PQ Encyclopedia

A product of the EPRI Solutions Power Quality Knowledge-Based Services program

The Economics of Power Quality

Chapter 2

Contents

The impact of power quality on the productivity of international business is huge, as is the cost to electric power providers of ensuring good quality power. Imagine that one lightning strike or power supply fault anywhere within a few hundred miles can result in voltage sags that can interrupt manufacturing processes, causing thousands of dollars or Euros in lost production and labor, equipment damage, and creation of scrap. Or imagine you are a utility engineer responsible for power quality and reliability and, despite earnest efforts to quickly dampen or isolate the effects of that single lightning strike or isolated fault on a remote power grid, the entire distribution system sags—affecting hundreds, if not thousands, of digital systems, processes, and enterprises.

These unsettling scenarios are reality for virtually every major interconnected power grid in the world. Transmission-level problems can cause voltage disturbances—mostly sags, in which voltage on one, two, or all three phases drops below normal levels for a brief period—in distribution systems over a wide region.

Recent work by EPRI and others suggests that across all business sectors, the U.S. economy is losing approximately $100 billion a year to outages and another $15 billion to $24 billion to PQ phenomena. These losses drive the economics of power quality.

About the EPRI Solutions Power Quality Knowledge-Based Services program

The EPRI Solutions Power Quality Knowledge-Based Services program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, www.mypq.net, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

For more information, please visit www.mypq.net.

About EPRI Solutions

EPRI Solutions, Inc. provides a complete portfolio of engineering and technical services, management consulting, and information products—serving more than 100 major energy-industry companies in North America and around the world. EPRI Solutions is a wholly-owned subsidiary of the Electric Power Research Institute (EPRI). For more information about EPRI Solutions, please contact us at 865-218-8000 or visit www.eprisolutions.com.

Business activities have become increasingly sensitive to disturbances in the power supply.

THE COST OF ELECTRIC POWER RELIABILITY AND POWER QUALITY PROBLEMS TO INTERNATIONAL BUSINESSES

The importance of reliable, high-quality electrical power continues to grow as society becomes ever more reliant on digital circuitry for everything from e-commerce to industrial process controllers to the onboard circuitry in toasters and televisions. With this shift to a digital society, business activities have become increasingly sensitive to disturbances in the power supply. Such disturbances not only include *power outages* (the complete absence of voltage, whether for a fraction of a second or several hours) but also *power quality phenomena* (all other deviations from perfect power such as voltage sags, surges, transients, and harmonics).

The most definitive study done of the costs of electrical phenomena to a variety of industrial end users was funded by the EPRI IntelliGrid Initiative and conducted by Primen, now a part of EPRI Solutions.[1] The study, which included detailed interviews with nearly 1,000 businesses, found that three sectors of the U.S. economy are particularly sensitive to power disturbances:

- **Digital economy** (DE). This sector includes firms that rely heavily on data storage and retrieval, data processing, or research and development operations. Specific industries include telecommunications, data-storage and retrieval services (including collocation facilities or Internet hotels), biotechnology, electronics manufacturing, and the financial industry.
- **Continuous-process manufacturing** (CPM). This sector includes manufacturing facilities that continuously feed raw materials, often at high temperatures, through an industrial process. Specific industries include paper; chemicals; petroleum; rubber and plastic; stone, clay, and glass; and primary metals.
- **Fabrication and essential services** (F&ES). This sector includes all other manufacturing industries plus utilities and transportation facilities such as railroads and mass transit, water and wastewater treatment, and gas utilities and pipelines.

These three sectors account for roughly two million business establishments in the United States. Although this is only 17% of all U.S. business establishments, these same three sectors account for approximately 40% of U.S. gross domestic product (GDP). Moreover, disruptions in each of these sectors—but especially DE and F&ES—have an almost immediate effect on other sectors that depend on the services that they provide.

Number of Business Establishments Surveyed by Sector and Size in the Primen Study

Number of Employees	Digital Economy	Continuous Process Manufacturing (CPM)	Fabrication & Essential Services (F&ES)	Total
1 to 19	179	166	159	**504**
20 to 249	101	87	101	**289**
250+	62	74	56	**192**
Total	342	327	316	**985**

Data suggest that across all business sectors, the U.S. economy is losing between $104 billion and $164 billion a year to outages and another $15 billion to $24 billion to PQ phenomena.

Power outages cost each of the roughly two million establishments in these three sectors more than $23,000 a year on average. Industrial (the combination of CPM and F&SE) and DE firms are collectively losing $45.7 billion a year to outages. The bulk of this loss ($29.2 billion in total) is concentrated in the F&ES sector, which is particularly vulnerable to equipment damage. DE firms lose $13.5 billion to outages annually, primarily from lost productivity and idled labor. The greatest costs per establishment are among CPM firms, which suffer the loss of raw materials as well as the costs incurred by other sectors.

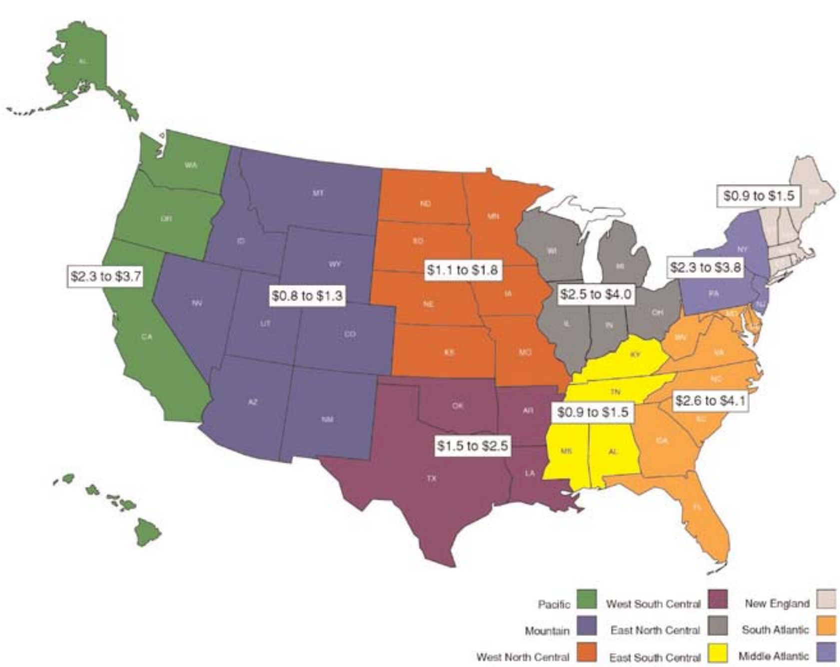
Costs vary with the length of the outage, but even short outages are costly. Even a one-second outage can damage equipment and disrupt highly sensitive operations to the point where labor becomes idled as systems are reset and brought back on-line. The average cost of a one-second outage among industrial and DE firms is $1,477 versus an average cost of $2,107 for a three-minute outage and $7,795 for a one-hour outage. Brief outages are also more frequent than outages of an hour or more; industrial and DE establishments report that 49% of the outages that they experience last less than three minutes.

Industrial and DE companies lose another $6.7 billion each year to power quality (PQ) phenomena. DE firms have lower PQ-related losses per establishment than either of the other industrial sectors. The F&ES sector seems to be particularly sensitive to PQ phenomena, losing more than $9,600 annually per establishment and accounting for 85% of the aggregate losses across all three sectors. Once again, equipment damage seems to play a large role in the costs to industrial facilities.

Among the individual U.S. states, California has the highest costs for both outages and power quality phenomena (between $13.2 billion and $20.4 billion), followed by Texas ($8.3 billion to $13.2 billion) and New York ($8.0 billion to $12.6 billion). Because the economies of these states are comparable to those of many international countries, they provide perhaps more useful metrics for the costs of power quality in countries around the world.

