPS operating with reverse power flow. A review of isolated converter data published by the California Energy Commission shows that such efficiencies are in the range of 94% at 50% load, with the best performance being 96%. This provides significant confirmation of the validity of the 96.5% assumed efficiency in the model for DC UPS.

Nevertheless, research at Schneider Electric suggests that it is possible to eventually improve the efficiency of DC UPS systems to slightly above 96.5%. Therefore, we believe it is conceivable that an optimized DC UPS could provide efficiency almost as great as the commercially available AC UPS. If this were achieved, then the best DC and AC power distribution systems would basically have equivalent efficiency, the only difference being any efficiency gain in the IT power supply resulting from conversion to DC.

Efficiency improvement possible by converting IT power supplies to DC

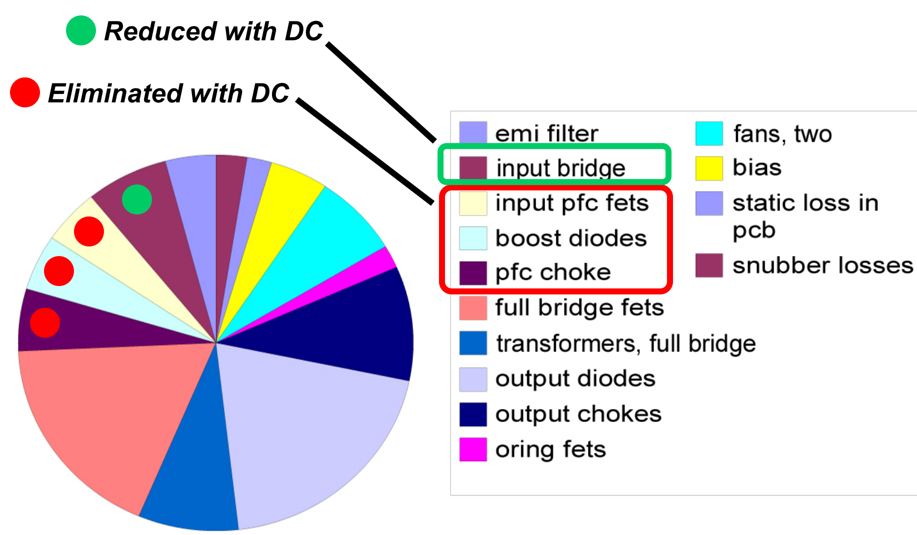
There is general agreement that conversion of IT power supplies (PSUs) to 380 V DC input will improve efficiency. This paper has shown that new AC power supplies have efficiency values above 92% over a broad load range. In fact, some models shipping in 2012, are already achieving peak efficiencies of 95%. This means **the maximum theoretical efficiency advantage for DC power supplies is only 5%** (100% – 95% = 5%) **even if a DC power supply were 100% efficient**.

For the purposes of the analysis in this paper, an improvement of 0.9% was used based on data from Delta Electronics. The fact that these improvements were obtained does not answer the question as to whether a 0.9% gain in efficiency is expected, or what possible improvement might be achieved in the future. The following discussion provides the theoretical basis to determine how much the efficiency of a power supply can be increased by converting to DC operation.

The PSU serves two primary functions:

- To provide safety isolation between the computing circuits and the incoming power supply
- To convert the incoming AC power to a regulated 12 V DC

Using DC distribution does not eliminate the need for safety isolation, nor does it eliminate the need to provide regulated 12 V DC. However, some of the circuits of the PSU that are responsible for the conversion of AC to DC can be eliminated if DC distribution is used. A recent publication by Sun Microsystems provides quantitative insight into the potential efficiency gain of converting a PSU from AC to DC input operation. **Figure A1**[14] shows a detailed breakdown of the electrical usage within a server PSU. The items tagged "Eliminated with DC" are losses due to parts that can definitely be eliminated if the PSU is converted to DC. The item tagged "Reduced with DC" are losses that cannot be completely eliminated because of the need for back-feed protection, but might be reduced by up to half if the PSU is converted to DC.



