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ELECTRICITY CASE: MAIN REPORT – RISK, CONSEQUENCES, AND ECONOMIC ACCOUNTING

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Center for Risk and Economic Analysis of Terrorism Events
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Electricity Case:
Main Report – Risk, Consequences, and Economic Accounting

CREATE Report

Preliminary Report, May 31, 2005

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Abstract

As a critical infrastructure sector, electricity enables numerous other critical infrastructures to function, and in many cases is the critical path for their operation. This is underscored by the fact that historically, electric power outages have played a central role in disruptions of many other infrastructures. As a consequence of the centrality of its role, electricity is potentially a key target for terrorist attacks. This case sets forth risks in terms of hypothetical alternative attack scenarios in the form of various grid configurations that are vulnerable based on both natural events in the U.S. and terrorism internationally as well as in terms of the odds that outages will occur and other characteristics of outages will change. Consequences are then identified based on hundreds of events and other records that portray the effects that electric power outages have on key public services and businesses. Economic accounting is conducted in terms of human premature death and injury and business loss for some of the key consequence areas, using a wide range of economic factors.

The work presented in this report is complemented by the work of other team members. In the risk area, Bier's study at the University of Wisconsin portrays the effect on the capacity of hypothetical grids to carry and redistribute electricity under alternative interdiction scenarios. For consequences, the work of Chen at USC identifies electric power system performance following a catastrophic event. As consequences and economic accounting, Greenberg, Laer, and Mantell, part of the NYU team, are conducting a model of effect of electricity outage on the economy of New Jersey, the densest and wealthiest state in the U.S.

<u>Current Reports in the Electricity Case series (the Main Report should be used in conjunction with these other reports)</u>:

Electricity Case: Main Report – Risk, Consequences, and Economic Accounting – Report 1

Electricity Case: Economic Cost Estimation Factors for Economic Assessment of Terrorist Attacks – Report 2

Electricity Case: Statistical Analysis of Electric Power Outages – Report 3

Risk Analysis of Infrastructure Systems – Different Approaches for Risk Analysis of Electric Power Systems – Report 4

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LIST OF PUBLICATIONS AND CONFERENCE PROCEEDINGS SUPPORTED BY THIS PROJECT

R. Zimmerman and C. Restrepo (2005 forthcoming) "The Next Step: Quantifying Infrastructure Interdependencies to Improve Security," *International Journal of Critical Infrastructures*, UK: Inderscience Enterprises, Ltd.

R. Zimmerman, C. Restrepo, N. Dooskin, J. Fraissinet, R. Hartwell, J. Miller and W. Remington (2005) "Diagnostic Tools to Estimate Consequences of Terrorism Attacks Against Critical Infrastructure," Proceedings of the U.S. Department of Homeland Security conference, *Working Together: Research and Development Partnerships in Homeland Security*, Boston, MA.

R. Zimmerman (2005 forthcoming) "Critical Infrastructure and Interdependencies," in *The McGraw Hill Handbook of Homeland Security*, David Kamien, ed. New York, NY: McGraw Hill, 2005.

R. Zimmerman (2005) "Mass Transit Infrastructure and Urban Health," *Journal of Urban Health*, Vol. 82 (1) 2005, pp. 21-32. http://jurban.oupjournals.org/cgi/content/abstract/jti005?ijkey=72UoUhyHAe1hI&keytype=ref

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Jared C. Carbone, Daniel G. Hallstrom, and V. Kerry Smith (2005 forthcoming) "Can Natural Experiments Measure Behavioral Responses to Environmental Risks?" *Environmental and Resource Economics*.

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EXECUTIVE SUMMARY

Within the critical infrastructure sectors, electricity enables numerous other critical infrastructures to function, and in many cases is the critical path for their operation. Moreover, historically, electric power outages have played a central role in disruptions of many other infrastructures. As a consequence of this, electricity is potentially a key target for terrorist attacks. The risks associated with a hypothetical attack arise are associated with various configurations of and components within the electric power grid, that have shown to be vulnerable during both natural events in the U.S. and terrorism attacks in over two dozen countries internationally. Consequences appear in the form of delays in and destruction of facilities that provide key public services and support businesses. Typically the largest consequences are direct impacts on businesses in terms of losses in production and revenues, damaged equipment, and other factors. Economic accounting can begin to quantify human premature death and injury and business loss for some of the key consequence areas, using a wide range of economic factors.

GOALS OF THE ELECTRICITY CASE

The goals of the electricity case are to: (1) identify risks, consequences and economic accounting for hypothetical attack scenarios on the electric power grid, including an extreme and a relatively more moderate scenario, and (2) as an outcome of the analysis, develop a tool to support the assessment, anticipation and prioritization of risks, consequences, and economic impacts of terrorist attacks on electric power. The unique contribution is the use of experiences of domestic non-terrorist outages and terrorist attacks internationally to understand terrorist attacks in the U.S. with which the U.S. has had no direct experience.

APPROACHES TO RISK, CONSEQUENCE AND ECONOMIC ASSESSMENT

The risk of an electric power disruption occurring is estimated in terms of general configurations of the electric power grid that contribute to its vulnerability to attack and the probability of such a disruption occurring using a combination of statistical analyses to identify components at risk. These statistical analyses are conducted for databases of international terrorist attacks on electricity and domestic disruptions from non-terrorist, but including criminal causes that are analogous to terrorism. Consequences are primarily identified through extensive case and literature reviews, incorporating interdependencies among critical infrastructure systems. Indicators of interdependency are developed as a means of portraying the direction and extent of consequences. Economic assessment has as its centerpiece an accounting framework that draws heavily upon a set of economic factors based on extensive case reviews and literature. These factors are presented and described in a separate report. The accounting is conducted in the areas of human premature death and injury, business losses, and disruptions in public services.

Risk

Risks of attack on electric power outages encompass the likelihood that attacks on electric power will occur, the vulnerability of components of the electric power system to being damaged in or targets of such attacks, and the likelihood and severity of those vulnerabilities being taken advantage of in attack strategies. Risk of attacks on electric power outages has little history in the U.S. upon which to base such estimates, so two approaches are taken.

First, the manner in which disruptions are likely to occur and their severity within the electric power system are portrayed in terms of general configurations of the grid based on inputs from team experts in the electric power field, the advisory board, literature reviews and an analysis of the components that have disrupted in past events. Given the knowledge about how the grid and its components operate, illustrative scenarios are constructed that reflect combinations of component and their characteristics that will lead to varying degrees of damage. These are shown in the Figure 1 and described in the main report, and are as follows.

Extreme Scenario: Selection of Extreme Electric Power Configuration plus Extensive Consequences / Economic Impacts. The most extreme configuration of an electric power failure is in a region that relies on (1)transmission lines that follow only one or two routes (2)very few large substations and transformers connected to transmission and (3)no in-region capacity to produce independent electric power. Examples of such cities are Seattle, San Francisco and Chicago. The scenario assumes that the electric power system becomes disabled at all three of these levels - no transmission, substations, and generation capacity.

Moderately Extreme Scenario. Moderately Extreme Electric Power Configuration plus Extensive Consequences / Economic Impacts. This is the same as Scenario 1 is the same as arrangement as in scenario 1 but with substantial in-region capacity to produce independent power. NYC is an example of such an area. Its major transmission lines are very constrained coming in at two locations from the north and west, but by law NYC has 80% in-city generation, that is, power plants within the city are required to provide 80% of the generation capacity needed. In spite of this requirement, however, programming and operational procedures cause those plants to shut down if the equipment is threatened as it was in the 2003 blackout.

Moderate Scenarios. These involve smaller areas with or without incity generation, but which rely on electric power sources from many different directions. Thus, disabling some will not necessarily be totally disabling.

Discussion and Rationale: Why transmission? An extensive statistical analysis of U.S. non-terrorist electric power outages and non-U.S. terrorist attacks on electric power shows that transmission systems are the most frequently disabled systems – usually sixty percent of terrorist attacks to ninety percent of non-terrorist events show disabling directly of transmission. Why transformers? Transformers are the most unique and difficult to replace components of an electric power system. On-site repairs can take at least two weeks. Repairs requiring the transport of the transformer can take several months, and the complete replacement of a transformer can take about a year, given that transport of transformers requires specialized trucks and permits, only a few construction facilities exist, and each transformer is unique requiring special wiring to install it.

Second, electric power outages from terrorist attacks in countries outside the U.S. and non-terrorist attacks within the U.S. are in addition to identifying electric power components at greatest risk, also portray the likelihood of events occurring in the future. An analysis of international terrorist attacks on electricity is undertaken. However, given that few if any direct terrorist attacks have occurred on electric power in the U.S., an “all-hazards” approach is initially adopted to identify key points of failure and vulnerability as inputs to conducting risk and consequence assessments. The all-hazards approach is consistent with the governmental strategy that has been put forward for emergency response (U.S. DHS, March 2004). In the case of electricity outages, non-terrorist hazards are primarily related to natural hazards such as storms, earthquakes, and floods as well as accidents and incidents that provide analogies to terrorism such as sabotage and vandalism. The evaluation of U.S. outages yields the following result: the odds that an outage event will occur increases by about 9% per year (based on actual outages between 1990 and 2004). The statistical analysis arrived at a similar finding for duration at the level of individual events – about 14% per year, however, the change in duration of the events is non-linear over time. The change in duration was largely attributed to changes in the causes of events over time.

Consequence

Consequences of electric power outages are characterized in terms of which sectors are disrupted and the magnitude and severity of those disruptions. These are identified in several ways.

First, databases on critical infrastructures and business dependency on electric power provide a basis for identifying those sectors at greatest risk of disruption from electric power outages based on how much electric power they use. These databases include conventional input-output tables (U.S. Department of Commerce, Bureau of Economic Analysis (BEA), but also data on sales by specific utilities to other sectors of the economy from trade associations (Edison Electric Institute) and government utility data (U.S. Department of Energy, Energy Information Administration).

Second, the databases of previous electric power outages provide a rich set of cases of outage consequences for statistical and case-based analysis. Databases for both non-terrorist domestic outages and international terrorist attacks on electricity were used in order to arrive at common modes and consequences of attack. This was accomplished by mapping components attacked in terrorist incidents (where no information on consequences was available) to similar components in non-terrorist outages (where consequences were known). In that way, consequences of potential terrorist attacks could be inferred or “assigned” from non-terrorist databases.

Third, the event databases are also used to develop indicators to quantify interdependencies between electric power outages and impacts as a basis for understanding and estimating the direction and magnitude of consequences (Zimmerman and Restrepo 2005). The databases are also used to conduct in-depth statistical analyses to derive predictive models of the impact of outages.

Fourth, research on selected specific activities in critical infrastructure sectors provides information not only about how much electricity is used, but how it is used to drive critical functions. For example, there are 9 billion passenger trips on transit systems in the U.S. per year (U.S. DOT 2003). These systems are vulnerable, through their dependency on electrified rail and diesel electric motors that result in the abrupt termination of train service, signaling systems, fare collection systems, elevators, and escalators and there are potentially high consequences due to the concentration of people in those systems at certain times during their operation. Roadway vulnerability is reflected in the dependency of traffic lights and gas station pumps on electric power and although traffic is distributed over a larger number of miles, local congestion is increasingly a problem and is like transit concentrating larger numbers of people in a few locations.

Fifth, extensive case histories of electricity outages provide a rich dataset of the kinds of consequences likely to occur from outages. One key example is a transit disruption by electric power - large mass transit usage (with constrained choices at the regional level) dependent on the affected power grid, a dense, easily congested roadway with a few massive bottlenecks, and/or the existence of large or a large number of industrial, commercial, or residential users of electricity. The NY region, for example, has the largest system and accounts for the majority of ridership in the nation with 40% of the 9 billion passenger trips a year on the nation's transit systems (USDOT, FTA, National Transit Database) or 1.4 billion boardings for urban rail in the city, and following NY is CA ridership. Since 1959 when it sold most of its substations to Con Edison (Payne), it is dependent on Con Ed, the major electricity provider, for power. Moreover, although the system has a lot of flexibility for rerouting riders within the City, there are some extreme bottlenecks for regional transit. The long-distance rail bottleneck is the Portal Bridge over which Amtrak and NJ Transit depend and the PATH tunnels. Surface alternatives are also constrained by the existence of only two nearby bridge options – the George Washington and Verrazano bridges and two tunnel options (the Holland and Lincoln Tunnels). Several other east-west crossings exist are much further to the north, though if these were used as options, they would depend on only 3 or 4 major north-south crossings to bring passengers into or around the city and numerous other smaller crossings between the Bronx and Manhattan, basically equivalent to narrow streets. The City has generally adopted a policy to shutdown or severely restrict travel on roadways leading into the city in the event of a crisis as it did on September 11, 2001. Given the failure of all surface (road) and transit options, the city would have to depend upon water and air transport to move goods, services, and people.