Data suggest that across all business sectors, the U.S. economy is losing between $104 billion and $164 billion a year to outages and another $15 billion to $24 billion to PQ phenomena. The map at left shows the estimated annual cost of PQ problems to all sectors by region (in billions of dollars).

Annual PQ Losses to U.S. Economy by Region ($Billion U.S.)



A single power interruption lasting more than an hour costs over 200% more than a single power interruption lasting less than an hour.

WHAT ARE THE INCREMENTAL COSTS OF POWER QUALITY AND RELIABILITY TO TYPICAL BUSINESSES?

Little question exists that PQ and reliability issues are costly to both U.S. and international businesses. But what form do these losses take, and how sensitive are they to outage duration? IEEE Standard 493-1997 (The Gold Book) provides practical guidance on the impact of power interruptions on U.S. businesses.[2] The standard classifies business losses into four categories:

1. Damaged plant equipment
2. Spoiled or off-specification product
3. Extra maintenance costs
4. Cost for repair of failed components

Data generated by IEEE research reveal the costs of power interruptions in industrial and commercial facilities. The cost is expressed in dollars per kW of load for a short interruption plus dollars per hour for the total outage time.

The IEEE also investigated the cost of a single power interruption as a function of the interruption duration for office facilities containing computers. The table below shows that the difference in average cost between 15 minutes, one hour, and greater than one hour is less than 10%. However, the difference in maximum cost is quite large: A single power interruption lasting more than an hour costs over 200% more than a single power interruption lasting less than an hour. The figure at the top of p. 4 provides additional information on interruption costs.

Average Cost of a Single Power Interruption for Industrial and Commercial Facilities

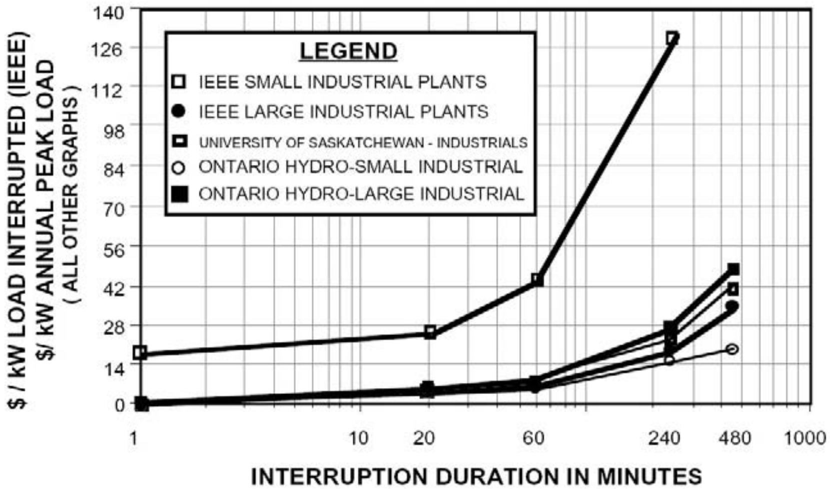
Type of Facility	Cost of a Single Power Interruption
Industrial: All facilities	$6.43/kW + $9.11/kWh
Facilities > 1000 kW max demand	$3.57/kW + $3.20/kWh
Facilities < 1000 kW max demand	$15.61/kW + $27.57/kWh
Commercial: All facilities	$21.77/kWh not delivered
Office facilities only	$26.76/kWh not delivered

Cost of Power of a Single Power Interruption as a Function of Duration for Office Buildings Containing Computers

Duration of Power Interruption	Sample Size	Cost/Peak kWh Not Delivered		
		Maximum	Minimum	Average
15 minutes	14	$67.10	$5.68	$26.85
1 hour	16	$75.29	$5.68	$25.07
> 1 hour	10	$204.33	$0.48	$29.63

Source: IEEE Standard 493-1997

Cost of a Single Power Interruption Versus Duration[3]



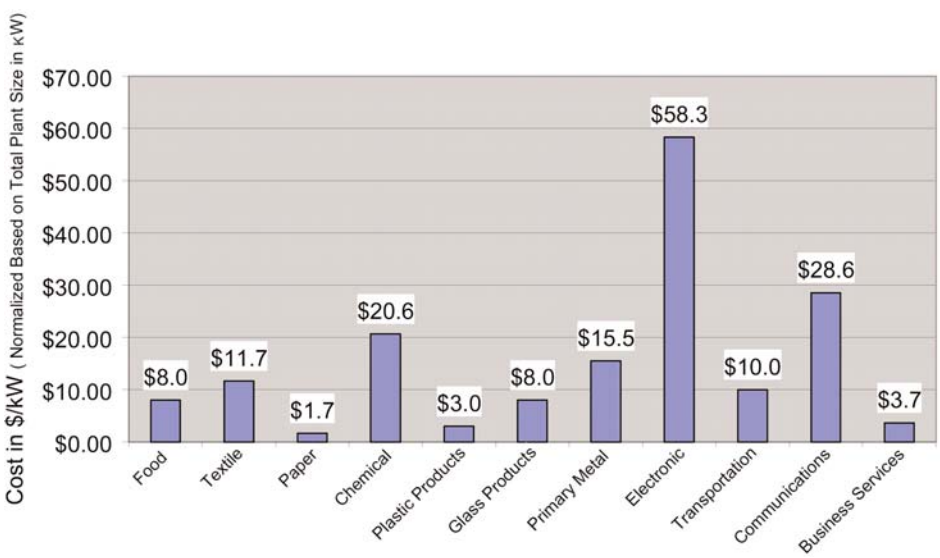
Source: IEEE Standard 493-1997

WHAT INDUSTRIES ARE SUFFERING THE MOST FROM POWER QUALITY AND RELIABILITY PHENOMENA?

Data from hundreds of PQ investigations conducted by EPRI Solutions over the last several years enable an assessment of the annual costs of power quality to a variety of industries, particularly for the continuous-process manufacturing (CPM) sector. This sector includes manufacturing facilities that take in raw materials, subject them to an industrial process, and produce a finished project. Example industries include paper; chemicals; petroleum; rubber and plastic; stone, clay, and glass; and primary metals.

The figure below shows the annual cost of PQ to specific industries within the CPM sector normalized to the total demand in kW. While cost for any specific customer will depend on the unique characteristics of that customer, these numbers provide a range of "typical" cost for the specific industry segment that can be used for macro-level planning purposes.

Industry-Specific Annual Cost of Power Quality for the Continuous-Process Manufacturing Sector Based on EPRI Solutions Site Investigations



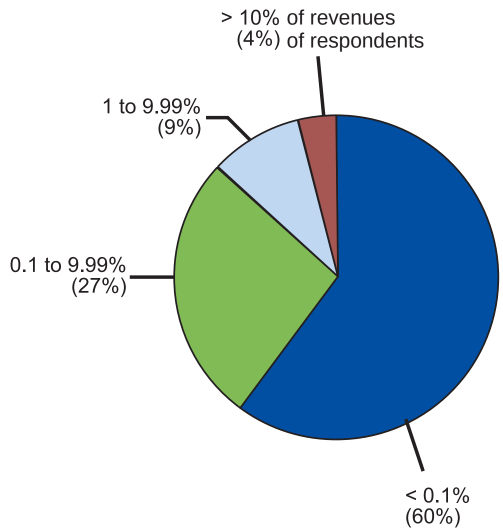
Nearly 13% of U.S. businesses report PQ and reliability related losses exceeding 1% of revenues, while 60% report virtually no losses at all.

