Electrical Efficiency Modeling for Data Centers

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White Paper #113

Legendary Reliability®

Revision 1

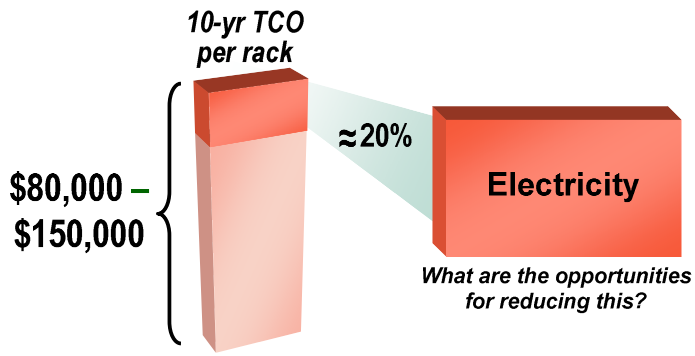
Executive Summary

Conventional models for estimating electrical efficiency of data centers are grossly inaccurate for real-world installations. Estimates of electrical losses are typically made by summing the inefficiencies of various electrical devices, such as power and cooling equipment. This paper shows that the values commonly used for estimating equipment inefficiency are quite inaccurate. A simple, more accurate efficiency model is described that provides a rational basis to identify and quantify waste in power and cooling equipment.

Introduction

The 10-year total cost of ownership (TCO) for network-critical physical infrastructure (NCPI) in a typical data center can be $80,000 to $150,000 per rack. Of this cost, the cost of electrical power consumption is a significant contributor, on the order of 20% of the total cost[1]. This is of interest because much of the electrical power consumption is wasted (in the form of heat energy) and a significant amount of this waste is avoidable. It is estimated that, world-wide, data centers consume 40,000,000,000 kW-hr of electricity per year and the reduction of waste associated with this consumption is a significant public policy issue as well as a major financial concern to data center operators.[2]

***Figure 1** – Electricity is a significant portion of TCO*



Typical simplistic models of data center efficiency grossly underestimate electrical waste in data centers. The entitlement to improved efficiency is consequently much greater than commonly believed. This paper presents an improved model that provides better accuracy for data center losses and suggests where energy improvement opportunities are available.

What is "Data Center Efficiency"?

The efficiency of any device or system is the fraction of its input (electricity, fuel, whatever makes it "go") that is converted to the desired useful result – anything other than the useful result is considered to be "waste." This fraction of ***useful out*** to ***total in*** is usually expressed as a percent.

"Useful" is whatever is considered the desired result for the particular system, which may depend not only on the nature of the system, but also on the context of its use. For example, a light bulb whose output consists of 5% light and 95% heat can be viewed as a 5% efficient light bulb or a 95% efficient heater, depending upon whether it is being used to light a room or heat a room. "Useful output" is whatever makes sense for the system under consideration.

For data center physical infrastructure, the input is *electricity* and the useful output is *power for the computing equipment*. In this paper, a data center is modeled as an electrical system whose "total input" is

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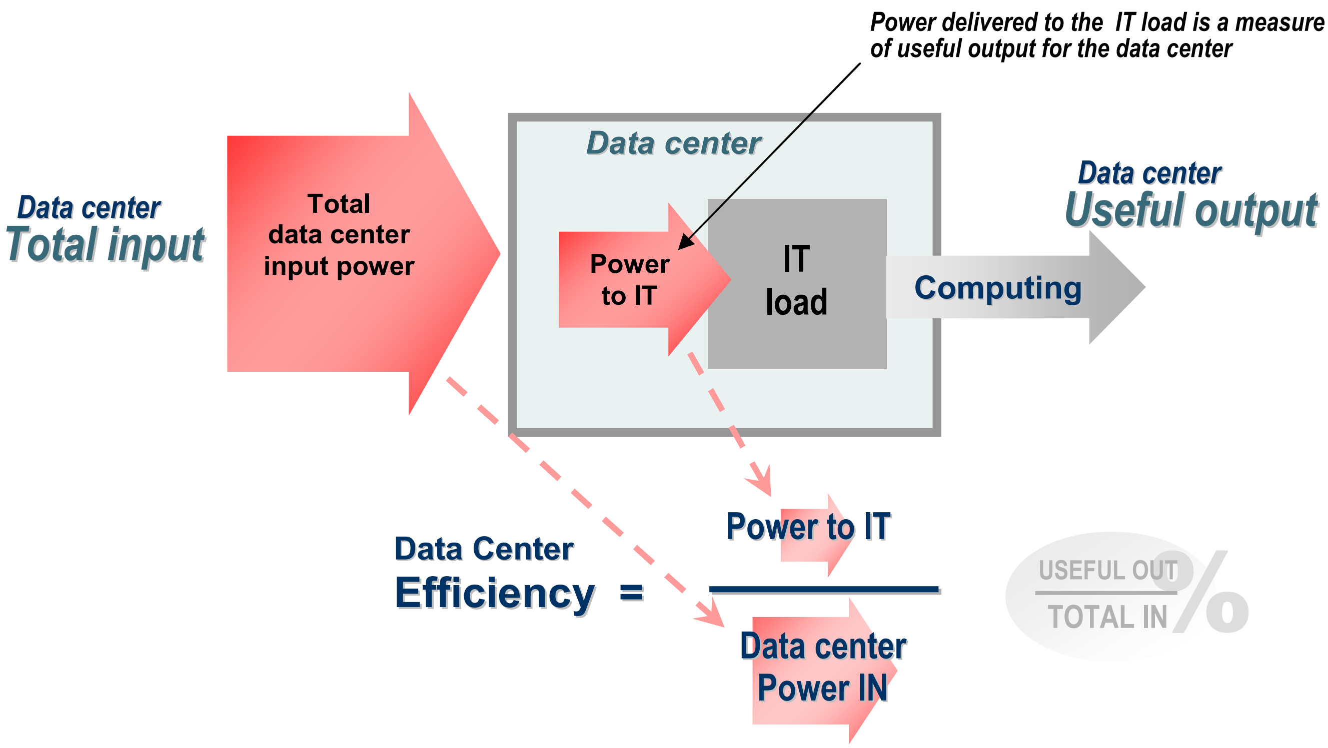
[1] Details on the contributors to TCO are described in APC White Paper #6, *Determining Total Cost of Ownership for Data Center and Network Room Infrastructure*
[2] http://www.eei.org/magazine/editorial_content/nonav_stories/2004-01-01-NT.htm (accessed June 14, 2006).

the power it consumes from the utility and whose "useful output" is the amount of power for computing it provides, which can be represented by the amount of electrical power delivered to the IT equipment.[3]

$$\textbf{Data center efficiency} = \frac{\textbf{IT load power}}{\textbf{Total data center input power}}$$

Figure 2 illustrates this general model of data center efficiency.