Source: Sun Microsystems

Figure A1

Breakdown of losses within a server power supply unit (PSU), showing losses that can be eliminated or reduced by converting to DC input

[14] Sun Microsystems Presentation by Mike Bushue, DC Data Center Stakeholders Meeting, hosted by Lawrence Berkeley National Labs, July 12, 2007, composite PDF page 19 of 67, slide 9.
http://hightech.lbl.gov/presentations/dc-powering/dc-stakeholders/1-Voltage.pdf

From **Figure A1**, it can be seen that approximately 20% of the losses of the PSU can be eliminated by conversion to DC. To determine how much this reduction in loss improves the efficiency of the power supply, the following calculation is used:

$$\begin{aligned}\Delta\eta &= \eta' - \eta \\ &= (1 - \text{loss}') - \eta \\ &= (1 - (1 - \eta) \times (1 - \text{PSLR})) - \eta \\ &= (\eta + \text{PSLR} - \eta \times \text{PSLR}) - \eta \\ &= \text{PSLR} \times (1 - \eta)\end{aligned}$$

Where **η** is the AC power supply efficiency, **η'** is the efficiency after modification to DC input, and PSLR is the power supply loss reduction due to the DC conversion. Given a best-case power supply efficiency of 95%, and a reduction in power supply losses of 20% through conversion to DC, the expected future improvement in efficiency is only 1.0%.

It is important to note that the efficiency gain is greatly affected by the starting efficiency of the power supply; therefore the efficiency gains of conversion to DC are likely to be higher for power supplies with lower efficiency. However, for the high efficiency data center of the future, we must assume efficient power supplies are inevitable, and that efficiency gains of only around 1% are feasible.

Given the PSU efficiency of over 93% for the current generation of IT equipment, the calculation shows that the efficiency gain of converting IT equipment power supplies to DC is expected to be approximately 0.8% to 1.5%. This finding is consistent with the published performance results by Delta Electronics, and consistent with the finding of other published analysis.

Effect of IT load variation on efficiency

The power path efficiency comparisons in this paper have been computed for 50% of IT load. The efficiency of the power distribution system – and therefore the efficiency of the complete data center – varies as a function of the IT load. The relationship between efficiency and IT load can be accurately modeled as explained in White Paper 113, *Electrical Efficiency Modeling for Data Centers*.

The efficiency comparisons in this paper include the efficiency of the PSUs (power supply units) within the IT equipment. When the aggregate IT load varies in a real data center, it is primarily due to a change in the *quantity* of IT equipment rather than *load variation* on existing IT equipment. Therefore, a change in the aggregate IT load of the data center is reflected in the load on the UPS and distribution wiring systems, but generally does not correlate with the operating load of individual PSUs. Although power flows from the UPS, through the distribution wiring, and through the IT power supply to the IT load, this does not mean that all of these devices are operating at the same percentage of their rated capacity (i.e., at the same operating load). The total power typically flows into many, even thousands, of IT devices.

Consider a data center operating at 5% of capacity – you could reasonably assume that the UPS is at a 5% operating load (5% of its capacity), but this doesn't tell you anything about the operating load on the individual downstream IT PSUs. The 5% load on the UPS could result from:

- A small number of IT devices operating at 100% of their rated input power, or
- Twenty times as many IT devices operating at 5% of their rated input power, or
- One hundred times as many IT devices operating at 1% of their rated power

The 5% operating load on the UPS is clearly linked to the aggregate operating loads of all the IT devices that it feeds, but the individual operating loads of the IT devices are not related to each other, and not identically linked to the 5% operating load on the UPS.

This means, of the three segments of the data center power path (since the distribution wiring has little effect on efficiency no matter what the load), it is the variation of the *UPS efficiency* with load (either AC or DC) that has the greatest influence on the variation of overall data center efficiency as the IT load varies.

For the above reasons**, the effect of IT load variation on efficiency is small, and there is no reason to believe either AC or DC has any advantage at different IT operating loads.**

Therefore, the effect of IT load variation on the analysis and conclusions of this paper are insignificant.

Confidence summary

There is considerable confidence in the numeric values used in the comparison of the AC and DC power distribution systems. The DC and AC UPS efficiency values are expected to vary less than 1% from the efficiency values used. The wiring losses are immaterial because they are so small. Power supply efficiencies are expected to improve incrementally, which benefits both the AC and DC systems. The efficiency gain from conversion from AC to DC is found to be constrained to be on the order of 1% for a 95% efficient power supply.

Based on this analysis, it unlikely that future DC supplies will achieve greater percent efficiency gains than studied here. However, there is also the possibility of a move to 277 V AC power supply standard which would improve the efficiency of North American AC installations by approximately 1%. If achieved, this would effectively place the AC and DC distribution methods at parity.

Resources

AC vs. DC Power Distribution for Data Centers
White Paper 63

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

Review of Four Studies Comparing Efficiency of AC and DC Distribution for Data Centers
White Paper 151

Electrical Efficiency Modeling for Data Centers
White Paper 113

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