Economic Assessment

Consequences are a necessary prerequisite for economic impacts. These impacts range from the direct cost to business of lost production, sales, equipment damage, etc., cost of delays in public services given the duration of an outage that support economic and social activity, and loss of life and injuries. Cost estimates are obtained from the literature on public service disruption and delay as well as from prior outages and other extreme events. Risk management and risk reduction options are discussed and their potential to alter the magnitude and direction of the risks, consequences and economic impacts.

Economic accounting proceeds in several different stages. First, for illustrative purposes some simple computations are provided to bound the problem of economic assessment. Second, a forthcoming work to estimate the impact of a temporary electric power outage on the State of NJ will use a number of models applied to economic characteristics of that state as a model for other areas.

As a frame of reference, a loss of $40 billion is used, which approximates the amount paid out for losses after the September 11, 2001 attacks (though it does not include amounts for rebuilding and reconstruction). The objective of each computation is to derive the effects that would be required to reach a total cost of $40 billion in terms of premature deaths and business losses, computed separately. Obviously, any combination of different estimates (many of which are presented in the "Electricity Case: Economic Cost Estimation Factors for Economic Assessment of Terrorist Attacks" report should be used to create more complex scenarios. These calculations aim at answering the question of how many premature deaths or a duration of an outage would it take to reach a $40 billion loss.

Premature Deaths. This computation assumes the U.S. EPA estimate of $5.8 million (adjusted to 2005 dollars from the original $4.9 million) per premature death. If no other impact is included, this implies that <u>6,897 deaths</u> would comprise a loss of $40 billion from premature deaths alone. This is more than double what actually occurred in the U.S.'s worst terrorist attack, however, it is many times lower than the instantaneous loss of 230,000 lives in the Tsunami disaster of December 2004. For such a level of premature deaths to occur by means of an electric power outage would require civil unrest of a magnitude greater than what occurred in the 1977 outage or a secondary attack intentionally accompanying and taking advantage of the outage, such as an attack on a heavily populated building or train system as happened in Madrid in 2004 or a dam near a heavily populated area.

Business Loss. An average Gross Domestic Product (GDP) can be computed for any region or the nation as a whole by dividing the GDP by the applicable population. For the nation as a whole, this comes to $112.84 of GDP per person per day. The details of this calculation are contained in the economics report. A check on the estimate is provided by the August 2003 blackout. Multiplying $112.84 by the 50 million people affected yields $5.64 billion in business losses, which is at the lower end of the estimates of economic impact of the outage estimated at between $6-10 billion (there were few other categories of loss, such as premature death). For the New York Region with a population of about 20 million (in the 21 county region), estimated loss for an outage lasting one day would be $2.26 billion. This means that an outage would have to last <u>17.8 days</u> in order to incur a loss of $40 billion from business losses alone (multiplying $112.84 by 20 million and dividing $40 billion by that amount, i.e., by 2.26 billion dollars).

Public Services. Time delay created by congestion, often intense, constitutes the major cost in a catastrophe. An extensive array of estimates is available per capita, per hour, per hourly wage, by income of passengers, by type of vehicle, etc. Using the more common per hour and per hourly wage estimates of $35 per hour and $50% of the hourly wage rate, and applying them to prevailing wage rates and the entire population in the hypothesized four urban areas, one obtains the following estimates (these tables appear in the Consequences section as well):

Table E-1. Estimating the cost of a 24-hour outage for the New York Metropolitan Area

Hourly Wage	Total wages	Cost of congestion (50% of hourly wages)	Cost of a 24-hour outage
9.10	92,601,008	46,300,504	1,111,212,096
16.00	162,814,960	81,407,480	1,953,779,520
22.04	224,277,607	112,138,804	2,691,331,296

Note: This table is identical to Table 8 in the Detailed Report below.

The workforce of the New York Metropolitan Area in 1990 was 9,346,645 (New York State Department of Labor figures. See: http://www.labor.state.ny.us/labor_market/lmi_business/eeo/nyjcnmsa.htm - access date May 31, 2005). This represents about 48% of the total population. Considering that the total population of the New York Metropolitan Area in 2000 was 21,199,865 (U.S. Census Bureau. Census 2000 PHC-T-3. Ranking Tables for Metropolitan Areas: 1990 and 2000. Table 1: Metropolitan Areas and their Geographic Components in Alphabetic Sort, 1990 and 2000 Population, and Numeric and Percent Population Change: 1990 to 2000. Available at: http://www.census.gov/population/cen2000/phc-t3/tab01.pdf), the estimated total workforce is estimated to be 10,175,935. This figure is multiplied by the hourly wage in the column titled 'Total wages' to obtain an estimate for the total hourly wage of the workforce in the New York Metropolitan Area, which includes New York City, northern New Jersey and southern Connecticut. The figures for total wages and then multiplied by 0.5 to obtain an estimate for cost of congestion for the total workforce for one hour. These figures are then multiplied by 24 to obtain an estimate of the cost of a 24-hour outage. The results suggest a range of $1,111,212,096 to $2,691,331,296 for the cost of a 24-hour outage in the New York Metropolitan Area. One should note that although a power outage might last as long as 24-hours, the congestion might not last that long, but the calculations are based on the assumption that in fact the congestion does last as long as the outage.

Table E-2. Estimating the cost of a 24-hour outage for New York City

Hourly Wage ($/hour)	Total wages ($)	Cost of congestion (50% of hourly wages - $))	Cost of a 24-hour outage ($)
9.10	33,296,900	16,648,450	399,562,800
16.00	58,544,000	29,272,000	702,528,000
22.04	80,644,360	40,322,180	967,732,320

Note: This table is identical to Table 9 in the Detailed Report below.

The workforce of New York City in 2000 was approximately 3,659,000 (New York State Department of Labor figures. See: http://64.106.160.140:8080/lmi/laus_results2.jsp?PASS=1&area=21093561New+York+City – access date May 31, 2005). This figure was multiplied by the hourly wage figures to obtain an estimate of the total wages for the New York City workforce for one hour. The figures for total wages and then multiplied by 0.5 to obtain an estimate for cost of congestion for the total workforce for one hour. These figures are then multiplied by 24 to obtain an estimate of the cost of a 24-hour outage. The results suggest a range of $399,562,800 to $967,732,320 for the cost of a 24-hour outage in the New York Metropolitan Area.

These estimates are the time lost to the individual. While the blackout is occurring, these costs might already be included as business losses, and hence be double-counting. However, in the day or two days afterwards, when power is restored there is a catch-up effect and these costs can reflect that as an added cost.

DECISION TOOL AND ILLUSTRATION

The illustrations above provide the basis for a decision tool for conducting an economic accounting of disabling electric power systems in the event of a terrorist attack. Users of this information will be able to first select from among outage scenarios based on different kinds of vulnerabilities of the electric power system. These outage scenarios can then be linked to specific geographic areas and hence, alternative consequences, and to economic estimates for a final accounting. Flexibility is afforded by the range of estimators available. Choices are made at a number of levels, namely, the choice of: an electric power outage configuration, the linkage of the outage to consequences, and the linkage of consequences to economic impacts. It must be clear that it is the combination of the choices at each of these three levels that leads to a worst case scenario. That is, a worst case outage might not lead to a worst case outcome if the consequences and economic of the outage are very modest. Likewise, a moderate level outage may become a worst case if the consequences and economic impacts are vast. There are obviously many more combinations possible.

DETAILED REPORT

BACKGROUND

Importance of Electricity as a Critical Infrastructure and its Vulnerability
(Portions of this section are drawn from Zimmerman 2005c forthcoming)

Significance for the Economy

Electricity has an important place in the U.S. economy. This is evident from its share of the gross domestic product (GDP), its share of GDP relative to other infrastructure, and the nature of the trends in energy usage. This context is important as a basis for framing the consequences of electricity disruption. Lave (May 2005: 1; see Appendix B) provides a first approximation, noting that: "A first way to examine the cost to the nation of a power failure is to observe that the electricity sector sold $270 billion of power in 2003, about 2.4% of GDP (U.S Energy Information Agency, U.S. Department of Commerce (BEA website))." In terms of the place of electric power relative to other infrastructure as a whole, Henry and Dumagan (2004: 155) point out that infrastructure sectors account for about 10% of the economy, thus, electric power accounts for about one quarter of that. Translating this into an initial estimate of a power outage using these broad economic relationships, Lave notes further that ". . . the economic loss could be approximated as $740 million dollars per day for a nation-wide power outage." This, however, is a lower bound estimate, since it underestimates subsequent impacts, for example, the use of electricity for heat and lighting as well as for communication, electronics, and operations for many sectors.

Between 1998 and 2002, electricity use in the United States has increased 14-fold from about 255 billion kilowatt-hours to about 3,600 billion kilowatt-hours. This increase is at a far greater rate than the increase in population, which less than doubled in that same period, increasing from 152,271,000 in 1950 to 282,434,000 in 2000 (U.S. Bureau of The Census; Zimmerman et al. 2005). The rise in energy usage over time is shown in Appendix Figure A-1 in terms of energy consumption and Figure A-2 in terms of electricity consumption.

The significance of electricity is also reflected in what has happened in past outages. Interruptions in electricity in the form of intermittent outages have accompanied the dramatic rise in the consumption of electricity. The U.S.-Canada blackout of August 14, 2003, is estimated to be between $6 billion and $10 billion, and the upper part of this range approaches about a quarter of the estimated costs to victims of the September 11, 2001 attacks on the World Trade Center. Reliability problems in general in electric power have been estimated nationwide by different studies to be $26 billion, $150 billion and $119 billion (summarized by LaCommare and Eto 2004: 11-14).

Industry Concern

One measure of the extent to which the electric power industry is concerned about terrorism is its purchase of terrorism insurance. The insurance industry uses the measure "take-up rate" to connote "the percentage of companies buying the coverage" (Marsh 2005: 2). In 2004, 6.3% of the insurance premiums paid by utilities (a category that includes electricity, gas and water combined) was paid out for terrorism insurance. This was an increase over the 2003 percentage that was 4.9%. Utilities ranked fourth out of fifteen industrial categories with respect to percentage that terrorism insurance was of all insurance purchased by the sector. (Marsh 2005: 11).

Public Perception and Concern

The significance of electric power is reflected in public concern. Herron and Jenkins-Smith (2003) conducted a survey in 2002 and 2003 that revealed that out of a set of eight critical infrastructure areas (including banking and finance and emergency services), electric power systems ranked third (behind water and oil and gas) in terms of infrastructures of concern to the public with respect to security. The actual rating on a scale from 0 (no threat) to 10 (extreme threat), was 6.39 in 2001 and 6.63 in 2002 for electric power systems (Herron and Jenkins-Smith 2003: 28).

Vulnerability by Design

The electricity sector is particularly vulnerable to terrorist attack by virtue of its design and other characteristics.

Electricity is provided through a highly centralized production system and decentralized, but highly linear, single path networks for distribution.

Centralization, concentration, or disproportional distribution can be measured in a number of different ways. One method is through the use of location quotients or concentration ratios, scalable to any geographic area. The quotients compare the amount of a given activity or assets in a given area compared to some other distribution such as population, employment or value. This work is proposed for Year 2, however a few observations illustrate the problems.

Production. Electric power generation is relatively concentrated. The U.S. Department of Energy (DOE) reports 2,776 power plants in the U.S., about half of which (51.4%) are concentrated in only 11 states (Zimmerman, forthcoming 2005c; calculated from the U.S. DOE, EIA http://www.eia.doe.gov/cneaf/electricity/ipp/html1/ippv1te1p1.html). This characteristic does not even include the fact that "upstream" from electricity production critical infrastructures exist upon which electric power depends that are even more centralized, such as oil and gas refineries and extraction sites. There are a total of 225 petroleum refinery facilities, that are highly concentrated geographically, with about half (54%) located in only four states; in order of the number of facilities the states are Texas, California, Louisiana, and Pennsylvania (Zimmerman, forthcoming 2005a; calculated from U.S. Bureau of the Census 1997).