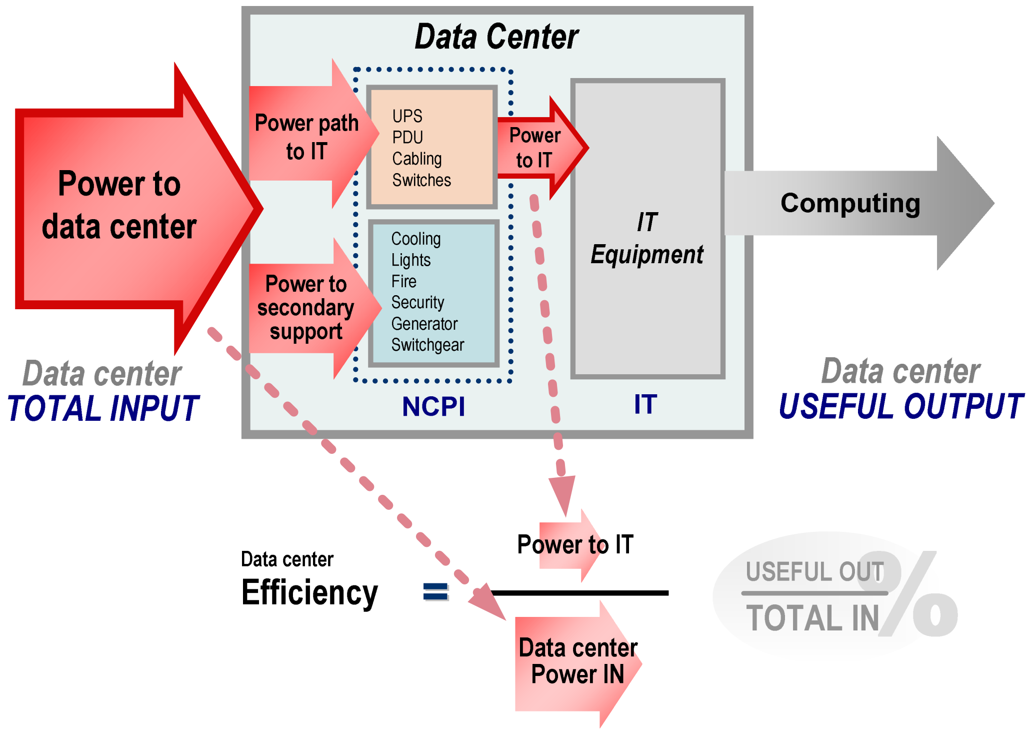
***Figure 2** – Data center efficiency is defined as the fraction of input power delivered to the IT load*



If the data center were 100% efficient, all power supplied to the data center would reach the IT loads. In the real world there are a number of ways that electrical energy is consumed by devices other than IT loads, because of the practical requirements of keeping IT equipment properly housed, powered, cooled, and protected so that it can provide its useful computing. (These duties are the job of the data center's network-critical physical infrastructure, or NCPI.) Non-IT devices that consume data center power include such things as transformers, uninterruptible power supplies (UPS), power wiring, fans, air conditioners, pumps, humidifiers, and lighting. Some of these devices, like UPS and transformers, are in series with the IT loads (because they provide the power path that feeds them) while others, like lighting and fans, are in parallel with the IT loads because they perform other support functions in the data center. **Figure 3** illustrates these internal components of power consumption in the data center efficiency model.

[3] The exact relationship between electrical power and "bits moved" is beyond the scope of this paper, but electric power consumed by IT equipment is a fair measure of computing delivered, for the purpose of this analysis. Improvements in efficiency from reducing power consumption of the IT equipment itself are important but are not the subject of this paper.

Figure 3 *– Detail of power consumption in data center efficiency model*



The concepts of "useful" and "waste" in the data center efficiency model

In an efficiency model, "waste" is everything other than what has been defined as the system's useful output. Clearly, the data center's NCPI (network-critical physical infrastructure) does other useful things besides provide power to the IT load – these are called "secondary support" in **Figure 3**. It could be argued that the useful output of these NCPI subsystems (cooling or lighting, for example) should also be considered part of the data center's "useful output."

This is a frame-of-reference issue. The subject of this analysis is overall efficiency of the *data center* in producing its useful output, which is *computing.* Data centers are not built to produce cooling or fire protection or any of the other good things NCPI accomplishes. While these NCPI outputs are extremely useful to the *internal* workings of the data center in helping it to produce and protect its useful output (computing) they are not themselves "useful output" of the data center, nor is there any reason to believe that they *must* consume electricity. Non-power-path NCPI activities should be considered a necessary evil in supporting the data center's computing – therefore, in the *data center* efficiency model they are considered "waste" that should be minimized to the extent possible. All should be considered fair game for alternative designs and new technologies to reduce overall power consumption in the data center. For example, there are data centers that use "free cooling" methods, which take advantage of cool outdoor air using techniques such as heat wheels and plate-and-frame cooling. This can decrease the amount of electric power expended on cooling, which increases the efficiency of the data center.