WHAT PORTION OF U.S. INDUSTRIAL BUSINESSES SUFFER SIGNIFICANT LOSSES FROM POWER QUALITY PHENOMENA?

To assess the level of suffering or loss because of electric power reliability and PQ issues, it is best to examine how much companies say that they are losing as a percentage of their revenues.

The figure below shows the percentage of industrial businesses in the United States that are suffering high levels of economic loss because of PQ and reliability problems. Approximately 4% report crippling losses greater than 10% of revenues. Nearly 13% of U.S. businesses report losses exceeding 1% of revenues. This implies that approximately one in eight industrial customers would benefit significantly from technologies and techniques that would (1) improve the quality of electric power supply, (2) make end user processes less sensitive to power supply problems, or (3) otherwise reduce the economic impact of less-than-perfect electric power supply.

Power Quality and Reliability Losses for U.S. Businesses as a Percentage of Revenues



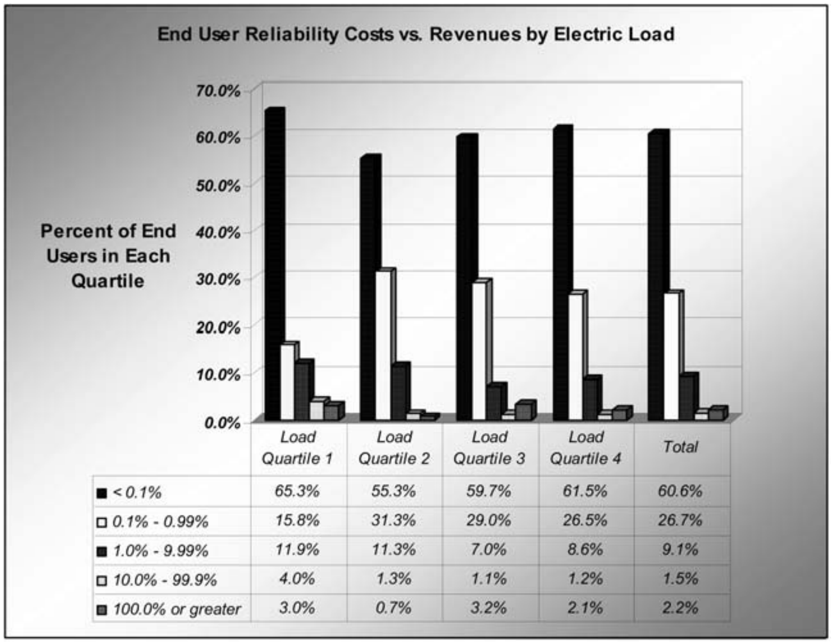
Partitioning the Reliability Market by the Load Size of End-User Facilities

The size of an end user's electric load is an important metric for understanding the costs of PQ. Not only will differently sized solutions be required to solve problems at large versus small facilities, but entirely *different* technologies may also be appropriate. The data on reliability costs can be further segmented by the size of a facility's electrical load. The IntelliGrid *Cost of Power Disturbances* study divided end users into four load quartiles, demarcated as:

- **Quartile 1:** Small, with an annual electric power consumption of less than 25.6 MWh
- **Quartile 2:** Medium, with an annual electric power consumption more than or equal to 25.6 MWh but less than 66.7 MWh
- **Quartile 3:** Large, with an annual electric power consumption more than or equal to 66.7 MWh but less than 247 MWh
- **Quartile 4:** Extra Large, with an annual electric power consumption more than or equal to 247 MWh

The figure on the following page, *End User Reliability Costs Versus Revenues by Electric Load*, shows the percentage of end users in different load quartiles—very small loads (quartile 1) through very large loads (quartile 4)—that reported varying degrees of losses due to power quality and reliability phenomena. The first thing that is clear is that across all the quartiles, the percentage reporting negligible losses is pretty consistent, hovering between 55 and 65% of quartile companies. However, the data also make clear that all sizes of companies suffer from losses due to reliability, and that there are some marked similarities across different loads.

End User Reliability Costs Versus Revenues by Electric Load



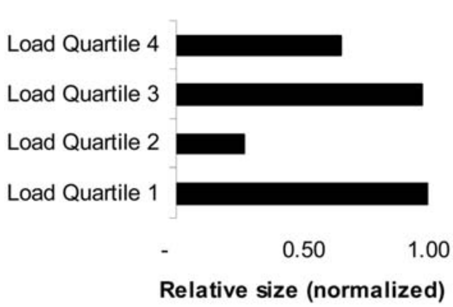
	Load Quartile 1	Load Quartile 2	Load Quartile 3	Load Quartile 4	Total
< 0.1%	65.3%	55.3%	59.7%	61.5%	60.6%
0.1% - 0.99%	15.8%	31.3%	29.0%	26.5%	26.7%
1.0% - 9.99%	11.9%	11.3%	7.0%	8.6%	9.1%
10.0% - 99.9%	4.0%	1.3%	1.1%	1.2%	1.5%
100.0% or greater	3.0%	0.7%	3.2%	2.1%	2.2%

The smallest companies (Quartile 1) offer something of a paradox in that this quartile has both the highest percentage reporting no significant costs due to poor reliability (65.3%), and the greatest percentage report losses greater than 1% of revenues (18.8% versus 13.3%, 11.3%, and 11.9%, respectively for quartiles 2, 3, and 4). For quartiles 2, 3, and 4, 40-50% of respondents report no losses due to reliability.

Which size customers are suffering the most from power quality costs relative to their revenues? As shown in figure below, left, Quartiles 1 and 3 (small and large companies, respectively) have, on average, almost identical suffering due to reliability costs and have, on average, the highest cost (or "level of pain") from reliability problems. Medium-sized companies, however, have conspicuously lower costs on average, making the prospect of finding individual companies with high costs more difficult in this size. The very largest companies (Quartile 4) have, on average, a level of pain that is about 40% less than their Quartile 1 and 3 peers. In short, it is more likely that individual Quartile 1 and 3 companies will have PQ problems requiring mitigation.

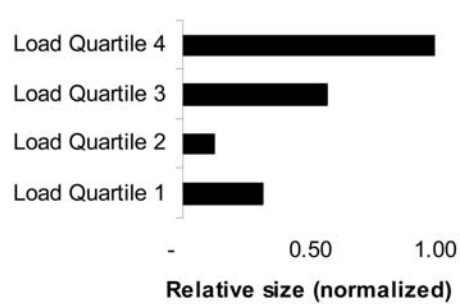
As shown in the figure below, right, the sheer size of Quartile 4 companies more than makes up for their lower losses in terms of percentage of revenue.

A Comparison of Average End User Losses as a Percentage of Revenues in Each Quartile



Load Quartile 4 reflects the very largest companies. Losses are normalized to those of Quartile 1.

Which Load Tier has the Greatest Overall Reliability Losses—A Comparison of Total Losses for Each Quartile

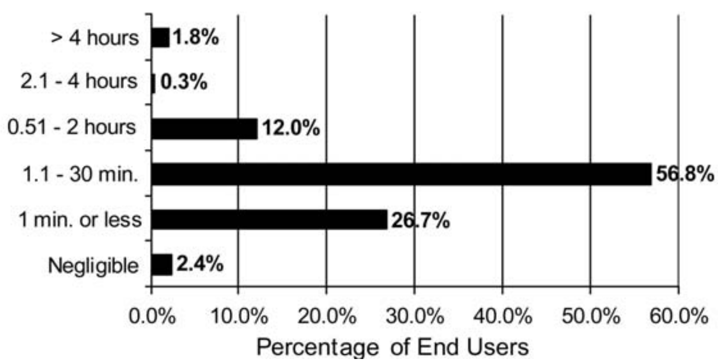


Results normalized to Quartile 4.