Distribution. Distribution systems for electricity are extensive and at the level of fuel transport and transmission are usually single lines with few branches, making alternatives to a break in lines difficult to accommodate. There are 1.3 million miles of gas pipelines and 200,000 miles of oil pipelines upon which energy generation depends and 160,000 miles of electric power transmission lines in the U.S. (Zimmerman, forthcoming 2005c; compiled from National

Research Council 2002). Some argue that these long networks may be a consequence of deregulation. Albert, Albert and Nakarado (2004: 1) observe that "As a result of the recent deregulation of power generation and transmission, about one-half of all domestic generation is now sold over ever-increasing distances on the wholesale market before it is delivered to customers" (citing EPRI, Electricity Technology Roadmap, 1999 Summary and Synthesis http://www.nerc.comtildafilez/rasreports.html)

Proven Target of Terrorist Attacks

Although terrorist attacks directly targeting electric power have not been identified to any great extent in the U.S., numerous attacks have occurred in other countries that provide an important perspective for non-terrorist disruptions in the U.S. One data base, analyzed in more detail below, has recorded about 200 attacks on electric power systems alone by terrorists. The events appear to be increasing at least during some portions of the time period, occur in just a few countries, and transmission systems dominate the kinds of components attacked. Another database identified close to fifty incidents, with transmission systems being the most common component targeted.

Interdependencies

Interdependencies and their influence on the performance of infrastructure in general have been identified in a number of publications (see for example, Haimes and Jiang 2001; Haimes 35 al. 2005; Rinaldi, Peerenboom, and Kelly 2001; Zimmerman 2005a). Key to understanding the magnitude and direction of impacts is how an electric power outage actually propagates to other activities.

In the U.S., industry, transportation, residential and commercial sectors consume about an equal share of electric power – 33%, 27%, 22% and 18% respectively (U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, October 2004). Individual sectors are noteworthy. For example, water uses 3% of the energy consumed annually, and electric power generation uses close to a half (39%) of fresh water use (8 gallons per kW generated) (Solley, Pierce and Perlman 1998).

Individual facilities are also noteworthy in indicating the manner in which energy is used. Most water and wastewater treatment facilities, for example, use most of the energy consumed for pumps and the treatment process. The East Bay Municipal Utilities District in Oakland, CA uses 27% of its energy to run the oxygenation plant and 22% for its activated sludge mixing facilities (Hake, Bray and Kallal 2004).

The interdependencies between electricity and many other sectors of the economy are also reflected in the sale of electric power to each of these sectors. This data is contained in a Table in the section on consequences below.

RISK – CONSEQUENCE – ECONOMIC ACCOUNTING

Risk

Grid Configurations

There are many standard grid diagrams for individual power configurations, ranging from internal generation figure configuration to broad networks consisting of a number of facilities.

A generalized portrayal of the electric power grid and areas in which it is vulnerable was developed by Schuler (2005 forthcoming) for the bulk power system. The bottom line is that operators have little control over which line electric power will flow because of Kirchhoff's Laws, and this is complicated by the speed with which things happen in an electric power system. Schuler (2005: 6) points out that "having parallel (redundant paths is essential for maintaining the reliability of the power system." Salmeron, Wood and Baledeck (2004) developed several configurations consisting of a number of standard components including transmission lines, transformers, generators, buses, and substations, to evaluate terrorist scenarios against the electric power grid. Others have constructed grid complexes for much larger systems to capture complexity. Albert, Albert and Nakarado (2004: 1), for example, use a map of facilities (no longer available on the web), and construct a model that "represents the power grid as a network of 14,099 nodes (substations) and 19,657 edges (transmission lines). . . [they] distinguish three types of substations: generators are the sources for power, transmission substations transfer the power among high-voltage transmission lines, and distribution substations are at the outer edge of the transmission grid, and the centers of local distribution grids." Their grid ultimately consists of 1,633 power plant nodes and 2,179 distributing substation nodes. They acknowledge that configurations are highly heterogeneous with respect to the number of edges connected to nodes, called node degree, and what they regard as a good indicator of importance (Albert, Albert and Nakarado 2004: 2).

Figure 1 shows five alternative scenarios for grid configuration disruptions.

Extreme Scenarios: The most extreme configuration of an electric power failure (shown as #5 in Figure 1 below) would exist in a region that relies on (1) transmission lines that follow only one or two routes (2) very few large substations and transformers connected to transmission and (3) no in-region capacity to produce independent electric power. Examples of such cities are Seattle, San Francisco and Chicago. The waterways near where these cities are located create serious constraints to more flexible routing of transmission lines. The most extreme scenario assumes that the electric power system becomes disabled at all three of these levels - no transmission, substations, and generation capacity. A second slightly less extreme scenario (shown as #4) is equivalent to the first one and is the same as the first, except that generation capacity is not lost, which is a common situation, given the fact that switches enable power plants to shut down automatically in an overload situation to avoid damaging the equipment.

Moderately Extreme Scenario. This is the same arrangement as in #4, but with substantial in-region capacity to produce independent power (this is shown as #3 below). NYC is an example of such an area. Its major transmission lines are very constrained coming in at two locations from the north and west, but by law NYC has 80% in-city generation, that is, power plants within the city are required to provide 80% of the generation capacity needed. In spite of this requirement, however, programming and operational procedures cause those plants to shut down if the equipment is threatened as it was in the 2003 blackout. However, because they were able to shutdown and preserve the equipment, city generation could be restarted in a day or two. Thus, if transmission corridors were removed, the City could still eventually generate the 80% in-city power. “Black start” capacity, or the ability to have sufficient energy to power up the system is now required to be available from localized backup sources.

Moderate Scenarios. These involve smaller areas with or without in-city generation (shown as #1 and #2 in Figure 1 respectively), but which rely on electric power sources from many different directions. Transmission lines come in from many different directions, thus, disabling some will not necessarily be totally disabling.

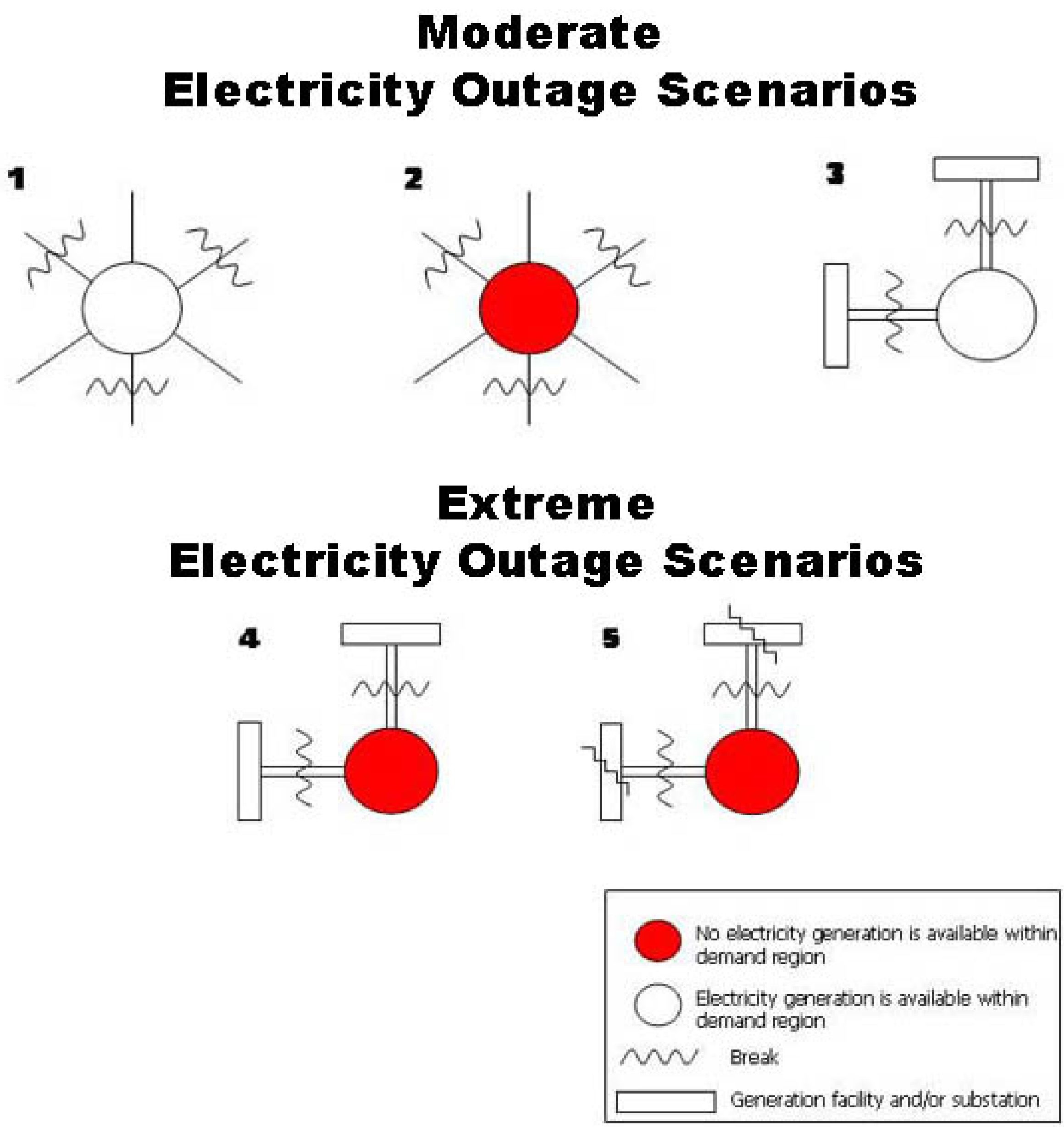
Although as analyzed in the following section, transmission lines are more frequently disrupted in an outage than almost any other component, generation facilities and substations containing transformers are important elements to portray as well, incorporated into the Figure 1 scenarios. Transformers in particular pose a vulnerability given their uniqueness, and the difficulty in replacing them, since there are very few manufacturing facilities available and special transportation arrangements have to be made to transport them to those sites.

The next step is to link grid configurations with geographic areas in a way that allows realist consequences to be evaluated. In terms of cities to which scenarios can be linked, the following observations are noteworthy. Cities vary in the degree to which they are sensitive to threats as reflected in the purchase of terrorism insurance. Marsh (2005: 13) provides data on the take-up rates (defined as “the percentage of companies buying the coverage” (Marsh 2005:2)) and premium rates for terrorism insurance for major metropolitan areas. The data show that Boston has by far the highest take-up rate of 69%, and Washington, D.C., NYC and Houston have the highest premium rates for terrorism insurance. Boston, Washington, DC and NYC were directly involved in the September 11 attacks, and Houston is where much of the energy industry is concentrated.

For cities with vulnerable configurations, data were available on insurance for three of the cities - NYC, Chicago, and San Francisco, which had take-up rates of 54%, 58%, and 37% respectively.

New York City’s vulnerability to electric power outages is high based on its reliance on mass transit, which is a heavy user of electric power. Chicago is a major rail freight center.

Figure 1. Alternative Grid Configurations and Hypothetical Outage Scenarios



Grid Components Likely to be Disrupted

An analysis of two event databases were used to identify common components disrupted in electric power outages – one dataset was for international terrorist attacks against electric power (n=200) and another was for North American events of non-terrorist origins (n=513) with a subset of of n=400 for just the U.S.

Grid components for these databases categorized broadly as follows. *Generation* includes power stations and dams. The category *substations* includes substations and transformers. *Transmission* includes power grids, pylon and utility towers. *All others* includes distribution, electric relays, human resources, junction boxes, offices, storage, vehicles, etc. In some cases more detail was available, and was tabulated.