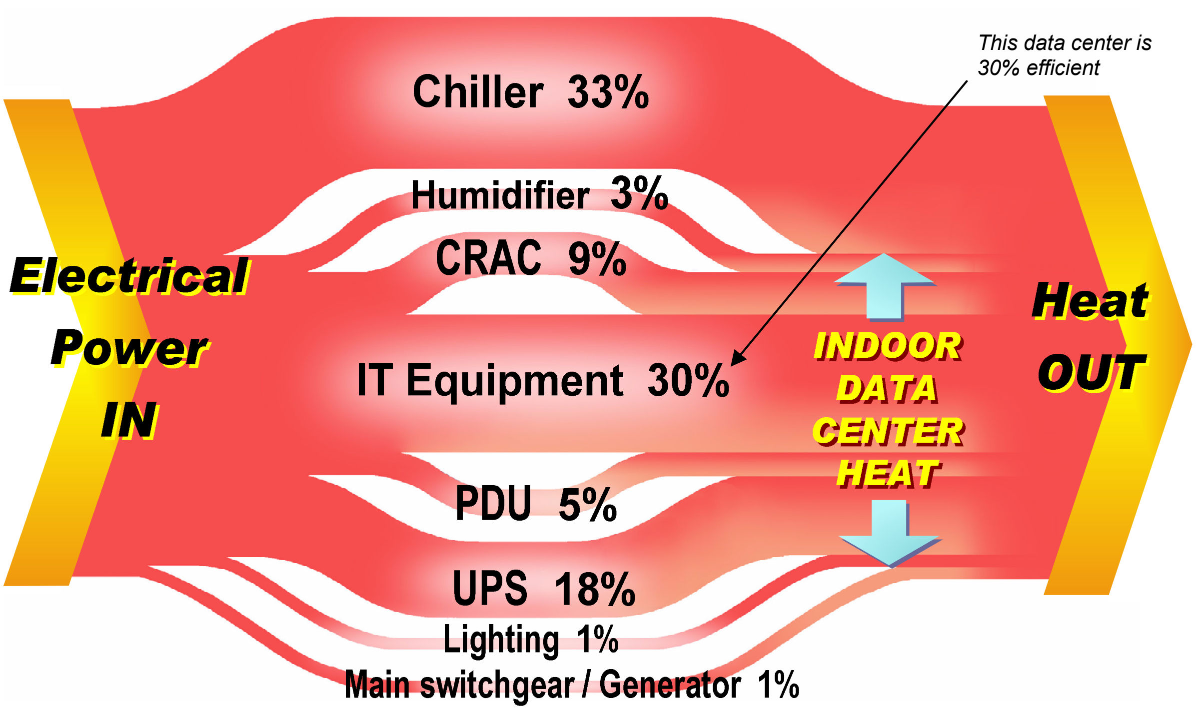
The "useful output" of the NCPI components themselves will be of critical concern later in this paper, in the analysis of individual component-by-component efficiency – a smaller frame of reference for efficiency *within* the data center – to reduce internal inefficiencies (waste) in the larger overall data center model.

Where does data center power go?

Virtually all of the electrical power feeding the data center ultimately ends up as heat. A diagram showing where electrical and heat power flows in a typical data center is shown in **Figure 4**. This is a power analysis of a typical highly available dual-power-path data center with N+1 CRAC units, operating at a typical load of 30% of design capacity. (The 30% load and 30% efficiency are coincidentally the same number in this data center, but they are not the same thing – although low loading and low efficiency are related, as will be discussed later in this paper.)

Note that less than half the electrical power feeding a data center actually is delivered to the IT loads. The data center in this example is said to be 30% efficient.

***Figure 4** – Power flow in a typical data center*



Opportunities for increasing data center efficiency

Data center efficiency can be increased in three ways:

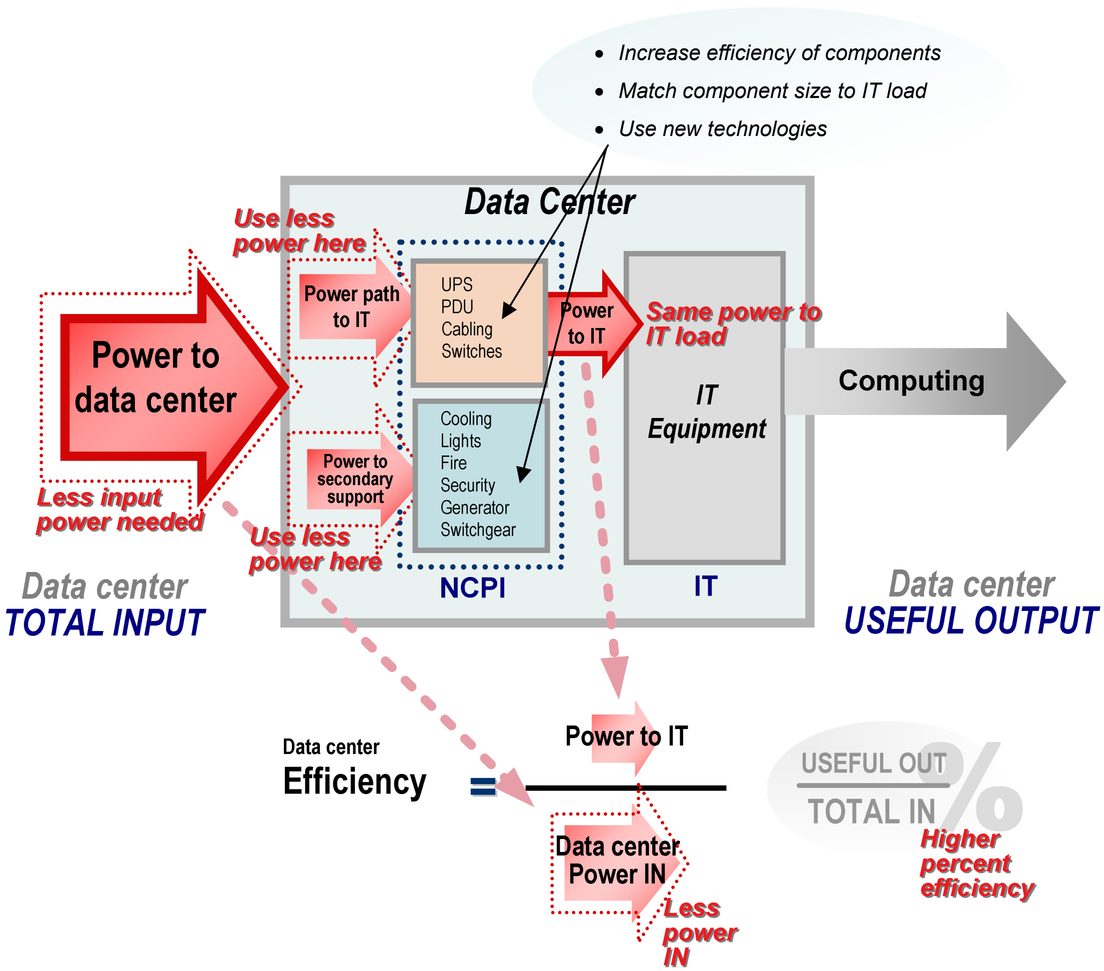
1. Improve the internal design of NCPI devices, so they consume less power in doing their job
2. Match the sizing of NCPI components more closely to the actual IT load ("rightsizing") so that the components operate at a higher efficiency

3. Develop new technologies that reduce the need for electric power to supply NCPI support functions (such as the "free cooling" techniques mentioned earlier)

(As will be shown, #2 provides the greatest immediate opportunity for increasing data center efficiency.)