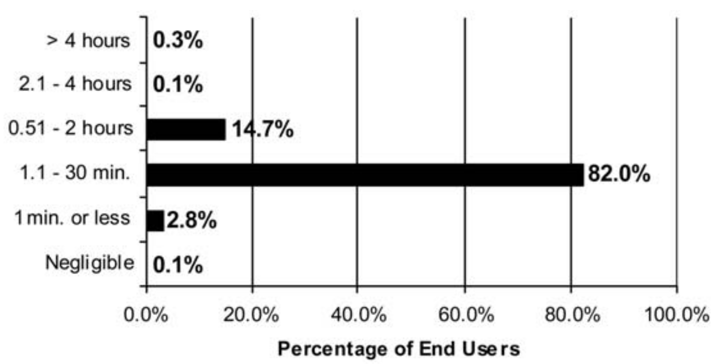
Understanding the Impact of Reliability Events on End-User Productivity

The IntelliGrid *Cost of Power Disturbances* study asked electric power end users about the impact on their operations of a number of different reliability events, including outages of 1 second, 3 minutes, and 1 hour. Paramount to understanding the market for reliability is first gaining an appreciation for how the impact of comparable reliability events varies from end user to end user.

Duration of Facility Outage Following a 1-Second Power Interruption



Duration of Facility Outage Following a 3-Minute Power Interruption

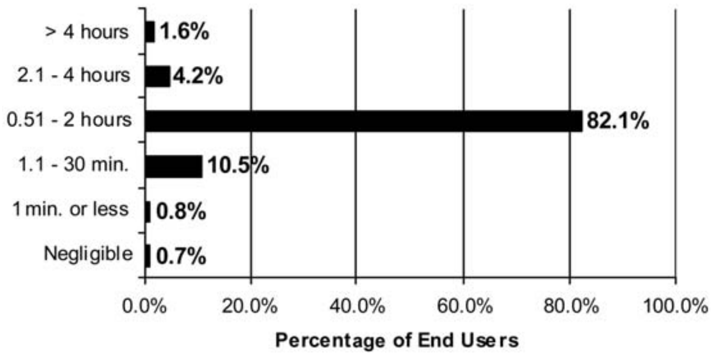


The figure at top left, shows the results of the impact of a 1-second interruption in utility-supplied power on end users. Almost 30% of end users are able to get their facilities up and running in less than one minute after a 1-second outage, and over 85% are down less than 30 minutes. However, just over 14% of end users' facilities are down more than 30 minutes, and just over 2% are down for more that 2 hours. The average time that a facility is down after a 1-second outage across all companies is approximately 21 minutes.

If a 1-second outage is injurious, how much worse is one lasting three minutes? The data show, interestingly, very little overall difference between the two events in terms of average outage duration. As illustrated in the figure at bottom left, the only significant change is that fewer companies can weather a 3-minute outage with only a minute or less of downtime, an unsurprising result. The average outage duration across all companies is 22 minutes, essentially unchanged from the 1-second outage. The portion of companies experiencing an outage of 30 minutes or more increases by about three percentage points, from 12% to 14.7%.

It is also interesting to note that those reporting very long interruptions (in excess of 2 hours) actually decline for 3-minute power interruptions versus 1-second interruptions. This can logically be attributed to equipment damage and psychological effects. Manufacturing equipment, motors, and electronics are much more likely to be damaged by quick cycling of power than by outages that allow all spinning loads to stop and capacitors to discharge. Psychologically, manufacturing facilities are much more confident that resumption of power after a three-minute interruption is likely to hold, while brief outages are perceived as more likely to recur, making it counterproductive to attempt restarting a complicated process too quickly following such an interruption.

Duration of Facility Outage Following a 1-Hour Power Interruption



When the outage duration is increased to one hour, the impact on end-user productivity is more profound, as shown in the figure above. With this type of outage, nearly 90% of end users experience a process interruption exceeding 30 minutes, and close to 6% are down for more than 2 hours. The average duration of facility interruption nearly trebles to 62 minutes.

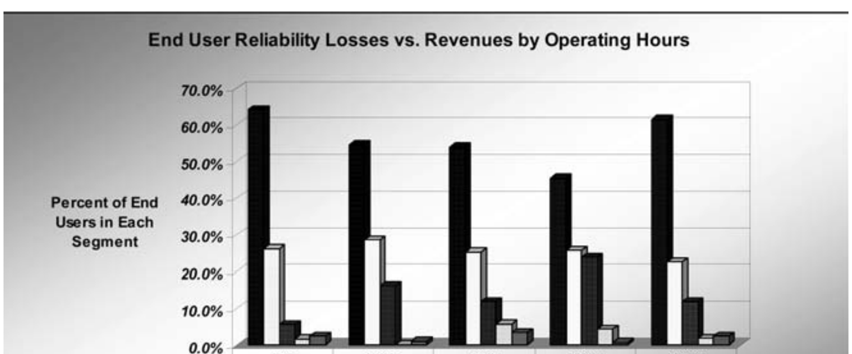
Partitioning the Reliability Market by End-User Facility Operating Hours

Having differentiated the reliability market by end-user load size and by the types of reliability events they experience, the IntelliGrid *Cost of Power Disturbances* study also allows differentiation among end users based on the hours that their facilities are open for business.

The figure at bottom right shows the distribution of operating hours across industry (hours x days). Nearly three of five businesses have a traditional work schedule: 8 hours a day, 5 days a week (8 x 5). Only 9% are open 24 hours a day, seven days a week (24 x 7). Over 75% of businesses close on weekends.

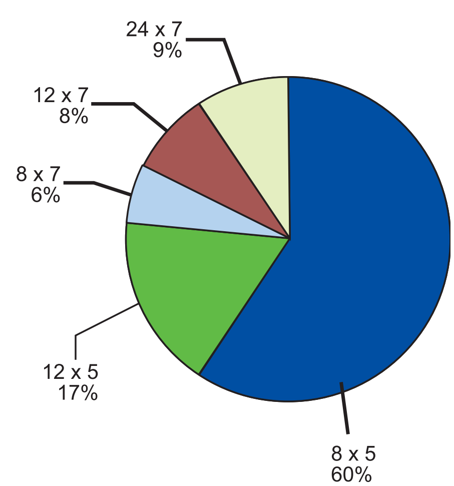
How do costs from reliability problems map to facility operating hours? The figure below left shows reliability losses versus facility revenues for the five different operating schedules. Interestingly, those segments with the greatest percentage of end users claiming no reliability losses are the 8x5 and the 24x7 operators—the two extremes in

Distribution of End Users by Operating Hours



	8X5	12X5	8X7	12X7	24X7
< 0.1%	64.1%	54.5%	53.9%	45.3%	61.5%
0.1% - 0.99%	26.1%	28.5%	25.2%	25.8%	22.6%
1.0% - 9.99%	5.6%	16.1%	11.8%	23.9%	11.8%
10.0% - 99.9%	1.7%	0.0%	5.7%	4.3%	1.7%
100.0% or greater	2.5%	0.9%	3.4%	0.7%	2.4%

Distribution of U.S. Businesses by Operating Hours



One-shift operations that are open seven days per week (8x7) report the highest average reliability costs.

terms of hours open for business. By one measure, the segment suffering the most is the 12x7 segment, where nearly 29% of these operators report reliability losses that are greater than 1% of revenues. The 8x7 segment is second, with 21% reporting similar losses.