Past Studies of Component Disruptions

This study extends work currently done in this area by looking across a large number of cases in order to identify common components affected, how the type of component failed changes over time, and ultimately their importance in contributing to a failure. Few U.S. studies of the NERC/DOE data have focused on components. Components have been analyzed qualitatively across cases in a study from the Netherlands (Wels 2003), but not apparently with the U.S. data. Components are significant, since these components and the loadings on them play a key role in contributing to the probability of a blackout occurring. Wels (2003) analyzes one component, gas turbines, in detail, and concludes that recovery and distance between failures again are not so much a function of the type of turbine but rather how soon the problem is fixed. Wels (2003: 9) for example shows that the recurrence interval of outages is affected by how quickly the components causing a failure are corrected. The issue of component replacement is very much bound up with the issue of inventorying and storing spare parts. Many power plant components are unique and take time to replace. The storage issue has often been portrayed economically as a function of the cost of stockpiling against the waiting time for obtaining a spare part (Wels 2003: 10). Carreras et al. 2002 focus on component loading, that is, the amount of electrical load a particular component has to carry, as a key factor in the potential for failures. Component interactions are a key aspect of this, however, recognizing that there is a very delicate balance in the effect on one component of changing loads on another component (Carreras, et al. 2002: 5), and one that is difficult to capture. A few studies have focused on hypothetical scenarios for the rupture of a particular grid, but not using actual data (Salmeron, Wood and Baldick 2004).

The count of components provides but an overview, i.e., where to look further. Wels looks at the component level and finds that time to repair components determines when the next outage will occur. Liao, Apt and Talukdar (2004) model outages of a component as a discrete event, and identify abrupt phase transformations as indicating risk of failures and ultimately how what is connected to the systems will be affected.

Results

Table 1 gives a comparison of information provided by the two events databases with respect to components affected by electric power disruptions. In the case of the international event database these are terrorist attacks. In the case of the domestic event database, these are breakages as a result of natural hazards and accidents and attacks in the case of sabotage and vandalism.

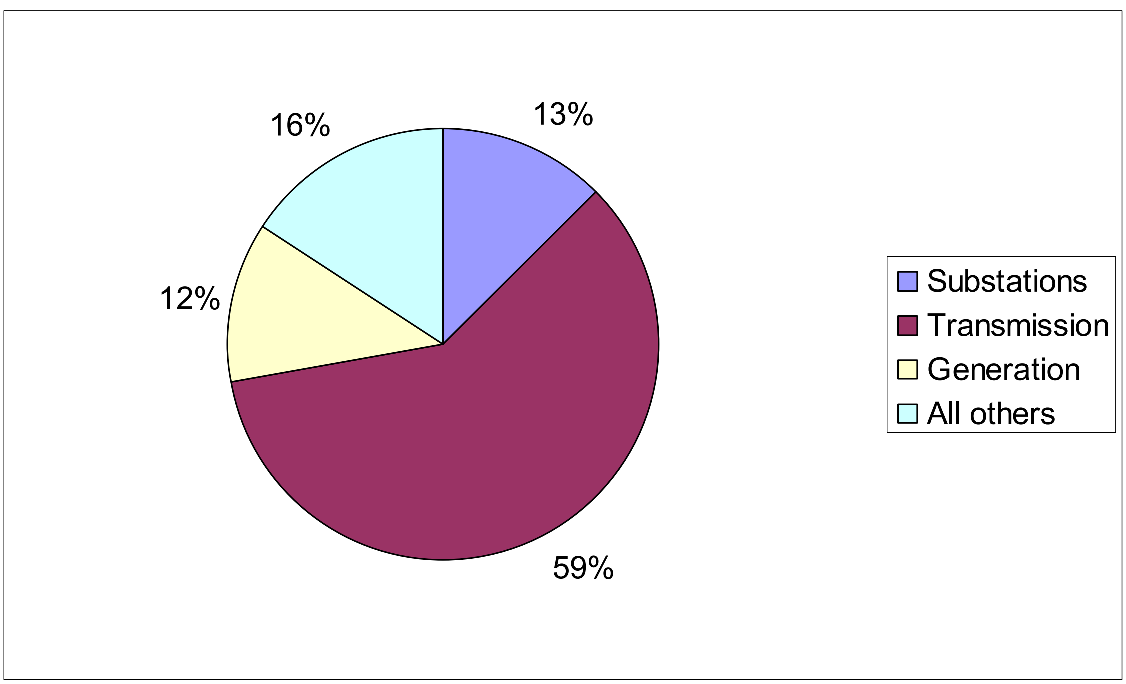
Table 1. Distribution of Electric Power System Components Disrupted by Type of Component for North America and International Outage Databases

	North America	International
	Number	Number
Component Disrupted		
Transmission lines and towers	182	122
Distribution lines	60	2
Circuit breakers	33	0
Transformers	29	7
Substations	21	19
Generation facilities	19	20
Switches and buses	15	0
Other	0	37

Note: For the North American database, more than one component per event could be tabulated in this database so totals do not add to the total number of events in each dataset.

Figure 2 below provides a more generalized picture of components attacked in the international database.

Figure 2. Components Targeted in International Attacks - Electricity Sector



Thus, both data sets point to transmission systems as being a key vulnerability. Transmission lines, towers, or pylons are the most commonly attacked, accounting for 60% of international attacks and 90% of domestic outages. Thus, this indicates that transmission and distribution and where a lot of lines converge is key. One or two air attacks on the energy generation or production facility occurred, but this is very rare. Nevertheless, given that the database of terrorist attacks does show other components such as substations presenting threats they are included in the scenarios. This provides the basis for the construction of various scenarios above to portray alternative ways in which electric power systems could become disrupted and the ultimate consequences of such patterns of disruption. The scenarios at the level of the bulk electric power system combine alternative configurations and disruption patterns for transmission lines, substations, and generation facilities. Each scenario when combined with the specific characteristics of an urban area or region generates other scenarios that link to urban area population and business size and characteristics.

At the transmission level, the degree of damage is a function of the length of the line damaged and the number of places these lines are disrupted. Relative to other components, they are easier to replace, since their design is not usually unique and replacement parts are available in many locations. However, replacement can be an issue if many lines are damaged at the same time, which strains both human resources and manufacturing capacity as occurred in the January 1998 ice storm in the U.S. and Canada.

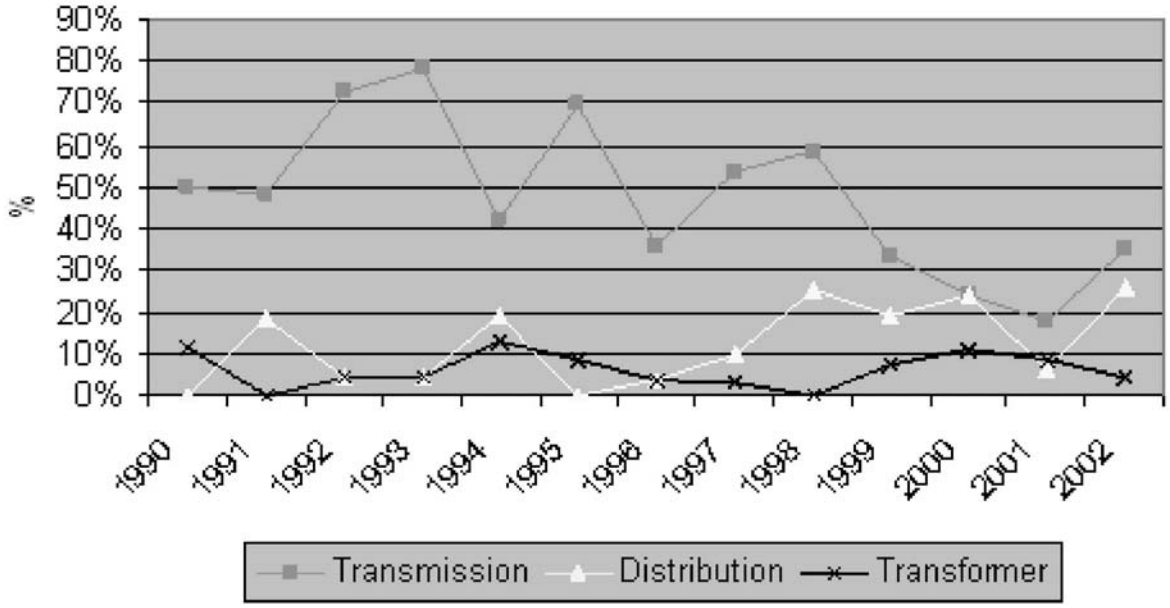
Once disrupted, transmission lines are likely to be damaged for a number of reasons. Transmission reliability has over the years declined, usually measured in terms of the extent to which transmission capacity is able to meet demand is indicated in part by “Requests for Transmission Loading Relief” or exceptions to contractual obligations to provide transmission. These requests have increased steadily since 1997, from close to zero to over 1600 annual requests, and transmission demand and investment have been out of sync with capital expenditures leveling off after a long decline and revenues have also leveling off (EPRI 2003: 2-3 and 2-4 from NERC).

The analysis of the North American database revealed the following trends over time in disruptions of transmission vs. distribution components of the electric power system shown in Figure 3. Over time, the types of components that were impacted changed. Attacks on transmission lines decreased, while attacks on distribution lines (further downstream from the power generation units and transmission systems) increased.

- Share transmission lines of total decreases as distribution share increases
- Number of transmission line failures decreases while distribution line failures increase
- The percentage of transmission line failures decreases while percentage of distribution line failures increases

According to discussions with electric power operators, this is consistent with the absence of a change in Megawatts of demand lost over time, in the statistical analysis below.

Figure 3. Change in Component Share of Total Events by Component Type and Year, 1990-2002



Transformers. Although attacks on transformers have not been common due to access, once a transformer is disabled, restoration can range anywhere from a couple of weeks to a year or year and a half depending on the seriousness of the outage. The extensive duration of a transformer disruption is because each transformer, mainly the larger ones, has a unique configuration and the wiring is done in place. Outages of shortest duration are those where transformers can be repaired on site. Outages of intermediate duration are those requiring transport of a transformer to a place of repair, usually involving special flat bed trucks for transport and associated permits to move on the nation's highways. Outages of the longest duration, estimated at about a year to a year and a half (unless expedited by government intervention) are those involving complete replacement of a transformer. The most extensive time delay is because transformers are manufactured in very few places, and most of them are outside of the U.S. Although government intervention might shorten the duration in emergency situations, the only recourse is to bypass damaged transformers with another substantial and long-lasting source of backup power.

Generation. Electric power plants are probably the least accessible to attack of all of the components of the grid, yet like transformers, have such substantial restoration times that long-lasting backup generation would be required.

Statistical Analyses of Events Databases

Introduction

Risks of electric power outages in terms of the probability and magnitude are in part reflected in and thus can be estimated from historical disruptions. Two kinds of event databases are used to identify how disruptions in electricity have occurred. One consists of international terrorist attacks against electricity drawn from the Terrorism Knowledge Base of the database maintained by the National Memorial Institute for the Prevention of Terrorism (MIPT). This database is limited to country and locality of the attack, the date of the attack, mode of attack, and what components were attacked. The other database is from the North American Electric Reliability Council's (NERC) DAWG database. The latter database is more detailed, and includes information about the cause of the outage, components affected, number of customers affected, duration of the incident, megawatts lost, and cause among other characteristics. The causes were categorized to include weather, equipment failures, human error, fires, crime and sabotage, capacity shortages, demand reduction, and others based on the NERC database. Understanding how these different causes affect the nature of outages will allow the project to better estimate the potential impacts of a terrorist attack on the sector since some causes will be more relevant to terrorist attacks than others. Information from the events included in this database was first analyzed to identify time series trends for the variables mentioned above between 1990 and 2002. The yearly averages for number of outages (incidents), customers affected, average incident duration and megawatts lost are summarized below for the United States and Canada and just the U.S. for which the relevant information was available. The introduction to this section is summarized from a paper presented at the U.S. DHS conference in Zimmerman, et al. 2005 located on the conference web site and the details of the analysis are contained in a separate report as well as from the abstract of Report 3, "Statistical Analysis of Electric Power Outages."

Databases for event analysis in general exist in forms ranging from anecdotes to very detailed event reports such as those published in transportation for some of the more severe transportation accidents by the NTSB. Some events are organized in the form of chronologies, even categorized as infrastructure and specific sectors of infrastructure within the broader category of failures or terrorist-initiated failures, as well as compiled in a tabular form for analysis (though very few of these exist). Anecdotal compilations and chronologies are a foundation for and enhance databases in tabular form for statistical analysis. Event diagnostics have been recognized as critical to the study of disasters (to name just a few examples, see, Cooke 2003 and DeBlasio, Regan, Zirker, Lovejoy, and Fichter, 2004).