Figure 5 illustrates how reducing internal power consumption increases data center efficiency.

***Figure 5** – Increasing data center efficiency*



Correcting Misconceptions About Data Center Efficiency

While data center efficiency could be determined empirically by adding up the power consumption of all IT equipment and dividing by the total power input of the data center, the usual technique is to rely on manufacturers' statements of efficiency for major components such as UPS and CRACs. This may be easier, but typically yields a seriously overstated efficiency that obscures any information potentially helpful in identifying opportunities for saving on electrical costs.

Data center efficiency is more than "nameplate" component efficiency

Manufacturers provide efficiency data for power and cooling equipment. For power equipment, efficiency is typically expressed as the percent of power out to power in; for cooling equipment, efficiency is typically expressed as a related parameter called "coefficient of performance" – the ratio of heat removed to electrical input power.

The published values of efficiency for similar devices by different manufacturers do not vary dramatically, leading to the simplified view that the efficiency losses of a data center can be determined by simply adding up the inefficiencies of various components. **Unfortunately, this approach does not provide accurate results in the case of real data centers.** The use of manufacturers' efficiency ratings causes users or designers to dramatically *overestimate* efficiency, and consequently *underestimate* the losses, of real data centers.

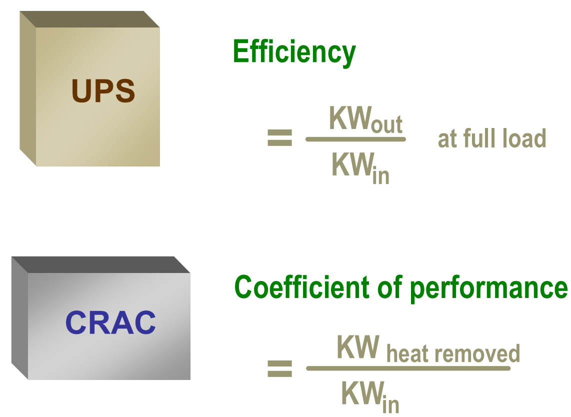


Figure 6 *– Manufacturers provide a single efficiency number for each component*

Wrong Assumptions

Table 1 lists three common misconceptions that cause significant errors in data center efficiency models.

Table 1 *– Common misconceptions about data center efficiency*

	Wrong Assumption	Reality
1	Efficiency of power and cooling components is constant and independent of IT load	Efficiency of components – especially CRAC units and UPS – significantly *decreases* at lower IT loads
2	Power and cooling components are operating at or near full design load	Typical IT load is *significantly less* than design capacity of the NCPI components used
3	The heat produced by power and cooling components is insignificant	The heat output of power and cooling components is a significant cooling burden, and must be included when analyzing the inefficiency of the cooling system

These major errors compound each other, particularly at the lower IT loads that are typical of most data centers. **As a result, data center electrical losses are routinely underestimated by a factor of two or even more.**

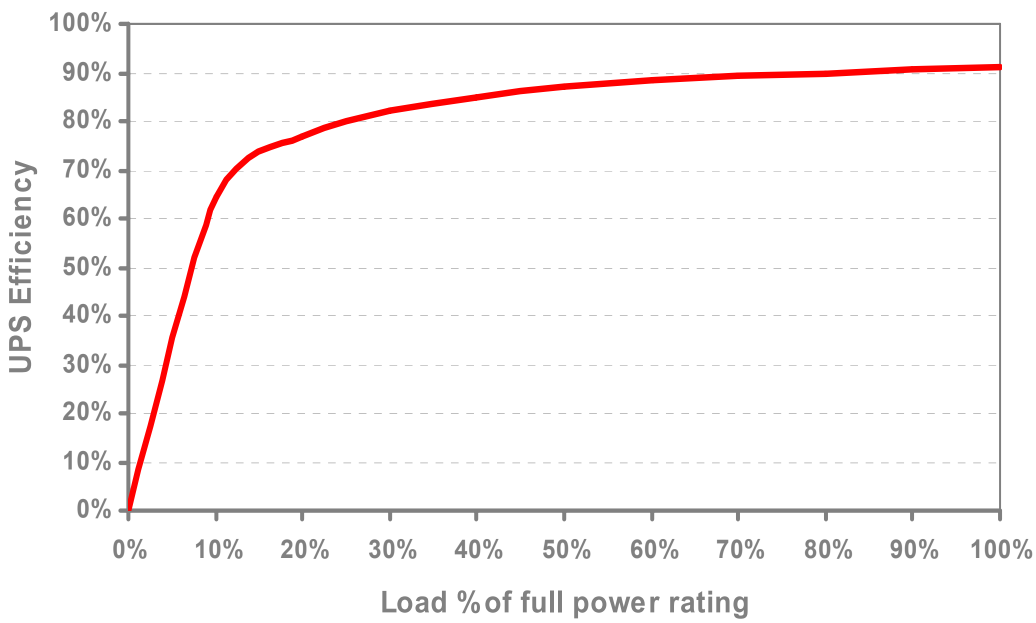
Fortunately, a simple model can be constructed that incorporates the above issues and provides for more reliable efficiency estimates.

Improved Models for Component Efficiency

An improved model for overall data center efficiency depends on how accurately individual components, such as UPS, are modeled. Characterizing power and cooling components by using a single efficiency value is the common method, but it is inadequate in real data center installations. The actual efficiency of a component such as a UPS is not constant, but rather a function of the IT load. **Figure 7** shows a typical UPS efficiency curve.