A more comprehensive weighted comparison of average end-user losses due to reliability problems is shown in the figure below left. Overall, one-shift operations that are open seven days per week (8x7) report the highest average reliability costs of any segment, perhaps because of the difficulty of such an operation to “make up” lost production. On average, 24x7 and 8x5 businesses suffer equally from reliability problems, although at a level about 40% lower than that reported by 8x7 operations.

The pain suffered by individual companies is, of course, important to understanding who among end users is most likely to need PQ solutions. The sheer number of 8x5 establishments makes this market segment the most potentially needy among the various operating-hours scenarios (see figure below right).

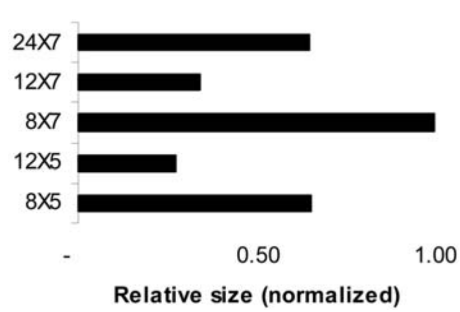
COST OF INDIVIDUAL OUTAGES TO BUSINESSES

The cost of an individual outage can vary significantly from one business to the next, depending on the size of the establishment, the industry it represents, and the processes or end-use technologies that it employs. Costs also vary by the duration and other characteristics of the outage.

Outage Costs as a Function of Duration of Outage

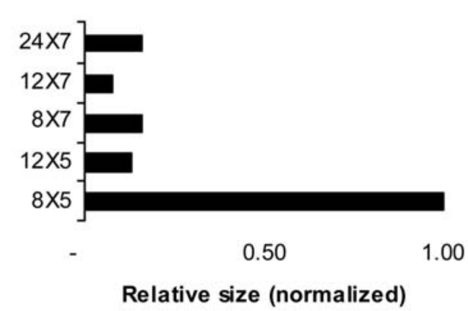
In the IntelliGrid *Cost of Power Disturbances* study, outage duration was divided into four categories: 1 second, recloser, 3 minutes, and 1 hour. A recloser event is a combination of brief outages, consisting of a one-second outage followed by another one-second outage a few seconds later.[4] Recloser events are relatively common and result when one or more automated switches in the distribution system try to interrupt an electrical fault by opening, interrupting electrical current, and then quickly reclosing in the case that the line voltage returns to normal (a self-clearing fault). If the fault does not self-clear after two or three recloser operations, the recloser locks open and must be manually reset.

A Comparison of Average End-User Losses by Facility Operating Hours



Normalized to 8x7

A Comparison of Overall Losses for All End Users by Operating Hours

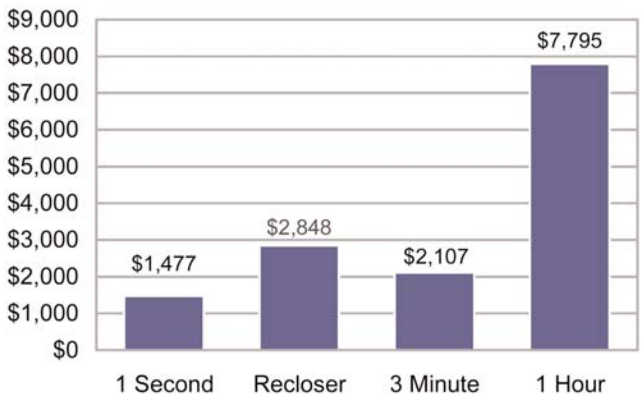


Normalized to 8x5

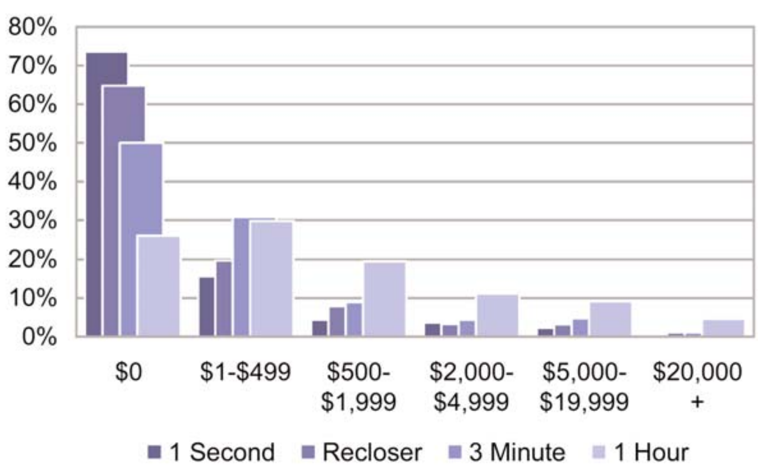
The average cost of a one-second outage is $1,477.

The average costs, shown in the figure at top left, combine the data from all three of the sectors surveyed: digital economy, continuous-process manufacturing, and fabrication and essential services. The figure shows the average cost of a single power outage to an individual business establishment based on the duration of the outage. Longer outages create greater costs for businesses, but, as shown in the figure, the relationship between outage length and cost is far from linear. The average cost of a one-second outage across the three sectors surveyed is $1,477, whereas the average cost of a three-minute outage is somewhat higher at $2,107. Although the average cost of a one-hour outage is considerably higher at $7,795, the difference between the cost of a one-hour outage and a one-second outage is far less than you would expect if costs accrued evenly from the beginning of an outage until its end. A one-second outage is less than 0.03% as long as a one-hour outage, but the cost of a one-second outage is almost 20% of the cost of a one-hour outage. Instead, the data show that an outage of any length, even 1 second, creates a substantial loss. Furthermore, the average cost of a recloser event is higher than a simple 1-second outage or even a 3-minute outage.

Average Cost per Outage by Duration



Distribution of Costs per Outage by Duration

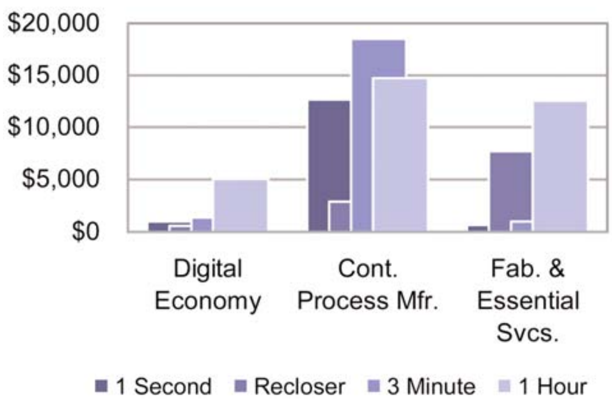


For each outage type, the figure at bottom left shows the percentage of surveyed business types that experience different levels of costs. What is most striking in this figure is how many businesses experience no costs at all from outages. Almost three-quarters (74%) can ride through a one-second outage with no costs, whereas 65% experience no costs from recloser events. Half of all businesses (50%) would not suffer measurable costs from a three-minute outage and a quarter (26%) would not experience real costs from a one-hour outage. The typical cost of a one-hour outage to most (56%) DE, CPM, and F&ES establishments is less than $500. How can the average cost of a one-hour outage be almost $8,000? The answer is that the majority of establishments with relatively small costs are balanced by a small number of establishments with very large costs. Five percent of the establishments in these sectors incur costs from a one-hour outage of $20,000 or more, with costs for individual establishments ranging as high as $1.5 million.