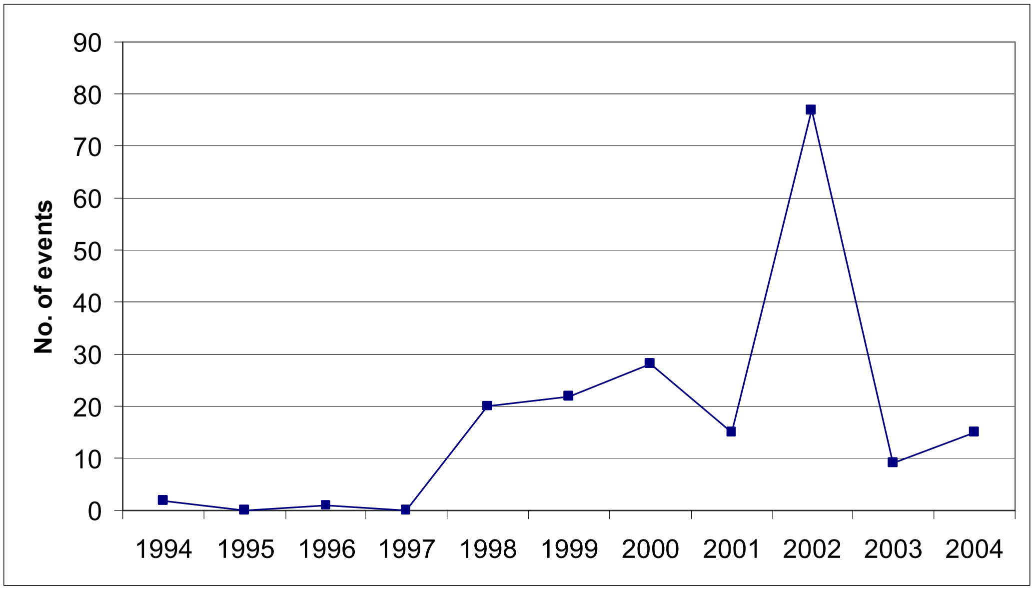
<u>International Terrorist Attacks</u>

Although there have not been any terrorist attacks against the electricity sector in the United States, a number of terrorist attacks have been documented around the world over the last few decades. Data on these attacks is available from the Terrorism Knowledge Base, a database maintained by the National Memorial Institute for the Prevention of Terrorism (www.MIPT.org). This section describes these events.

Figure 4 shows the number of international terrorist attacks on the electricity sector for the period 1994-2004. Figure 5 shows the distribution of these events by country. Twenty-seven countries are included in the database and these include: Afghanistan, Albania, Algeria, Brazil, Chile, Colombia, France, Georgia, India, Indonesia, Iraq, Israel, Kashmir, Kosovo, Latvia, Nepal, Pakistan, Paraguay, Philippines, Peru, Russia, Spain, Sri Lanka, Sudan, Sweden, Tajikistan and Turkey. In 2005 eleven events have been recorded. As Figure 2 shows, of the total number of attacks included in the database about 58% took place in Colombia and 6% in Spain.

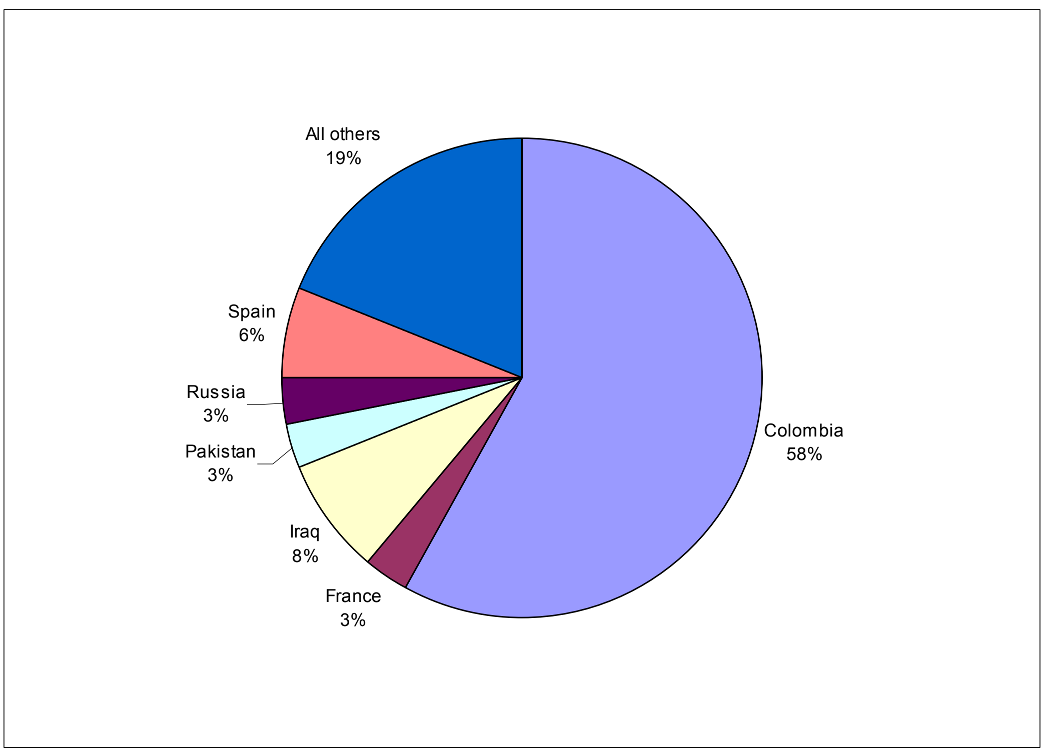
The rest of the countries accounted for less than 5% each. The electricity sector in Colombia, which has had an armed conflict for many decades now, has had numerous terrorist attacks during this period. According to one source, in 1999 alone 178 electric towers were bombed ("Colombia's rebels knock out 3 more electric lines" May 17, 2005). In March, 2000 members of the National Liberation Army (ELN) bombed an electricity sub-station and five high-voltage power pylons in Antioquia province, as well as six others throughout the country. As a result a third of the country was left without electricity. The attacks caused an estimated $10 million in lost revenue ("Rebel Attacks Knock out a Third of Colombia's Power" May 27, 2005).

Figure 4. Number of International Terrorist Attacks on Electricity Infrastructure: 1994-2004



Source: Graphed from a database extracted from the National Memorial Institute for the Prevention of Terrorism (MIPT) data.

Figure 5. Distribution of International Attacks by Country - Electricity Sector - 1994-2005



Source: Graphed from a database extracted from the National Memorial Institute for the Prevention of Terrorism (MIPT) data.

Domestic Outages

A search of databases of electric power outage events revealed about a dozen possible sources, however, the most consistent database was incident reports from the North American Electric Reliability Council (NERC) and the U.S. Department of Energy Energy Information Administration. Several researchers who work with this data agree that it is the best one. Carreras (2002: 1) say that “It is not clear how complete this data is, but it is the best-documented source that we have found for blackouts in the North American power transmission system.” Chen, Thorp and Parashar (2001: 1) point out that “It is the best-recorded source of blackouts in the North American power transmission system.”

Event diagnostics exist for databases similar to those in this research, and some has used the DAWG database in this work (Apt 2005; Talukdar et al. 2003; Chen, Thorp and Parashar 2001; Carreras et al. 2002; Amin 2004). Attributes beyond those provided in the initial database or interdependencies are usually not included in these analyses.

Statistical modeling based on actual events has been undertaken by in other instances to construct or verify models. Below is a summary review of some of the existing approaches to model the terrorist attacks on the electric power sector, in particular, to identify primarily impacts on the electric power sector directly. Few models attempt to go the next step to identify the consequences of such outages. The purpose of the review is to compare the construction of outage scenarios for the purpose of estimating consequences to other sectors in this project to state-of-the-art work. Second, it provides the basis for understanding where this work provides inputs to this project’s work as well as potentially being users of this project’s work.

Ezell et al (2000: 119) demonstration of the infrastructure risk analysis model (IRAM) (Ezell et al. 2000a) work uses real system design characteristics to construct an event tree for a water supply system, assigning likelihoods to the probability of the risks of failure identified as vulnerabilities using hierarchical holographic modeling developed by Haimes (1981). Actual event data can provide inputs to both structure and probabilities assigned in the event tree, complementing the estimation approach taken. Also, the number of interconnections to other infrastructure could be incorporated.

Salmeron et al (2004) model terrorist interdiction using assumptions from single references about duration and components affected during outages (Salmeron et al 2004: 910) and develop alternative scenarios in terms of sets of power grid components by using a network-interdiction model. Assumptions include: (1)attacks are physical not cyber, i.e. SCADA is hardened (Salmeron et al 2004: 905), and various assumptions about the way interdictions occur for lines, transformers, generators, buses, and and substations (Salmeron et al 2004: 906). The interdiction assumptions create a worst case situation within the grid, but not necessarily between the grid and other interconnected infrastructure. Event analysis can help refine the assumptions as well as provide the added dimension of interdictions outside of the grid. Scenario-based modeling of interdependencies for non-terrorist failures has been conducted by Masiello, Spare, and Roark (2004).

Using graph and network theory and fault/event tree analysis, Lemon and Apostolakis (2004) and Apostolakis and Lemon (2005) make certain assumptions about grid characteristics and where breaks are likely to occur. Lemon and Apostolakis (2004: 31) make certain assumptions about susceptibility areas and initiating events upon which fault event trees depend to derive end states. Actual event data can provide inputs into the actual structure and direction of the fault event tree and networks.

Description of the statistical analysis and database used:

An extensive statistical analysis of outage events is contained in CREATE Report 3 for the electricity case, entitled, "Statistical Analysis of Electric Power Outages" (2005). The abstract of the report describes the database and the type of analysis undertaken.

"This report analyses electricity outages over the period January 1990-August 2004. A database was constructed using U.S. data from the DAWG database, which is maintained by the North American Electric Reliability Council (NERC). The data includes information about the date of the outage, geographical location, utilities affected, customers lost, duration of the outage in hours, and megawatts lost. Information found the DAWG database was also used to code the primary cause of the outage. Categories that included weather, equipment failure, human error, fires, and others were added to the database. In addition, information about the total number of customers served by the affected utilities, as well as total population and population density of the state affected in each incident, was also incorporated to the database. The resulting database included information about 400 incidents over this period.

The database was used to carry out two sets of analyses. The first is a set of analyses over time using three-, six-, or twelve-month averages for number of incidents, average outage duration, customers lost and megawatts lost. Negative binomial regression models, which account for overdispersion in the data, were used. For the number of incidents over time a seasonal analysis suggests there is a 9.3% annual increase in incident rate given season over this period. Given the year, summer is estimated to have 65-85% more incidents than the other seasons. The duration data suggest a more complicated trend; an analysis of duration per incident over time using a loess nonparametric regression "scatterplot smoother" suggests that between 1990-93 durations were getting shorter on average but this trend changed in the mid-1990s when average duration started to increase, and this increase became more pronounced after 2002. When looking at average customer losses by season there is weak evidence of an upward trend in the average customer loss per incident, with an estimated increase of a bit less than 10,000 customers per incident per year. Similar analyses of MW lost per incident over time showed no evidence of any time or seasonal patterns for this variable.

The second part of the report includes a number of event-level analyses. The data in these analyses are modeled in two parts. First, the different characteristics related to whether an incident has zero or nonzero customers lost are determined. Then, given that the number lost in nonzero, the characteristics that help to predict the customers lost are analyzed. Unlike the first set of models described, in this section a number of predictors such as primary cause of the outage (including variables such as weather, equipment failure, system protection, human error and others), total number of customers served by the affected utilities, and the population density of the states where the outages were used in the analyses to gain a better understanding of the three key variables: customers lost, megawatts lost and duration of electric outages. Logistic regression was used in these analyses. For logged customers lost, the only predictor showing much of a relationship was logged MW lost. The total number of customers served by the utility was found to be a marginally significant predictor of customers lost per incident. Customer losses are higher for natural weather related events, crime, unknown causes, and third party, and lower for capacity shortage, demand reduction, and equipment failure, holding all else in the model fixed.

The analyses for duration at the event level find that the two most common causes of outages, equipment failure and weather, are very different, with the former associated with shorter events and the latter associated with longer ones. When the primary cause of the events is included in the regression models, the time trend for the average duration per incident found in earlier analyses disappears. According to the data, weather related incidents are becoming more common in later years and equipment failures less common, and this change in the relative frequency of primary cause of the events accounts for much of the overall pattern of increasing average durations by season. Holding all else in the model constant, these analyses also suggest that winter events have an expected duration that is 2.25 times the duration of summer events, with autumn and spring in between."