Wrong assumption #1
Efficiency of power and cooling components is constant and independent of IT load

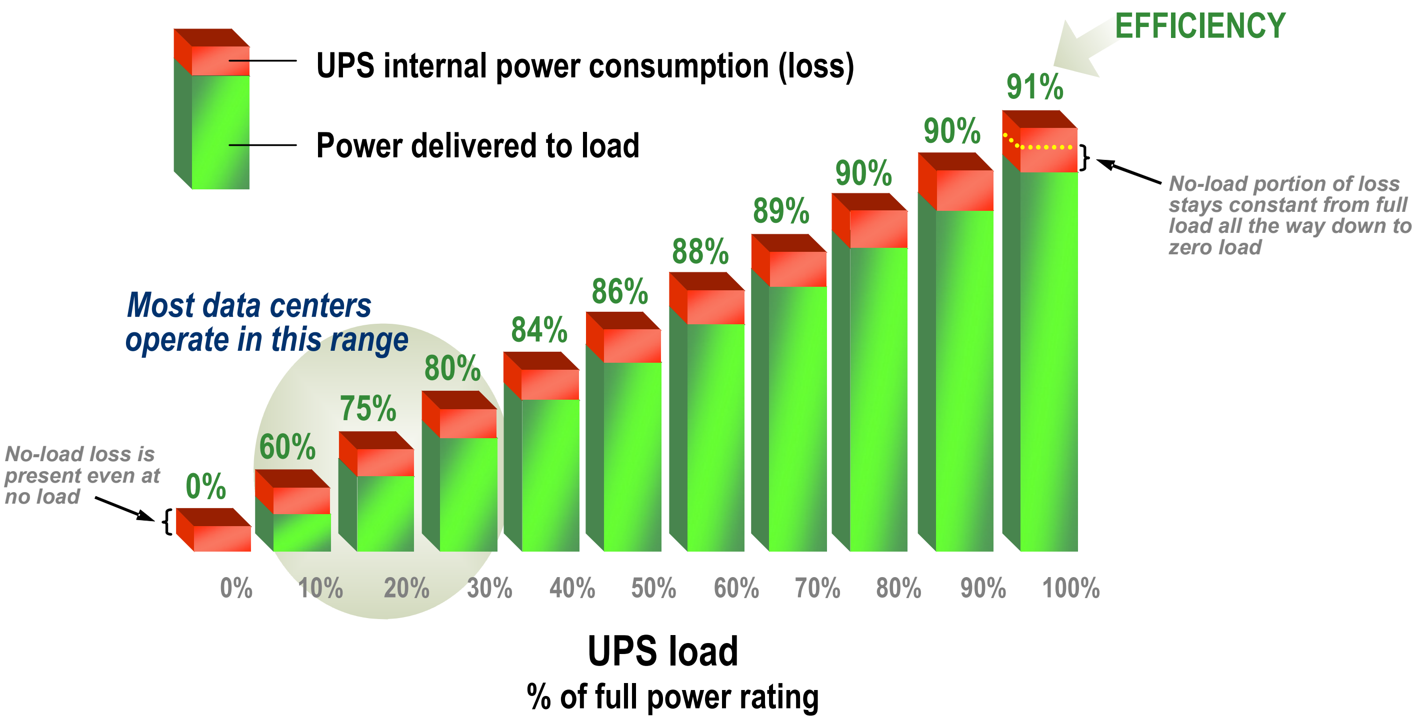
Figure 7 *– Typical efficiency of a UPS as function of load*



Note that when approaching very light loads, the efficiency of this device falls to zero. This is because there are some losses, such as control logic losses, that are independent of load. This constant loss that is independent of load is known by various names: *no-load*, *fixed*, *shunt*, *tare*, or *parallel* loss. This paper will use the term **no-load** loss.

Figure 8 is another view of the same data as **Figure 7**. Note that, as the load decreases, the internal power consumption of the UPS (the "loss," shown as the red portion of each bar) becomes a greater and greater fraction of the total power, thus reducing the efficiency percentage value. This is due to the no-load portion of the loss, which stays the same no matter what the load.

Figure 8 *– Effect of internal UPS loss on efficiency*



The UPS described by the data in **Figures 7** and **8** might be described as having 91% efficiency. However, this is the efficiency at *full load*, or best case scenario. At low loads, where most data centers operate, the description of this device as having 91% efficiency is grossly in error – for example, at 10% load the same UPS exhibits only 60% efficiency. Clearly, a single-parameter model for efficiency is inadequate in this case.

The three types of internal device losses

Careful inspection of **Figure 8** reveals that the device loss (the red part of the bars) *increases* as the load increases. This is due to an additional loss – over the no-load loss – that is *proportional* to the load. There can even be a loss component on top of this (not evident in this chart) that is proportional to the *square* of the load, which is usually not significant but can make overall efficiency fall at higher loads.

Table 2 shows typical values of these three types of losses for various types of equipment used in a data center. The losses are summed in the last column as the total loss for the component.

***Table 2** – Typical electrical losses of NCPI components expressed as a fraction of full load component rating*

NCPI Component	No-load loss +	Proportional loss +	Square-law loss =	Total loss (single parameter)
UPS	4%	5%	-	9%
PDU	1.5%	-	1.5%	3%
Lighting	1%	-	-	1%
Wiring	-	-	1%	1%
Switchgear	-	-	0.5%	0.5%
Generator	0.3%	-	-	0.3%
CRAC	9%	0%	-	9%
Humidifier	1%	1%	-	2%
Chiller plant	6%	26%	-	32%

From **Table 2**, it can be seen that by characterizing each type of device using no more than two parameters it is possible to create more complete models for the components used in data centers. Note that losses in this table are expressed as a percentage of **full load** rating of the equipment and that for actual loads less than full load, the percentage loss will change in the following way:

- No-load loss: Loss percent **increases** with decrease of load
- Proportional loss: Loss percent is constant (independent of load)
- Square-law loss: Loss percent **decreases** with decrease of load

The typical UPS efficiency depicted in **Figures 7** and **8** would not be accurately modeled by a single efficiency parameter, but has instead been appropriately modeled by the no-load (4%) and proportional loss (5%) parameters of **Table 2**.

Effect of Under-Loading on Component Efficiency

The previous section explains that efficiency of power and cooling systems decreases significantly when used below equipment design rating. This means that any analysis of data center efficiency must properly represent load as a fraction of design capacity.

Wrong assumption #2

Power and cooling components are operating at or near full design load

Simple efficiency models that use only a single efficiency value to model equipment are insensitive to loading (efficiency does not change with load in these models). Yet it is a fact that in the average data center, power and cooling equipment is routinely operated well below rated capacity. The result is that such models significantly overstate the efficiency of real data centers.