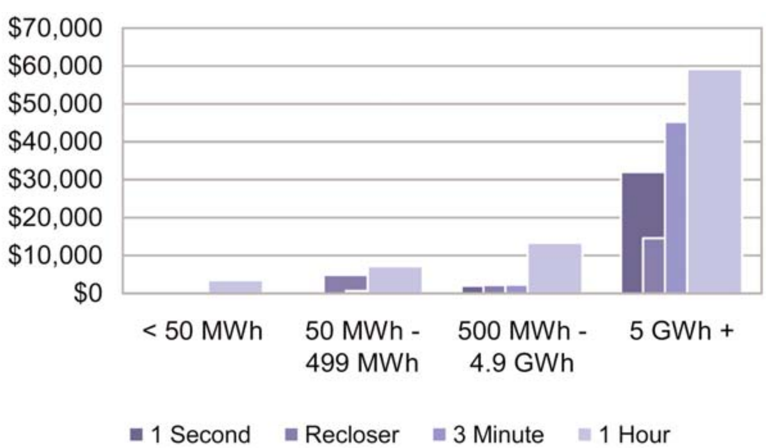
Outage Costs by Sector and kWh Consumption

Outage costs vary both by the duration of the outage and by sector. The figure below at top shows the average cost of each of the four outage types for each of the three sectors surveyed. Outage costs are highest in the CPM sector for one-second, one-minute, and one-hour outages, with average costs of $12,654, $18,476, and $14,746, respectively. The F&ES sector has the highest costs for recloser events, averaging $7,704. The DE sector has lower outage costs than the other two sectors across the board.

Average Cost per Outage by Sector and Duration



Average Cost per Outage by Annual kWh and Duration



The figure at bottom left charts these same outage costs, this time broken out by annual kWh consumption rather than sector. In terms of power consumption, larger business establishments experience larger costs from outages. The pattern is most dramatic at the highest end of the scale, with establishments that consume 5 GWh or more annually experiencing very high costs—for example, $32,000 for a one-second outage and more than $59,000 for a one-hour outage. To put this into perspective, the survey data show that 3% of all establishments across the three sectors consume 5 GWh or more annually.

Outage Costs as a Function of Business Activities and Equipment

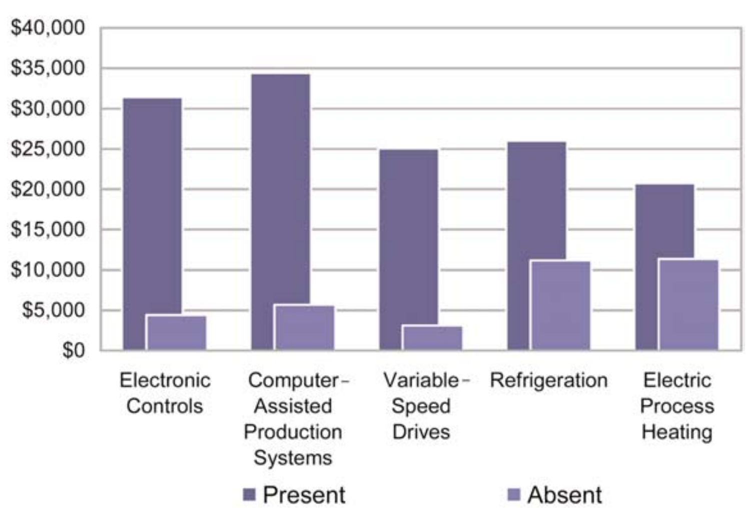
The logic for assuming that certain sectors, such as those surveyed for this study, have higher outage costs than others is that the disruption of certain types of industrial equipment or certain business processes is more likely than the disruption of other types. Where it was possible to capture data on the presence or absence of specific technologies, equipment, or processes among the establishments surveyed, their effect on outage costs was tested.

The figure at top of the following page compares the average cost of outages among DE establishments that have a significant data-processing operation onsite and DE sites that are not engaged in large-scale data processing. As expected, outage costs are consistently higher for DE establishments engaged in data processing. The difference is especially pronounced for the shortest outages. The cost of a one-second outage is 3.5 times higher for DE establishments with data-processing operations than for those without such operations; for recloser events, there is a six-fold difference in costs between the two types of establishments.

Average Cost per Outage for DE by Data Processing and Duration

The figure below makes similar comparisons for industrial establishments, both CPM and F&ES, with and without a variety of specific equipment and processes.[5] To simplify the presentation, we focus on a single outage type: one-hour. Similar patterns emerge for the other outage types. Here, the most dramatic cost differentials are for variable-speed drives—an eight-fold increase in costs versus establishments without these devices—although electronic controls and computer-assisted production systems yield similar cost increases.[6]

Average Cost of One-Hour Outage by Selected Industrial Equipment and Processes



The Impact of Advance Notice on Outage Costs

In the case of *planned* outages, in which the electric utility knows in advance when a power outage will be and which customers will be affected, the utility can notify business customers that an outage is on the way. In theory, such notification should allow them to change their operations and schedules to minimize the financial impact of the outage.

In California, the independent system operator (ISO) can often provide customers with a warning that rolling blackouts are *possible* the following day. The ISO typically has less advance information about when a rolling blackout will *actually* happen. Realistically, the most advance notice that the ISO can give customers for an actual rolling blackout is one hour, and the available notice is often much less.

But does either form of advance notice—a day's notice that rolling blackouts are likely or an hour's notice that a rolling blackout will occur—really allow businesses to reduce their outage costs? To explore this question, two additional outage scenarios were included in the survey to test the impact of advance notification. The first described a one-hour outage, preceded 24 hours earlier by a notice that rolling blackouts were possible the following day. The second described a one-hour outage, preceded one-hour earlier by a notice that a rolling blackout would occur.[7]

Being told that an outage *might* occur appears to be counterproductive.

The survey findings showed that advance notice can be effective if it is definitive about whether the outage will occur. The average cost for a one-hour outage when the customer was informed an hour before that it would occur was $6,918, versus a cost of $7,795 for a one-hour outage with no advance notice.

Being told the day before that an outage *might* occur, however, appears to be less helpful and perhaps even counterproductive. The average cost for a one-hour outage in this scenario was $8,173—slightly *higher* than the cost of a one-hour outage with no notification.

Breaking Down Costs

Many different costs contribute to PQ and reliability losses, as shown in the sidebar on p. 14.

Lost Production

Lost production is calculated by taking the costs of lost production minus the cost of production that would be made up over time.

Cost Variables

Several factors should be considered when calculating total cost of an outage:

Labor costs:

- Idle labor: Salaries and wages paid to staff who are unable to work
- Additional labor: Labor costs to make up lost production, sales, or services (such as overtime pay and extra shifts)

Material costs:

- Damage or spoilage to materials, finished products, or inventory

Additional Costs:

- Extra restart costs
- Overhead: Ongoing overhead expenses incurred during the outage and the restart period
- Equipment damages: Damage to an organization's building or equipment
- Extra backup costs: Costs to run and/or rent backup equipment
- Other: costs identified by respondents as a result of outage

Savings Variables

In addition, possible savings realized during an outage should also be considered:

- Unused material: Savings from unused materials or inventory
- Energy savings: Realized savings on energy bill
- Labor unpaid: Savings from wages that were not paid
- Other: Other savings identified by respondents as a result of outage

SOLVING THE PROBLEM: FINDING OPTIMAL SOLUTIONS FOR PQ AND RELIABILITY ISSUES

As described in detail above, PQ and reliability phenomena are extremely expensive for industry. How, then, are we to optimally mitigate these problems? The first step is to define quality levels that help characterize the quality of the supply and conversely help define what level of quality we need from a power system (combination of the utility and local support equipment). For simplicity, four levels of quality are specified here:[8]

- **Quality Level 1:** moderate voltage sags that fall within the ITI (CBEMA) curve
- **Quality Level 2:** Severe voltage sags
- **Quality Level 3:** Momentary power interruptions
- **Quality Level 4:** Long-duration power interruptions

Elements of Outage Costs—Where Does the Money Go?