Database characteristics (descriptive statistics):

Between 1990 and 2004 (part), the aggregate database had the following characteristics:

For U.S. and Canada cases:

Time period: 1990 through mid-2004
Number of events: 513
Total number of customers affected: 78,968,024
Total number of megawatts of demand lost: 342,489
Total duration: 13,612 hours

For U.S. cases only:

Time period: 1990 through August 2004
Number of events: 400
Total number of customers affected: 60,930,578
Total number of megawatts of demand lost: 263,667
Total duration: 12,341 hours

Descriptive Statistics (U.S. Cases only)

	N	Minimum	Maximum	Mean	Std. Deviation
Duration	303	.02	822.00	40.7300	87.34293
Customers	345	.00	3125350.00	176610.3710	347031.23046
MW	333	.00	22934.00	791.7919	2201.89477
TotCust	347	13.00	34870671.00	3433351.2277	6968247.44251
Valid N (listwise)	203				

Note: Events used in the analysis exclude actions such as load shedding and other forms of demand reduction, which although valuable in preventing an outage, were not associated with an outage occurring. The number of customers affected is not equivalent to people affected, since a given customer may consist of a number of people. Thus, the number of people affected would be far greater than the number of customers. Duration is a difficult parameter to estimate since power is restored at different times in different locations.

Relationships among event characteristics are portrayed by the correlation matrix in Table 2 below.

Table 2. Correlation Matrix

Correlations

		ResCust	TotCust	Duration	Customers	MW	PopDensity	TotPopulation
ResCust	Pearson Correlation	1	.999**	-.054	.194**	.094	.015	.464**
	Sig. (2-tailed)	.	.000	.453	.004	.183	.820	.000
	N	245	245	193	219	201	245	245
TotCust	Pearson Correlation	.999**	1	-.075	.188**	-.003	.004	.530**
	Sig. (2-tailed)	.000	.	.222	.001	.964	.941	.000
	N	245	347	268	302	286	347	347
Duration	Pearson Correlation	-.054	-.075	1	.120	.083	-.035	-.036
	Sig. (2-tailed)	.453	.222	.	.051	.177	.546	.533
	N	193	268	303	263	265	303	303
Customers	Pearson Correlation	.194**	.188**	.120	1	.521**	-.010	.083
	Sig. (2-tailed)	.004	.001	.051	.	.000	.855	.124
	N	219	302	263	345	288	345	345
MW	Pearson Correlation	.094	-.003	.083	.521**	1	.026	.003
	Sig. (2-tailed)	.183	.964	.177	.000	.	.632	.957
	N	201	286	265	288	333	333	333
PopDensity	Pearson Correlation	.015	.004	-.035	-.010	.026	1	-.027
	Sig. (2-tailed)	.820	.941	.546	.855	.632	.	.590
	N	245	347	303	345	333	400	400
TotPopulation	Pearson Correlation	.464**	.530**	-.036	.083	.003	-.027	1
	Sig. (2-tailed)	.000	.000	.533	.124	.957	.590	.
	N	245	347	303	345	333	400	400

**. Correlation is significant at the 0.01 level (2-tailed).

Significantly high correlations exist between total customers served by the utilities and population of the state in which the utility is located, total customers served and residential customers served, and customers and megawatts.

Interpretation: The low correlation between the duration of the electric power outage and MW of demand lost, is explained in part by the fact that an outage occurs in a split second. Carreras et al. (2002: 5) note that “A cascade of events leading to blackout usually occurs on a time scale of minutes to hours and is completed in less than one day.” Thus, no new load is lost after the initial outage, but obviously the duration of consequences (other than but related to electric power) probably increases dramatically with duration of the power continuing to be out (or restoration time).

Highlights of trends and patterns in events (outages), customers affected, MW of demand lost, and duration:

Between 1990 and 2004, in the U.S. only, the statistical analysis shows the following, portions of which were already described above in the abstract:

- The number of events increased by about 9.3% a year regardless of season, however, when events that had non-zero MW or customers were analyzed, this percentage was higher.
- Given the year, summer is estimated to have 65-85% more incidents than the other seasons.
- The number of customers and Megawatts lost stayed the same
- The average duration at the level of events shows an annual increase of 14.6% largely due to the changes in the kinds of causes of outages of over time, shifting from the shorter equipment related failures to the longer weather related failures.

Figures portraying the annual and seasonal trends in numbers of events, duration, MW and customers from this analysis are contained in the Appendix as FiguresA3-5.

The trends in duration are noteworthy, since much of the economic impacts seem to depend on duration of outages. Although there were no significant changes in duration over time annually or semiannually, at the seasonal level and at the finer events level there is an upward trend explained primarily because of changes in the mix of causes. A model for logged duration based on seasonal data, however, implies an annual increase in duration of 14.6%. At the event level the estimate is 11.6%. The observed average durations in the last 7 seasons (winter 2003 through summer 2004) are all higher than what is implied by the model. That is, the multiplicative model is picking up an increase in durations in the last two years, which the linear model can't pick up. However, there are only seven data points at the season level, so a clearer picture may be evident at the incident level. One quick summary gives a clue, however: the average duration up through autumn 2002 (not counting missing values, of course) was 27.2 hours; the average duration after that was 65.5 hours. The corresponding medians are 3.6 hours and 25.8 hours. Thus, there does seem to be evidence building up that durations have increased markedly in the past two years. Evidence of this is evident in a loess nonparametric curve for the durations. This is a nonparametric regression "scatterplot smoother." It is evident that after a long period of flat durations, the average duration first started increase in the mid 1990s, and then took off again after 2002.

Literature Review for Statistical Trends and Patterns

This work differs from prior work in the following ways, in that it:

- Verifies existing research on electric power outage characteristics and relationships
- Explores sensitivity of impacts to small changes in outage characteristics
- Uses a more extensive database and statistically based indicators to capture impacts between electricity and other infrastructure sectors
- Extends impacts to economic effects

- Incorporates terrorism dimensions using analogies to international events as well as expert elicitation techniques

Below are some of the previous studies of event databases upon which this work builds for trend and pattern analyses.

For electric power, two time series analyses were conducted of the NERC database by Chen, Thorp and Parashar in 2001 and by Carreras, Newman, Dobson and Poole in 2002, updating their earlier work in 2000. Both of these groups of researchers aim at testing various theories to explain the structure of the distribution of events over time. Chen, Thorp and Parashar look at the differences in structure of the time series for different regions.

These two studies use time series trends to evaluate a number of different descriptive models or tools to explain or describe how power systems operate in blackouts, that is, the tail of the distribution of blackout attributes. These tools include "scaled windowed variance" (SWV), "self-organized criticality" (SOC) and "highly optimized tolerance" (HOT) (Chen, Thorp and Parashar 2001: 1). Amin has added another concept that he calls the "self-healing grid." Carreras et al (2002) examined time series in order to determine what affects the probability of a large number of customers being affected. They find that events with larger effects in terms of number of customers affected have a lower probability as does other characteristics such as time between blackouts. This work has several findings that are significant to using events to project impacts of blackouts. First, weather (separating out weather driven blackouts from others) does not influence the value of a statistic ("H") used to describe the curve. Second, the structure of the grid (measured by different regional grids which have different structural characteristics) does not change the curve (p. 4). Third, a sandpile model (where successive additions of sand brings the sandpile closer to collapse) seems to provide a good fit regardless of the measure of loss. They create a qualitative analogy to the sandpile in an electric power system, where the grains of sand are analogous to the component of the electric power system and the loads on those components.

A third study by Wels (2003) evaluates event data from the Netherlands. The significance of this study is in its focus on the availability of components (see discussion below).

A fourth analysis by Amin (2004: 119-120) plotted the NERC databases between 1991 and 2000 to portray the distribution of events (outages) by number of customers affected and then separately by megawatts of energy. He then compares two time periods. Amin (2004: 119) concludes that "generally, a relatively small number of US consumers experience a large number of outages; conversely, outages that affect a large number of consumers are rare;" however, in comparing events aggregated for the periods from 1991-1995 to 1996-2000, he concludes that the numbers may be rising.

Consequences

Direct Consequences from Statistical and Case-Based Analysis of Event Databases

The statistical analysis of the U.S. database includes an analysis of consequences of electric power disruptions in terms of duration of the outages, time of the outage (seasonal), megawatts lost, customers affected, total customers served by the utility, and population and population density of the state in which the outage occurred. The characteristics and sources of the databases was described in the Risk section above. The separate report entitled, "Electricity Case – Statistical Analysis of Electric Power Outages."

Scoping of Consequences to Other Sectors from Incident Databases and Extreme Events

As a basis for economic accounting, a set of categories of consequences were derived from case histories including extreme events. Once at least the major categories are identified, the costs of disabling these other activities to varying degrees can be quantified. Another CREATE report that accompanies this report, entitled "Economic Cost Estimation Factors for Economic Assessment of Terrorist Attacks," sets forth these costs in detail.

Consequence Components

The history of other blackouts, terrorist attacks and other extreme events provide a basis for identifying what kinds of consequences are likely to occur as an outcome of an electric power outage. These are quite detailed.

For example CEIDS (2001: 2-9) identifies the following kinds of costs for business losses: "net lost production (or net lost sales), labor, materials loss or spoilage, equipment damage, backup generation (includes cost to run and/or rent backup generation), overhead, other restart costs." Savings exist as well, which they identify as "unused materials, savings on energy bill, and unpaid labor."

For public services, electricity directly or indirectly drives practically every component.

Indicators of Infrastructure Interdependency (Zimmerman 2004; Zimmerman and Restrepo 2005 forthcoming)

Given the considerable attention to and emphasis on interdependences among infrastructures and between infrastructure and other sectors of the economy, it is critical to begin to move from anecdotal and conceptual evidence to quantify these interdependencies. This section presents two separate analyses, using a couple of different database to ascertain and quantify the relative direction of infrastructure failure events where two or more infrastructures were affected by the same failure events (Zimmerman 2004; Zimmerman and Restrepo 2005). These are based on specific events and cases, and the objective is to develop indicators that will ultimately become predictive tools for consequence assessment.

Interdependencies among different infrastructures and between infrastructure and other sectors of the economy provide a basis for identifying how disruptions in one type of system can affect others. This phenomenon is often referred to as cascading (Rinaldi, Peerenboom and Kelly 2001). Cascading can either result in subsequent effects being greater than or less than the initial effect. Rinaldi, Peerenboom and Kelly (2001) refer to events where the magnitude of the effect on the secondary infrastructure affected is greater than that of the initiating infrastructure as escalating. Zimmerman and Restrepo (2005 forthcoming) refer to events whose effects are less than the effects of the initial event as attenuating. In economics, input-output techniques have been applied to the identification of infrastructure interdependencies (Haimes and Jiang 2001). Methods to quantify interdependencies are beginning to emerge.

Interdependencies in the context of events effecting more than one infrastructure were quantified by Zimmerman (2004) as an "effect" ratio, which compared different types of infrastructure with respect to the direction of the impacts. Using an illustrative database of about 100 cases, the ratio of the number of times a particular type of indicator affected others vs. the number of times others affected it were as follows for different kinds of infrastructure - water mains: 3.4; roads: 1.4, gas lines: 0.5; electric lines: 0.9; fiber optic/telephone: 0.5; and sewers and sewage treatment: 1.3. The table below provides more of the details of the calculation. According to the results from this data set, electric lines have an approximately an equal chance of *disrupting* other infrastructure as they have of being *disrupted by* other infrastructure.

Table 3. Illustration of Selected Infrastructure Interdependencies during Failure

1 Type of Infrastructure	2 # of Times Infrastructure (Column 1) <u>Caused</u> Failure of Other Infrastructure	3 # of Times Infrastructure (Column 1) was <u>Affected by</u> Other Infrastructure Failures	4 Ratio of Causing vs. Affected by Failure (Col. 2 divided by Col.3)
Water mains	34	10	3.4
Roads	25	18	1.4
Gas lines	19	36	0.5
Electric Lines	12	14	0.9
Cyber/ Fiber Optic/ Telephone	8	15	0.5
Sewers/ sewage treatment	8	6	1.3

<u>Source</u>: R. Zimmerman (2004) "Decision-making and the Vulnerability of Critical Infrastructure," *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, edited by W. Thissen, P. Wieringa, M. Pantic, and M. Ludema. The Hague, The Netherlands: Delft University of Technology. ISBN: 0-7803-8567-5. Based on an illustrative data set of approximately 100 cases.