For each type of power or cooling component, there are four reasons why a component might be operated below its rated capacity:

- **The data center IT load is simply less than the system design capacity**
- **The component has been purposefully oversized to provide a safety margin**
- **The component is operating with other similar components in an N+1 or 2N configuration**
- **The component is oversized to account for load diversity**

IT load is less than data center's design capacity. The research is clear: The average data center operates at 65% below the design value. This situation is described in more detail in APC White Paper #37, *Avoiding Costs From Oversizing Data Center and Network Room Infrastructure*. The next sections of this paper will show that underutilization is a very large contributor to data center inefficiency.

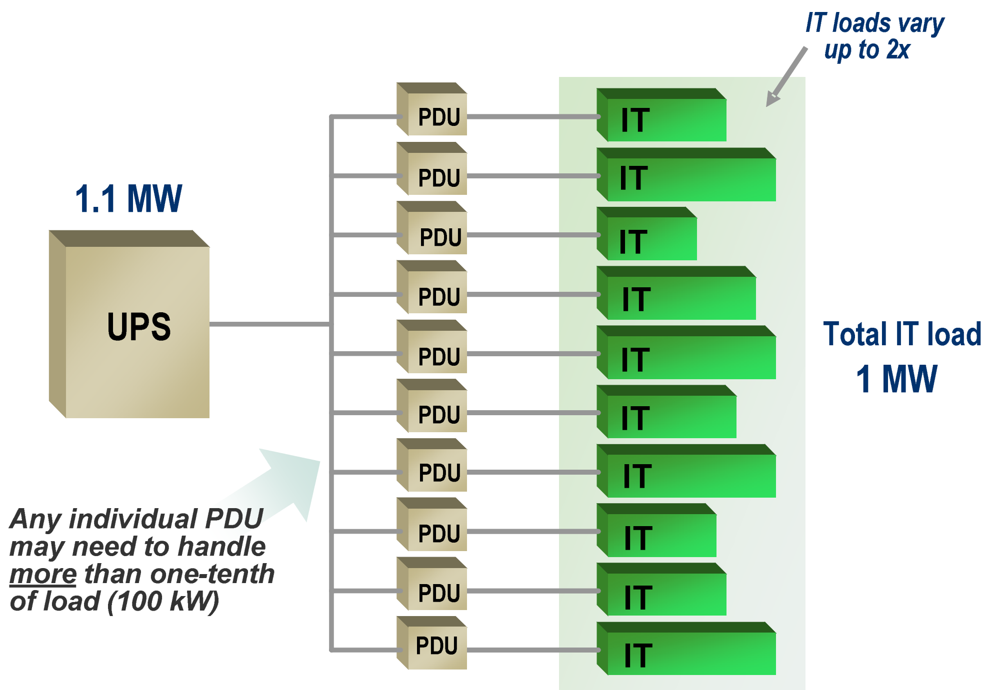
Component has been oversized to provide a safety margin. It is routine to oversize components in a common practice called "derating." The idea is to avoid operating components near their capacity limits. It is possible to operate facilities with no derating, but derating values of 10-20% are recommended design practice for highly available facilities.

Component is operating in an N+1 or 2N redundancy configuration. It is common practice to use devices in an N+1 or even 2N configuration to improve reliability and/or to allow concurrent maintenance of components without powering down the system. Operating the data center in such a configuration means the IT load is spread among more NCPI components, effectively reducing the components' loading. For a 2N system, the loading on any single component is less than half its design value. Efficiency of a data center is therefore strongly affected by the operation of devices in N+1 or 2N configurations.

Component is oversized to handle "load diversity." This effect is subtle and best illustrated by example. Consider a data center with a 1 MW load supported by a 1.1 MW UPS. Between the UPS and the IT loads are 10 power distribution units (PDUs), each feeding a portion of the IT loads. The question is: What are the ratings of each of these PDUs, and therefore what are they operating at for an average load? At first glance it would appear that if each were rated at 100 kW, the system design would be satisfied. Furthermore, if each PDU ran at full load the data center could run the entire load. However, in real data centers it is nearly impossible to assure balance of loads on PDUs. The load on a particular PDU is dictated by the nature of IT equipment in the region of the data center where the PDU is located. In fact, loads on various PDUs in real data centers often vary by a factor of 2. If a PDU feeds a section of data center that is physically utilized to capacity but is still not using the full power capacity of that PDU, then the remaining capacity on that PDU is unusable if the other 9 PDUs are fully loaded. In this configuration, the only way to ensure full capacity of the data center is to substantially oversize total PDU capacity. The typical oversizing of PDU capacity is on the order of 30% to 100%. As in previous examples, this oversizing degrades system efficiency. **Figure 9** illustrates the need for PDU oversizing to support load diversity.

It should be noted that the same problem that gives rise to PDU oversizing also drives oversizing of air handlers.

***Figure 9** – Effect of load diversity on PDU sizing*



Effect of Heat From Power and Cooling Equipment

Another major error in modeling data center efficiency is the assumption that heat output of power and cooling equipment (inefficiency) is an insignificant fraction of IT load and can therefore be ignored. In fact, heat generated by power and cooling equipment within a data center is no different from heat generated by the IT equipment itself, and must be removed by the cooling system. This creates an additional burden on the cooling system which creates the need for oversizing of the cooling system, which creates additional efficiency losses in the cooling system. To properly account for these losses the cooling load must include both IT equipment and losses of any power and cooling devices located within the conditioned space.

Wrong assumption #3
Heat from power and cooling components is insignificant

Putting It All Together: An Improved Model for Data Center Efficiency

Based on the discussion above, it is possible to construct an improved model for data center efficiency. The improved model has the following attributes:

- Components are modeled with a no-load loss, plus a loss proportional to the load, plus a loss proportional to the square of the load
- Oversizing due to component derating is incorporated
- Underutilization due to N+1 or 2N designs is incorporated
- The cooling load includes both IT load and heat load due to inefficiency of indoor power and cooling components
- For a given data center installation, the model provides a graphical output of efficiency as a function of load, understanding that typical data centers operate well below design capacity

Implementation of the model is straightforward and obeys the following general flow:

- Determine average degree of oversizing for each power and cooling component type, provided derating, diversity, and redundancy factors
- Determine operating losses of each type of component using input load, fraction of rated load for the component type based on over sizing, no-load loss, and proportional loss
- Determine additional proportional loss due to the need for cooling system to cool power and cooling equipment within the data center
- Sum all losses
- Compute and tabulate losses as a function of IT load in the data center

A computer model based on these principles has been implemented to compute energy consumption in the APC Data Center TCO analysis methodology, described in APC White Paper #6, *Determining Total Cost of Ownership for Data Center and Network Room Infrastructure*.