The table below breaks out the average net cost of outages of different durations by the individual costs that the Primen/Intelligrid survey participants provided.[9] The table also shows the generally small savings that were subtracted from the total cost to calculate net cost. The recloser events had a surprisingly high average cost. Most of the cost for a recloser event comes from damage to the customer's equipment.

The primary cost differences between a longer (one-hour) outage and a brief outage arise from lost production or sales, idled labor, and costs of restarting operations after a significant amount of downtime. At first glance, some of the losses may seem out of proportion to the length of the outage. How is it possible, for example, that a one-second outage can yield measurable losses in production? The answer is that the disruption of a business's operations doesn't end the instant that power is restored.

Types and Magnitudes of Costs Resulting from Different Outage Durations

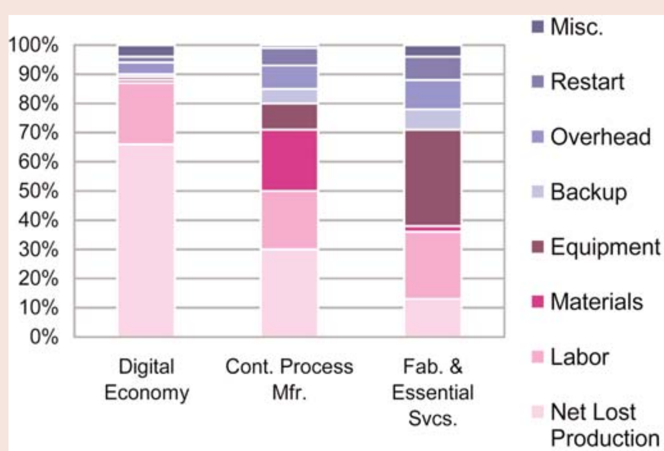
	1-Second	Recloser	3-Minute	1-Hour
Costs	**$1,489**	**$2,848**	**$2,124**	**$8,080**
Net lost production[a]	$284	$274	$466	$2,922
Labor	$433	$263	$590	$1,763
Materials loss or spoilage	$99	$68	$248	$231
Equipment damage	$554	$2,011	$500	$576
Backup generation[b]	$21	$64	$89	$449
Overhead	$33	$49	$101	$364
Other restart costs	$60	$46	$121	$1,457
Misc.	$5	$73	$9	$318
Savings	**$12**	**$0**	**$17**	**$285**
Unused materials	$10	$0	$14	$263
Savings on energy bill	$2	$0	$2	$16
Unpaid labor	$0	$0	$1	$6
SavingsNet cost	**$1,477**	**$2,848**	**$2,107**	**$7,795**

[a] Or net lost sales.
[b] Includes cost to run and/or rent backup generation.

The three sectors surveyed also differ in the types of outage costs that they experience. The figure at right shows the difference for a one-hour outage. The DE sector, which has the lowest net cost for a one-hour outage ($5,053), incurs most of its costs from lost production/sales and labor costs.

In contrast, CPM establishments, which have the highest net cost for a one-hour outage ($14,746), experience significant costs from raw materials loss, as well as some equipment damage. The F&ES sector, which also has a relatively high net cost of $12,562 for a one-hour outage, shows yet a third pattern: high losses from equipment damage but virtually no loss of raw materials.

Distribution of Typical Costs for Different Sectors (1-hour Outage)



An analysis to find power system and solution configurations to optimally mitigate PQ problems includes several steps:

1. Find the mean time between failure (MTBF) of each power system and solution configuration.
2. Estimate the annual equivalent configuration cost of each.
3. For each configuration, find the annual outage cost based on the MTBF.
4. Rank each scenario based on the total annual cost, which is the sum of the configuration costs and the outage costs.

The table below shows the typical number of events per year categorized by the type of utility system and the four utility supply quality levels. The further away from the transmission system and the lower the PQ level, the higher the number of events per year.

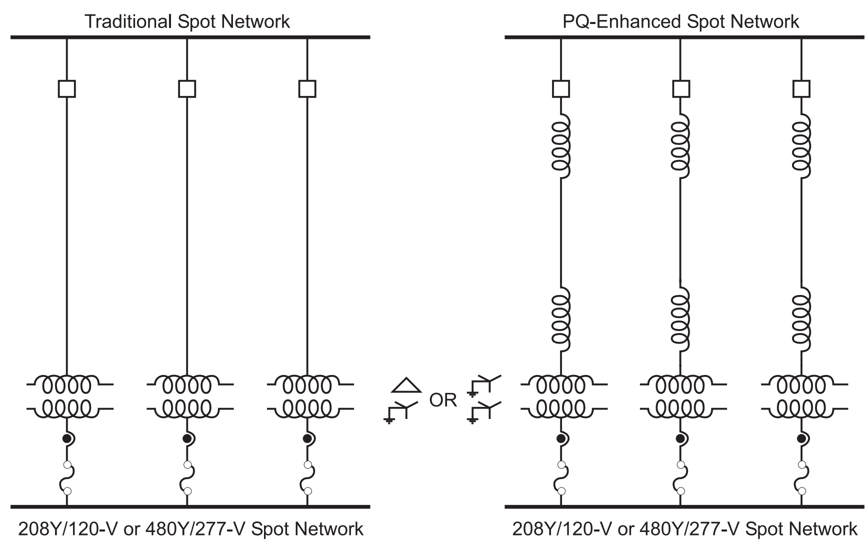
Optimizing Power System Design and Configuration

New utility-side solutions are needed to address voltage sags and momentary interruptions. For example, a PQ-enhanced spot network, as shown in the figure below, can mitigate the effects of voltage sags. The added reactors minimize the level of voltage sags caused by primary feeder faults. This configuration is just in the conceptual stage, but we could implement it with existing technology.

Default Utility Supply Characteristics for PQ and Reliability Analysis

Type of Utility System	Utility Supply Quality Levels			
	1 Moderate Voltage Sags	2 Severe Voltage Sags	3 Momentary Interruptions	4 Long-Duration Interruptions
Rural distribution supply	28	13	7	3
Suburban distribution supply	19	8	3	1.3
Urban distribution supply	12	4	0.7	0.2
Urban network supply	12	4	0.02	0.02

Comparison of a Traditional Spot Network to a Configuration with Added Reactors to Minimize the Voltage Sags Caused by Primary Feeder Faults



CASE STUDY

Finding Optimal Solutions: A Case Study

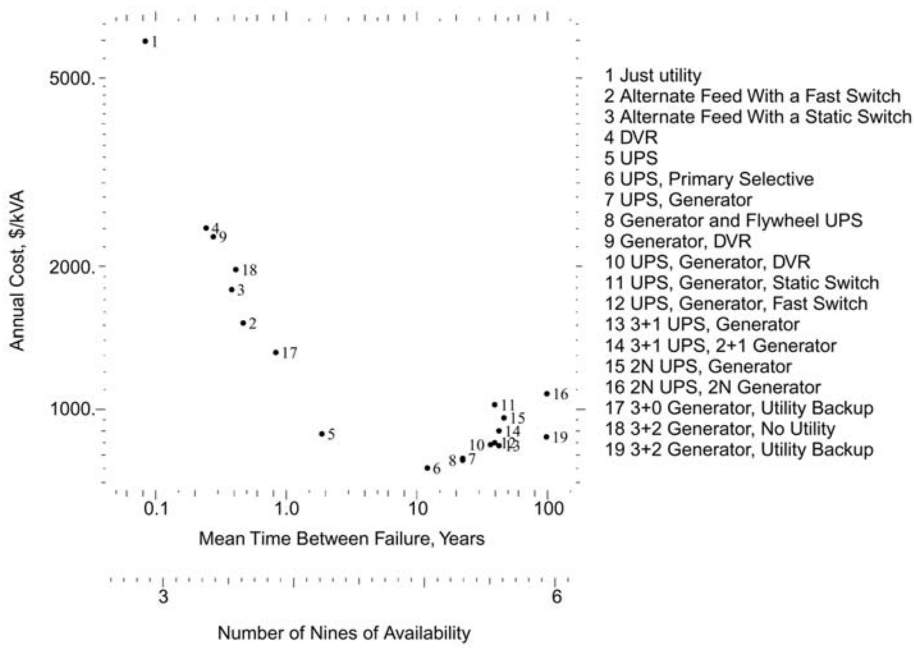
Data centers, especially Internet data centers, have grown phenomenally in recent years. In many ways, these facilities are considered great utility loads, because they have very high load densities and have a high load factor. Some of the features of Internet data centers are:

- They have load densities of 25 to 50 W/ft^2 or more.
- They demand very high quality power.
- Most of the load is either critical computer load, telecommunication load, or air conditioning.
- They typically have redundant UPS systems and redundant generators.

The figure below shows some of the utility-side and facility-side solutions that were investigated for a data center along with the cost of each. The figure shows the total costs of each configuration (outage costs plus configuration costs) for the case where one outage has a cost equal to the annual electric bill ($920k per outage).

In each case study, care was taken to first analyze the potential losses incurred by the facility versus the generalized cost of potential solutions. Then, cost estimates for a wide variety of potential solutions were estimated and ranked based on cost effectiveness. Each of the case studies had widely differing results and optimal solutions.

Finding the Optimum Solutions: Minimizing total combined costs of both process interruptions and mitigation



Finding the optimal solution to a facility's PQ and reliability problems is a balancing act between the cost of the mitigation and the cost of process interruptions. The goal should be to minimize these combined costs by investing only as much in mitigation as makes financial sense. In the example shown here, a data center with estimated cost-per-outage of $920,000 per event can achieve minimal combined costs (shown in annual costs per kVA of load) by using an uninterruptible power supply (UPS) incorporating two independent sources of primary AC power (shown as Option 6). Other options may offer better protection from interruptions, but at higher cost per kVA (those shown to the right of Option 6), while the remainder may be less expensive to install and operate, but do a poorer job of mitigating interruptions.

Some conclusions of the case studies include:

- One size doesn't fit all. The optimal solution depends on many factors: facility size, how convenient a second utility feed is, cost of facility interruptions, and the sensitivity and types of facility equipment.
- The outage cost plus the configuration cost does not represent what some facilities are willing to pay for performance. Some facilities are willing to pay much more for better performance (more redundancy, less chance of failure) than their actual outage costs.
- Load ride-through enhancements effectively increase performance in many situations for a relatively small cost.
- The utility-side options are most suitable for large commercial and industrial facilities.
- Distributed generation options look potentially viable for many high-performance needs (if the utility is present as a backup).

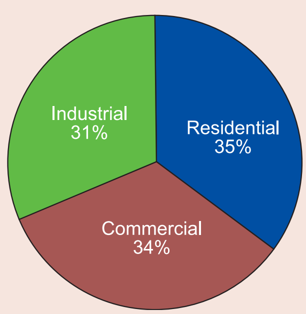
What Portion of the U.S. Electric Load Is Digital?

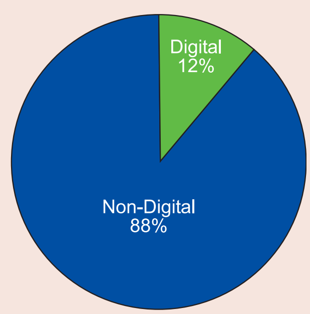
Digital technologies have a broad influence on modern societies. The basic digital building blocks such as microprocessors have enabled a wide range of applications, greatly influencing the residential, commercial, and industrial sectors. In turn, these capabilities support whole digitally enabled enterprises, whose modern form is entirely based on digital technologies. Examples include banking, security, data warehousing, telecommunications, etc.

In 2001, the residential, commercial, and manufacturing sectors in the United States used 3,392 trillion watt-hours (TWh) of electricity. Of this, 391 TWh, or 12%, were used for digital applications, whether directly by digital devices and applications, indirectly by manufacturing these systems, or indirectly by using these systems for digitally-based services. The table and figures below provide details of both digital and non-digital use of electricity by sector in 2001.

Amount of Energy Used by Sector (U.S.) and the Percentage of that Considered to be "Digital"

Sector	Total (TWh)	Digital (TWh)	Non-Digital (TWh)	% Digital
Residential	1,183	150	1,034	13%
Commercial	1,142	148	994	13%
Industrial	1,067	93	974	9%
Total/Average	3,392	391	3,001	12%





What Portion of the U.S. Electric Load Is Digital?, continued

In the industrial sector, approximately 9% of 2001 energy use could be characterized as "digital." The bulk of this came in the form of electronic component manufacturing and automated process control. The table below shows the digital and non-digital use of electricity by industry segments in 2001.

Digital and Non-Digital Energy Use (U.S.) by Various Industry Segments

Category	Total (TWh)	Digital (TWh)	Non-Digital (TWh)	% Digital	% of Digital Total
Digital segments					
3341 - Computer	7.7	7.7	—	100%	8%
333295 - Semiconductor	1.1	1.1	—	100%	1%
3335 - Metalworking	4.1	4.1	—	100%	4%
3342 - Communications	4.6	4.6	—	100%	5%
3343 - Audio & visual	0.8	0.8	—	100%	1%
3344 - Electronic component	21.5	21.5	—	100%	23%
3346 - Magnetic & optical	2.1	2.1	—	100%	2%
339112 - Surgical & medical	1.8	1.8	—	100%	2%
2245 - Navigational/control	8.3	8.3	—	100%	9%
Subtotal digital segments	**52**	**52**	**–**	**100%**	**55%**
End uses in non-digital segments					
Automated process control	32	32	—	100%	34%
Facilities support	14	7	7	100%	8%
Machine drive	564	2	562	0.3%	2%
Lighting	56	0	56	0.6%	0%
Other end uses	350	1	349	0.2%	1%
Subtotal end uses in non-digital segments	**1,015**	**42**	**974**	**4.1%**	**45%**
Industrial total	**1,067**	**93**	**974**	**9%**	**100%**

NOTES

1. The contents of this section draw heavily from the definitive work found in Shawn McNulty, Primen, *The Cost of Power Disturbances to Industrial and Digital Economy Companies*, TR-1006274, (Palo Alto, CA: IntelliGrid/EPRI, 2001).
2. IEEE Standard 493-1997: *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book),* (Piscataway, NJ: The Institute of Electrical and Electronics Engineers, 1997).
3. IEEE [2]
4. The precise timing and sequence varies by region according to local utility practice.
5. Digital economy establishments were excluded from this figure due to the low incidence of these types of equipment and processes in the DE sector.
6. Note that the cost increases associated with different technologies and processes are not additive.
7. Obviously, there are other issues beyond whether advance notification is helpful to customers, notably the public safety and security implications of broadcasting that a particular area will be without power at a particular time.
8. The content of this section relies heavily upon Tom Short, Bill Howe, *Analysis of Extremely Reliable Power Delivery Systems: A Proposal for Development and Application of Security, Quality, Reliability, and Availability (SQRA) Modeling for Optimizing Power System Configurations for the Digital Economy*, (Palo Alto, CA: IntelliGrid/EPRI, April 2002).
9. Shawn McNulty [1]