Zimmerman and Restrepo (2005 forthcoming) developed another simple measure of interdependency in the context of electric power outages and their effects on other sectors. That work analyzed electric power outage characteristics from secondary data for the August 14, 2003 outage in the U.S. and Canada as well as using data constructed for selected cases from 1990-2004 outages in the U.S. and Canada. The indicator compared the duration of outages in the initial electric power outage with the duration of the outages of specific public services and businesses affected, defined as the time to recover services.

Results showed that the duration of outages linked to the electricity outage for affected public services exceeded the duration of the initial power outage itself. In other words, they were cascading events that escalated. However, for industrial establishments, the results were less clear with impacts ranging from being far less than the duration of the initial power outage to far more, generally depending on the amount of damage to equipment. For example, extensive damage can occur when substances in industrial furnaces are not removed fast enough, resulting in cooling and hardening, making it difficult to remove the material. In this case, a relatively short-lived power outage can result in a longer-duration idling of industrial production.

Results from a larger events database that was a subset of the DAWG database were mixed, with a number of outages showed durations in infrastructures affected as being less than the duration of the overall outage, primarily because of the use of backup power.

Table 4. Outage Durations for the August 2003 Blackout

(Total Duration = 42-72 hours)

	T(i)/T(e)
Infrastructure	
Transit (NYC)	1.3
Traffic Signals (NYC)	2.6
Water Supply (Cleveland, OH; Detroit MI)	2.0-3.0
Industry	
Automotive	0.4-4.0
Steel	0.6-4.0
Chemical	0.6-4.0

Source: Summarized from R. Zimmerman and C. Restrepo, "The Next Step: Quantifying Infrastructure Interdependencies to Improve Security," International Journal of Critical Infrastructures, 2005. UK: Indescience Enterprises, Ltd. Summarized from Table 3.

Sector Analyses: Electric Power Usage by Business Sector

In order to develop estimates of potential consequences of electric power outages, a few selected sectors were identified that are either large users of electricity or would create major secondary impacts, particularly with respect to emergency operations, if electricity were disrupted, even if they use relatively little.

Transportation

Transportation accounts for 27% of the electricity consumed in the U.S. ((U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, October 2004).

Data from the Federal Energy Regulatory Commission (FERC) provides a detailed listing by utility of the usage of electric power by two transportation sectors: rail and highways/street lighting. This helps to focus on specific geographic areas or prototypical areas for a worst case scenario for a transportation outage associated with an electric power outage.

Components of rail transit systems disrupted from power outages include electrified rail, diesel electric motors, signals, and station support (lighting, etc.).

Other Infrastructure

Communications, water supply, and environmental services are areas that are highly dependent on electric power, and interruptions in these sectors could produce very profound impacts if the duration of an outage were long enough.

Business Interruption

The CEIDS study (2001) noted that three sectors of the economy account for 40% of the GDP – digital economy, continuous process manufacturing, fabrication and essential services.

On a national basis, industrial and commercial activities account for 33% and 18% of the electric power consumed in the U.S. (U.S. Department of Energy, Energy Information Administration, Monthly Energy Review, October 2004). Economic analyses of past electric power outages have indicated that business losses including property losses account for a very large share of the economic impact of an outage. For example, the 1977 outage in NYC which involved civil unrest in the form of looting and arson, resulted in a total of $350 million in losses of which $155 million were experienced by small businesses (considered indirect losses) and another $35 million were estimated as direct losses to selected businesses (not including utilities) according to Corwin and Miles (1978). Following the attacks on September 11, 2001, out of a total of $ 38.1 billion, business losses were the largest category estimated to account for $23.3 billion.

Below are business loss estimates for some of the most extreme outages and other events resulting in extremely high losses.

Consequences from Utility Specific Information

The largest impacts will occur where the highest number of users are. The FERC database provides revenues and and MW sold for U.S. utilities. Examples of some of the big users by category are given below.

Table 5. Customers, Revenues and MWhr Sales for Selected Utilities by Sector

Utility	Customers	Revenues	MWhr Sales
Commercial (Top 2)			
Southern California Edison Co.	509,536	$4,071,317,823	42,313,663
Consolidated Edison Co.	440,888	$3,439,997,137	17,451,830
Industrial			
Commonwealth Edison	1,532	$718,508,926	20,179,029
Entergy	7,309	$723,101,985	12,870,061
Pacific Gas and Electric	1,329	$1,246,646,957	14,652,572
PECO Energy Company	3,120	$1,120,773,267	15,608,188
Railroads (All)			
PECO Energy Co.	3	$52,049,367	712,859
Commonwealth Edison	2	$28,397,176	483,949
Potomac Electric Power Co.	3	$10,160,049	477,371
Connecticut Light and Power Co.	2	$14,844,825	192,330
Baltimore Gas & Electric	1	$4,789,661	184,768
Georgia Power Co.	1	$8,669,628	180,312
Florida Power & Light	23	$6,788,578	93,345
PPL Electric Utilities	1	$4,340,856	59,922
Southern California Edison	45	$6,567,726	57,949
Consolidated Edison Co.	0	$6,414,166	18,193
Northern Indiana PSC	1	$1,371,908	16,405
Public Street/Highway Lighting (Top)			
Oncor Electric Delivery Co.	0	$50,119,346	508,672
Consolidated Edison Co.	3,150	$41,146,307	502,512
Southern California Edison	12,093	$69,679,672	486,564
Florida Power and Light	2,613	$58,657,804	424,539
Georgia Power Co.	3,394	$44,899,084	415,431
Pacific Gas and Electric Co.	26,650	$68,588,608	412,345
Public Service Electric and Gas Co.	8,628	$56,155,630	365,683
The Detroit Edison Co.	891	$40,162,841	309,571
Virginia Power and Light	2,137	$38,587,093	279,916
Duke Energy Corp.	11,386	$28,258,460	271,662
Other Public Authority			
Commonwealth Edison Co.	13,810	$379,265,211	7,464,831
Virginia Electric Power Co.	27,673	$487,265,020	9,444,612

Economic Accounting

Application of Cost Factors to Extreme Scenarios

Either the moderate to extreme electric power outage scenarios described earlier could have a range of economic consequences. That is, there are a range of scenarios within the economic effects alone. In order to capture the extreme range of these effects, The accounting of economic effects for major categories of consequences uses a framework based upon value of human life and injury and business losses capping the loss to the $40 billion in paid out costs in connection with the September 11, 2001 attacks (though it does not include amounts for rebuilding and reconstruction) (Dixon and Stern 2004). The objective of each computation is to derive the effects that would be required to reach a total cost of $40 billion in terms of premature deaths and business losses, computed separately. Obviously, any combination of different estimates (many of which are presented in the "Electricity Case: Economic Cost Estimation Factors for Economic Assessment of Terrorist Attacks" report should be used to create more complex scenarios. These calculations aim at answering the question of how many premature deaths or a duration of an outage would it take to reach a $40 billion loss.

Obviously, the $40 billion is arbitrary, however, based on the only known real terrorist attack the U.S. has experienced in recent years. The approach remains robust regardless of what kind of cap is used. The cost factors that are a central part of the framework are documented in another CREATE report entitled, "Economic Cost Estimation Factors for Economic Assessment of Terrorist Attacks" – Report 2 (May 31, 2005), and this section should be used together with that report. Below is a summary table that contains some of the representative estimates. Users need to adjust cost estimates to current dollars.

For all of the calculations, populations of major cities and/or the metropolitan areas within which they are located are needed. As indicated under the grid alternatives, four areas are being considered: New York, Chicago, San Francisco and Seattle. The relevant population data are contained in the tables below.

Table 6. Population of Cities

City	7/1/2003 population estimate	4/1/2000 census population	4/1/1990 census population
New York City	8,085,742	8,008,278	7,322,564
Chicago	2,869,121	2,896,016	2,783,726
San Francisco	751,682	776,733	723,959
Seattle	569,101	563,374	516,259

Source: Extracted from: http://www.infoplease.com/ipa/A0763098.html - based on U.S. Census data.

Table 7. Population of U.S. Metropolitan Areas

Metropolitan Area	2000	1990
New York--Northern New Jersey--Long Island, NY--NJ--CT--PA	21,199,865	19,549,649
New York, NY PMSA	9,314,235	8,546,846
Chicago--Gary--Kenosha, IL--IN--WI CMSA	9,157,540	8,239,820
Chicago, IL PMSA	8,272,768	7,410,858
San Francisco--Oakland--San Jose, CA CMSA	7,039,362	6,253,311
San Francisco, CA PMSA	1,731,183	1,603,678
Seattle--Tacoma--Bremerton, WA CMSA	3,554,760	2,970,328
Seattle--Bellevue--Everett, WA PMSA	2,414,616	2,033,156

Source: U.S. Census Bureau. Census 2000 PHC-T-3. Ranking Tables for Metropolitan Areas: 1990 and 2000. Table 1: Metropolitan Areas and their Geographic Components in Alphabetic Sort, 1990 and 2000 Population, and Numeric and Percent Population Change: 1990 to 2000. Available at: http://www.census.gov/population/cen2000/phc-t3/tab01.pdf.

Premature Deaths and Injuries

$C(D,I) = P_1 (D) + P_2 (I)$

where
$C(D,I)$=total cost of deaths and injuries (spatially and temporally specified)
D = per capita estimate of the cost of deaths based on value of life estimates (e.g., $5.8 million)
I = per capita estimate of the cost of injury by type of injury
P_1=total population at risk of being injured
P_2=total population at risk of dying

The estimate below only involves deaths, since injuries are generally much lower per capita by many orders of magnitude. Even though the number of people injured may be greater than those dying, the lower per capita estimates in many cases don’t compensate for the greater number of people injured.

Premature Deaths. This computation assumes the U.S. EPA estimate of $5.8 million (adjusted to 2005 dollars from the original $4.9 million) per premature death. If no other impact is included, this implies that 6,897 deaths would comprise a loss of $40 billion from premature deaths alone. This is more than double what actually occurred in the U.S.'s worst terrorist attack, however, it is many times lower than the instantaneous loss of 230,000 lives in the Tsunami disaster of December 2004. For each of the four metropolitan areas under consideration, the percentages of are under 1% of the metropolitan area population. For such a high level of premature deaths to occur by means of an electric power outage would require civil unrest of a magnitude such as but greater than what occurred in the 1977 electric power outage in New York City or a secondary attack intentionally accompanying and taking advantage of the outage, such as an attack on a heavily populated building or train system as happened in Madrid in 2004 or a dam near a heavily populated area.

Business Losses

Business losses encompass three areas: (1) direct losses to business (2) the loss of public services that support business and (3)business-related property loss. Direct loss to business encompasses categories identified for example by CEIDS (2001: 2-9) applicable to any extreme event. These categories include: "net lost production (or net lost sales), labor, materials loss or spoilage, equipment damage, backup generation (includes cost to run and/or rent backup generation), overhead, other restart costs." Savings exist as well, which they identify as "unused materials, savings on energy bill, and unpaid labor."

An average Gross Domestic Product (GDP) can be computed for any region or the nation as a whole by dividing the GDP by the applicable population. For the nation as a whole, this comes to $112.84 of GDP per person per day. The details of this calculation are contained in the economics report. A check on the estimate is provided by the August 2003 blackout. Multiplying $112.84 by the 50 million people affected yields $5.64 billion in business losses, which is at the lower end of the estimates of economic impact of the outage estimated at between $6-10 billion (there were few other categories of loss, such as premature death). For the New York Region with a population of about 20 million (in the 21 county region), estimated loss for an outage lasting one day would be $2.26 billion. This means that an outage would have to last 17.8 days in order to incur a loss of $40 billion from business losses alone (multiplying $112.84 by 20 million and dividing $40 billion by that amount, i.e., by 2.26 billion dollars).

Service Interruption

For public services, however, in addition to the kinds of physical and functional losses applicable to businesses in general, the users of those services experience often serious and irrevocable delays that have far-reaching economic consequences. Therefore, attention was paid to this, emphasizing for this report, the transportation sector, since it is critical to the movement of resources of all kinds that promote the economy, including information, supplies, services, and human resources. For transportation, the applicable cost factors include the cost of delay expressed in a number of different ways, most commonly in terms of vehicle type, income of traveler, wages of travelers, and type of urban area.