Devices with multiple operating modes

Some NCPI subsystems – air conditioners, for example – may have multiple operating modes with different efficiencies associated with each one. For example, some air conditioning systems have an "economizer" mode for periods of low outdoor temperature, where the system efficiency is significantly increased.

Such devices cannot be modeled using a single efficiency curve based on the simple 3-parameter model (no-load loss, proportional loss, and square-law loss) described in this paper. To establish an efficiency model for a multi-mode device, a different technique is used. Fortunately, this technique is well-established and widely used in engineering.

Devices that switch between different operating modes can be modeled over an extended period using a straightforward technique called "state-space averaging." This is done by determining the relative amounts of time spent in the various modes, then generating a weighted average of the system's output. This technique is readily applied to efficiency and loss calculations.

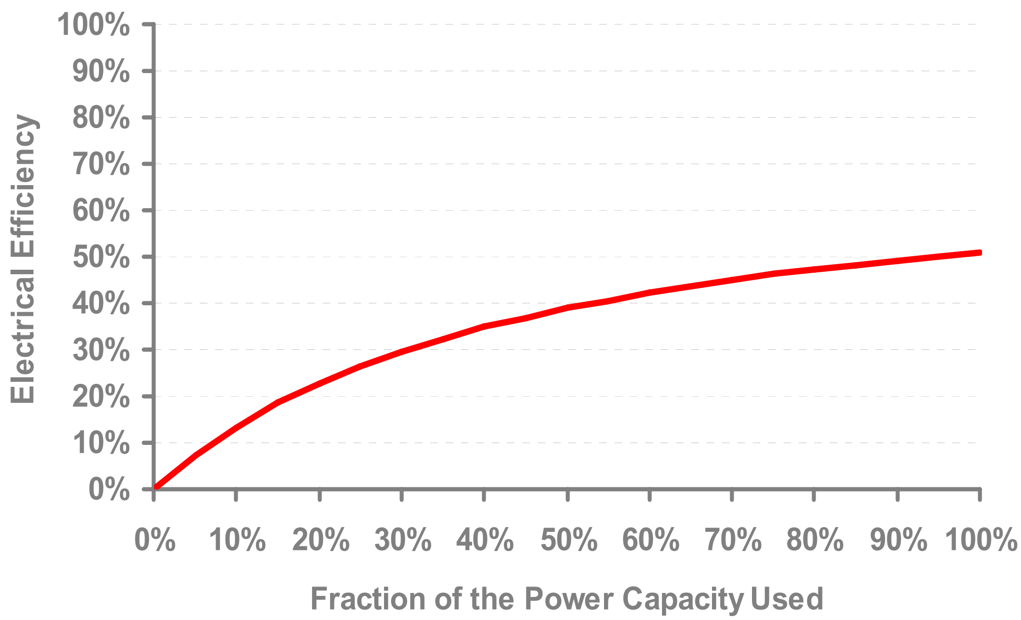
To use the efficiency model described in this paper with NCPI devices having multiple operating modes, the fixed, proportional, and square-law losses first must be determined for each operating mode. Then, the overall loss contribution over an extended period is computed by multiplying the loss in each mode by the expected fraction of the time spent in that mode. For example, a complete description of a system with two modes would require three efficiency curves:

- Efficiency curve in mode 1
- Efficiency curve in mode 2
- Expected overall efficiency curve, given a stated assumption of the amount of time spent in each mode

The Efficiency of Real-World Data Centers

Equipped with a better model for data center power consumption, it is possible to make improved estimates of data center efficiency. Using typical values for equipment losses, derating, load diversity, oversizing, and redundancy, the efficiency curve of **Figure 10** can be developed.

Figure 10 *– Efficiency of a typical data center using the improved model*



Note that this curve of efficiency vs. load is considerably different from estimates based on conventional calculations that use manufacturers' published component efficiency. **A conventional estimate of efficiency of the data center described by Figure 10 would be a value of 60-70%, independent of load.** Note the dramatic decrease in data center efficiency predicted by the improved model, particularly at lower loads where many data centers actually operate.

The model shows for very lightly loaded data centers inefficiency effects can be dramatic. For example, given a data center loaded to only 10% of its rated capacity, for every ten watts delivered to the data center only about one watt actually reaches the IT equipment. The remaining nine watts are lost to inefficiencies in the network-critical physical infrastructure.

Another way to look at these losses is in terms of financial cost. **Figure 11** shows annual electricity cost of a 1 MW data center as a function of IT load. This is based on a typical highly available dual power path design with N+1 CRAC units. An electricity cost of $0.10 per kW-hr is assumed for this analysis.

Figure 11 *– Annual electrical cost for a typical 1 MW data center as a function of the fraction of design capacity utilized*

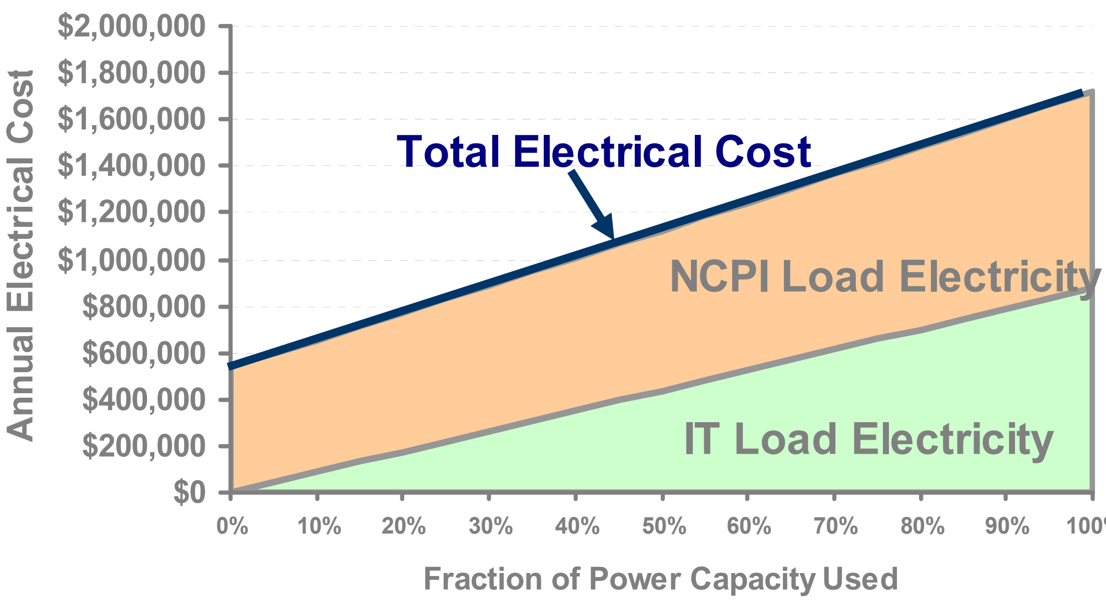


Figure 11 shows that total electricity cost of a 1MW data center ranges from $600,000 to $1,700,000 per year, depending on size of IT load. Note even if there is no IT load the cost is over $500,000 per year, driven by inefficiencies of power and cooling systems. **At the 30% capacity utilization level of the typical data center, over 70% of electricity costs are caused by inefficiencies of power and cooling equipment.**

Entitlement to Increased Data Center Efficiency

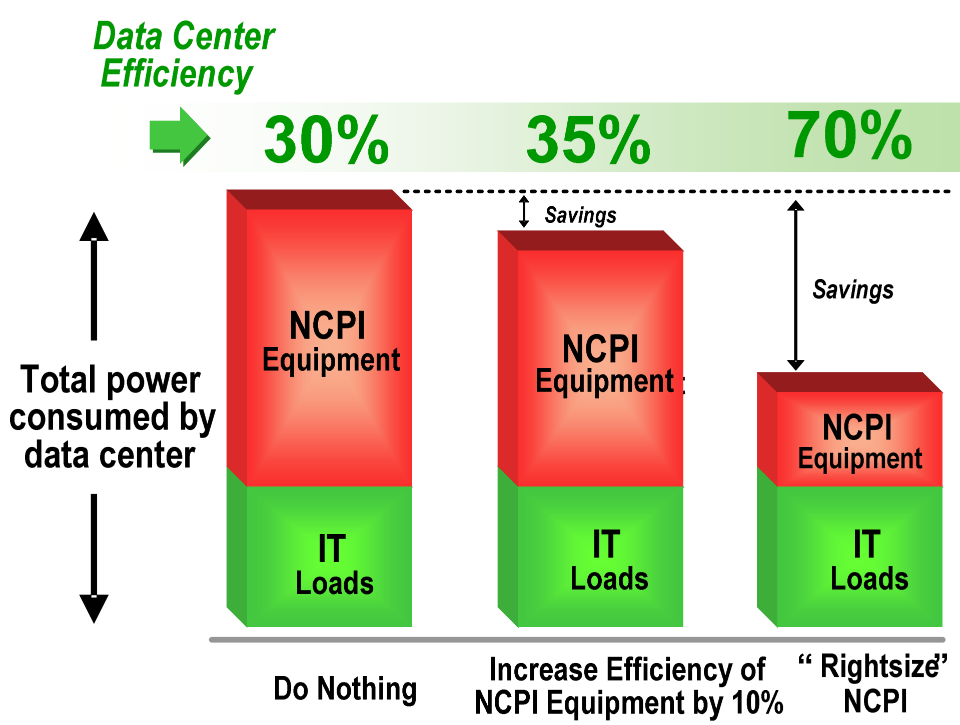
The model clearly shows that primary contributors to data center electrical costs are no-load losses of infrastructure components, which exceed IT load power consumption in typical situations. It is notable that no-load losses are ignored in conventional analysis; indeed, a review of product specifications shows that the important no-load loss specifications for power and cooling devices are not routinely provided by equipment manufacturers.

An analysis of the data can quickly identify and prioritize opportunities for reducing losses and improving operating efficiency of data centers:

- By far the biggest opportunity for savings is to reduce oversizing of data centers by using an adaptable modular architecture that allows power and cooling infrastructure to grow with the load. **Potential reduction in losses: 50%.**
- Improve efficiency of cooling systems. **Potential reduction in losses: 30%**
- Reduce no-load losses of power and cooling components in the data center**. Potential reduction in losses: 10%**

Figure 12 illustrates the relative efficiency entitlements from improved component efficiency and reduction of oversizing. A more detailed discussion of efficiency entitlements and efficiency improvement opportunities is the subject of APC White Paper #114, "Implementing Energy Efficient Data Centers".

***Figure 12** – Entitlements to improved data center efficiency*



Conclusion

Conventional models of data center efficiency typically overstate efficiency because they do not properly comprehend the degree to which equipment is oversized, nor do they comprehend reduction of efficiency at the reduced loads where most data centers operate. An improved model provides more accurate numeric values for data center efficiency, as well as insight into where the losses go and how they can be reduced.

Typical data centers draw *more than twice as much* power as IT loads require. The cost associated with this power consumption is a considerable fraction of the total cost of ownership of the system. All of the power consumed beyond the power needs of IT equipment is undesirable, and much of this may be avoidable.

Oversizing of data centers is the single biggest contributor to data center inefficiency, suggesting that scalable solutions that can grow with IT load offer a major opportunity to reduce electrical waste and costs. The potential electricity cost savings for a typical 1 MW data center are on the order of $2,000,000 to $4,000,000 over a typical 10-year life of the facility.

Due to the large amount of power and cost consumed by data center inefficiency, reduction of these losses should be a topic of paramount importance to all data center owners, as well as a significant issue of public policy.

About the Author:

Neil Rasmussen is the Chief Technical Officer of APC-MGE. He establishes the technology direction for the world's largest R&D budget devoted to power, cooling, and rack infrastructure for critical networks. Neil is currently leading the effort at APC-MGE to develop high-efficiency, modular, scalable data center infrastructure solutions and is the principal architect of the APC-MGE InfraStruXure system.

Prior to founding APC in 1981, Neil 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 MIT Lincoln Laboratories on flywheel energy storage systems and solar electric power systems.