Application:

The following low, average, and high hourly wage rates were used to illustrate this approach: $9.10 for the leisure and hospitality industry, $16.00 for the average across all private sectors, and $22.04 for the information industry. These rates were obtained from the U.S. Department of Labor, Table B-3. Average hourly and weekly earnings of production or nonsupervisory workers1 on private nonfarm payrolls by industry sector and selected industry detail Available at: http://www.bls.gov/news.release/empsit.t16.htm

In using this methodology, however, the actual wage rates need to be used and applied to the actual distribution of workers in a particular area. The illustration below is just for the New York Metropolitan area, and assumes that two-thirds of the 21,199,865 regional 2000 population is in the labor force (probably on the high side).

Table 8. Estimating the cost of a 24-hour outage for the New York Metropolitan Area

Hourly Wage	Total wages	Cost of congestion (50% of hourly wages)	Cost of a 24-hour outage
9.10	92,601,008	46,300,504	1,111,212,096
16.00	162,814,960	81,407,480	1,953,779,520
22.04	224,277,607	112,138,804	2,691,331,296

The workforce of the New York Metropolitan Area in 1990 was 9,346,645 (New York State Department of Labor figures. See: http://www.labor.state.ny.us/labor_market/lmi_business/eeo/nyjcnmsa.htm - access date May 31, 2005). This represents about 48% of the total population. Considering that the total population of the New York Metropolitan Area in 2000 was 21,199,865 (U.S. Census Bureau. Census 2000 PHC-T-3. Ranking Tables for Metropolitan Areas: 1990 and 2000. Table 1: Metropolitan Areas and their Geographic Components in Alphabetic Sort, 1990 and 2000 Population, and Numeric and Percent Population Change: 1990 to 2000. Available at: http://www.census.gov/population/cen2000/phc-t3/tab01.pdf), the estimated total workforce is estimated to be 10,175,935. This figure is multiplied by the hourly wage in the column titled 'Total wages' to obtain an estimate for the total hourly wage of the workforce in the New York Metropolitan Area, which includes New York City, northern New Jersey and southern Connecticut. The figures for total wages and then multiplied by 0.5 to obtain an estimate for cost of congestion for the total workforce for one hour. These figures are then multiplied by 24 to obtain an estimate of the cost of a 24-hour outage. The results suggest a range of $1,111,212,096 to $2,691,331,296 for the cost of a 24-hour outage in the New York Metropolitan Area. One should note that although a power outage might last as long as 24-hours, the congestion might not last that long, but the calculations are based on the assumption that in fact the congestion does last as long as the outage.

Table 9. Estimating the cost of a 24-hour outage for New York City

Hourly Wage ($/hour)	Total wages ($)	Cost of congestion (50% of hourly wages - $))	Cost of a 24-hour outage ($)
9.10	33,296,900	16,648,450	399,562,800
16.00	58,544,000	29,272,000	702,528,000
22.04	80,644,360	40,322,180	967,732,320

The workforce of New York City in 2000 was approximately 3,659,000 (New York State Department of Labor figures. See: http://64.106.160.140:8080/lmi/laus_results2.jsp?PASS=1&area=21093561New+York+City – access date May 31, 2005). This figure was multiplied by the hourly wage figures to obtain an estimate of the total wages for the New York City workforce for one hour. The figures for total wages and then multiplied by 0.5 to obtain an estimate for cost of congestion for the total workforce for one hour. These figures are then multiplied by 24 to obtain an estimate of the cost of a 24-hour outage. The results suggest a range of $399,562,800 to $967,732,320 for the cost of a 24-hour outage in the New York Metropolitan Area.

Economic Impact on the Economy of New Jersey

New Jersey is the densest and now the wealthiest state in the U.S. A study that will constitute Report 5 in the Electricity Case series will be undertaken to estimate the total economic impact of a temporary disruption in the delivery of electric power to the economy of the State of New Jersey. The same analyses could be conducted for larger regions and other combinations of disruptions. Using assumptions about the location where the power grid is damaged and the time it takes to repair the damage, the following will be estimated:

- the kilowatt-hours of electricity that would be not be delivered due to such a disruption;
- an estimate of a profile of New Jersey businesses and the number of electric-utility residential customers that would be affected directly by the grid's disruption; and
- a set of scenarios that bound business losses induced via other life lines (water, natural gas, transportation, and communications service) due to the temporary loss of electrical power.

For each scenario, the following would be estimated:

- the direct business losses that would be sustained by New Jersey and
- the total losses (in terms of business revenues, person-years, job earnings, personal income, tax revenues, and gross state product) to New Jersey's economy.

The specific tasks will involve identifying the spatial extent of electric power distribution interruption, identifying businesses and residents affected directly by power disruption, developing scenarios for New Jersey's direct business revenue losses, and then estimating the total economic losses to New Jersey. In order to produce these estimates, both R/ECON's structural econometric time series model of the state and its multiregional input-output (MRIO) model will be used. These models include the state's two main labor markets and those for the rest of the New York City and Philadelphia metropolitan areas. The rationale for using both is that R/ECON's econometric model expresses the timing of the economic loss and recovery that would result, while its MRIO model articulates industry impacts in more detail and also provides estimates of expected government revenue losses not available via the econometric model. Each model supports the other.

CONCLUSIONS AND SCENARIO-BASED DECISION TOOL

BASIS FOR SCENARIO CONSTRUCTION

Electric power configurations

The statistical analyses of terrorist and non-terrorist disruptions of electricity above revealed that transmission systems were the most commonly disrupted. In the U.S. database the percentage was 90% and for terrorist international events it was 60%. However, based on the assessments of the utility industry, transformers though not disrupted as often are the most difficult to replace, and may well present a critical point in the system, contributing to vulnerability. Thus, at the level of the grid, scenarios were constructed based on a combination of transmission and transformer and also generation combinations. For example, New York City, Chicago, San Francisco, and Seattle have transmission lines that are the most constrained geographically. The ability to replace transformers is probably equal across those areas, since most of the repair and production facilities are outside of the country.

Consequences

To each electric power configuration, geographic areas were assigned based on dependency upon electric power based on EEI data.

Computations as Illustrative of a Decision Tool

Given the dominance of transmission components in both terrorist and non-terrorist events as well as they key importance of substation and generation facilities, the following sets of disruption scenarios have been constructed that will be linked to consequences to generate another level of scenarios. Before describing the scenarios, the vulnerabilities and recovery times of each of the critical components of the grid comprising the scenarios are described along with explanations and conditions for each level of vulnerability.

An understanding of how electric power systems have become disrupted "provides the basis for the construction of various scenarios to portray alternative ways in which electric power systems could become disrupted and the ultimate consequences of such patterns of disruption. The scenarios at the level of the bulk electric power system combine alternative configurations and disruption patterns for transmission lines, substations, and generation facilities. An extreme scenario would be an area served by few transmission lines coming in at locations that require the lines to enter via very few corridors and be close together, combined with very few substations and no in-region generation capacity. Each scenario when combined with the specific characteristics of an urban area or region generates other scenarios that link to urban area population and business size and characteristics." (Zimmerman et al. 2005, p. 8).

OPPORTUNITIES FOR RISK REDUCTION AND RISK MANAGEMENT

Many examples of reducing risks of disrupting electricity to begin with and reducing the consequences once such a disruption occurs have been and are being developed in a variety of contexts applicable to terrorist attacks.

Examples from September 11

After the WTC attacks, a number of unusual efforts were undertaken to restore electricity quickly in order to reduce consequences.

- Redundancy/Service Alternatives: Ability to tap spare transformer vaults at the South Street Seaport to provide energy quickly to damaged areas
- Use of Slack Resources: Ability to access portable generators for temporary power
- Decentralization and Decoupling: Use of alternative, portable energy sources

Improvements in Energy Delivery: Distributed Energy

A substantial body of research exists on alternative ways of providing electricity in a secure manner that predates the August 2003 blackout and the upscaling of homeland security following the September 11 2001 attacks. (Zerriffi).

Improvements in Energy Technologies

Better technologies: For example, the strength of power lines can be increased to resist sagging by developing power lines with greater resiliency made of aluminum rather than steel (Matthew L. Wald, "To Avert Blackouts, A Sag-Free Cable," NYT, 3/4/04, G8).

Better sensors: Apt, Lave, Talukdar, Morgan, and Ilic (p. 4): "If the existing 157,000 miles of transmission lines in the U.S. were fitted with $25,000 sensors every 10 miles, and each sensor were replaced every five years, the annual cost would be $100 million. This would increase the average residential electricity bill (now 10 cents per kilowatt-hour) to 10.004 cents per kilowatt-hour. The total would be roughly one-10th the estimated annual cost of blackouts."

The following conceptualization helps to identify prioritize at least some of the options combining cost and uncertainty:

	Low Cost	High Cost
Low, Uncertain, or Geographically / Temporally Specific Effectiveness	Solar energy	Geothermal Sea heat gradient Wave Wind
High Effectiveness	Photovoltaics Light Emitting Diodes for Traffic Lights (LEDs)	Diesel fuel generators (health and fuel) Microturbines

Synopsis

In sum, preliminary analyses of electric power outages in the U.S. have been conducted using an all-hazards approach along with some initial identification of grid configurations and components affected, consequences, and comparisons to international terrorist attacks on electric power systems. In addition, some preliminary work on the development of indicators of interdependency among infrastructures especially during failures as a means of anticipating the direction of effects, and potentially applicable to terrorist situations. This work has shown that:

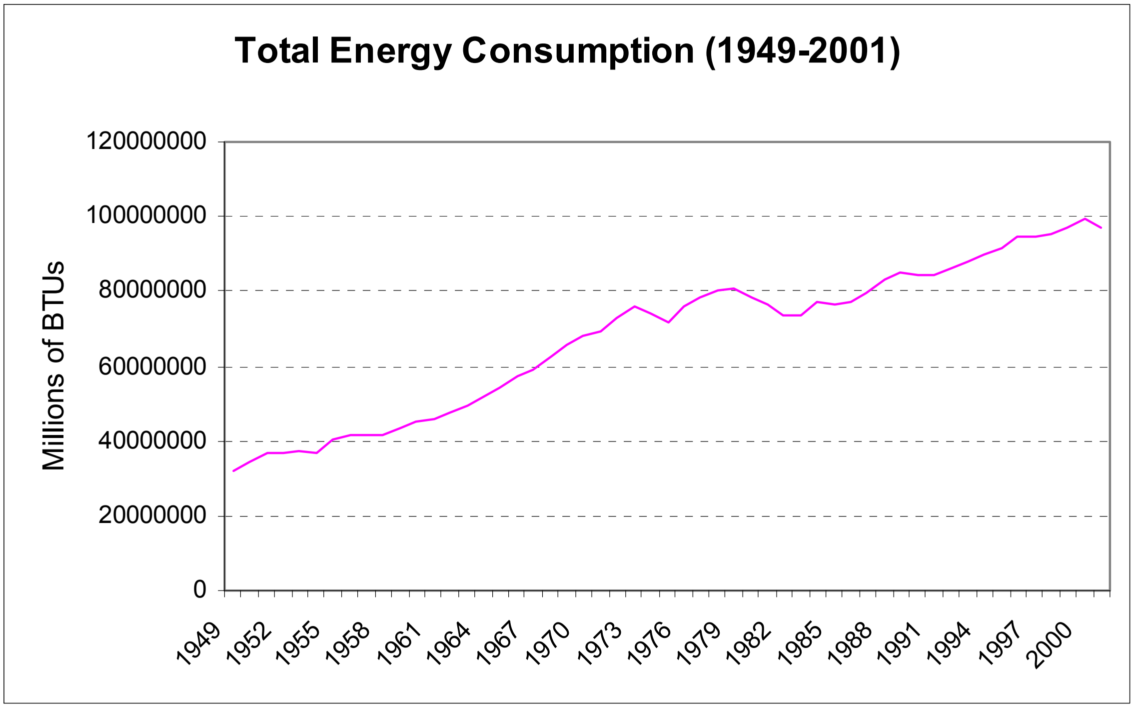
- Electric power is a key driver of other infrastructure and impacts other infrastructure in extreme events
- Grid configurations, common component failures and their consequences guide risk estimates of terrorist attacks
- Risk reduction alternatives exist that can alter vulnerability of energy service configurations to attack
- Outputs of case-based diagnostic methods and indicators provide inputs to risk and economic models

APPENDICES

APPENDIX A. Figures

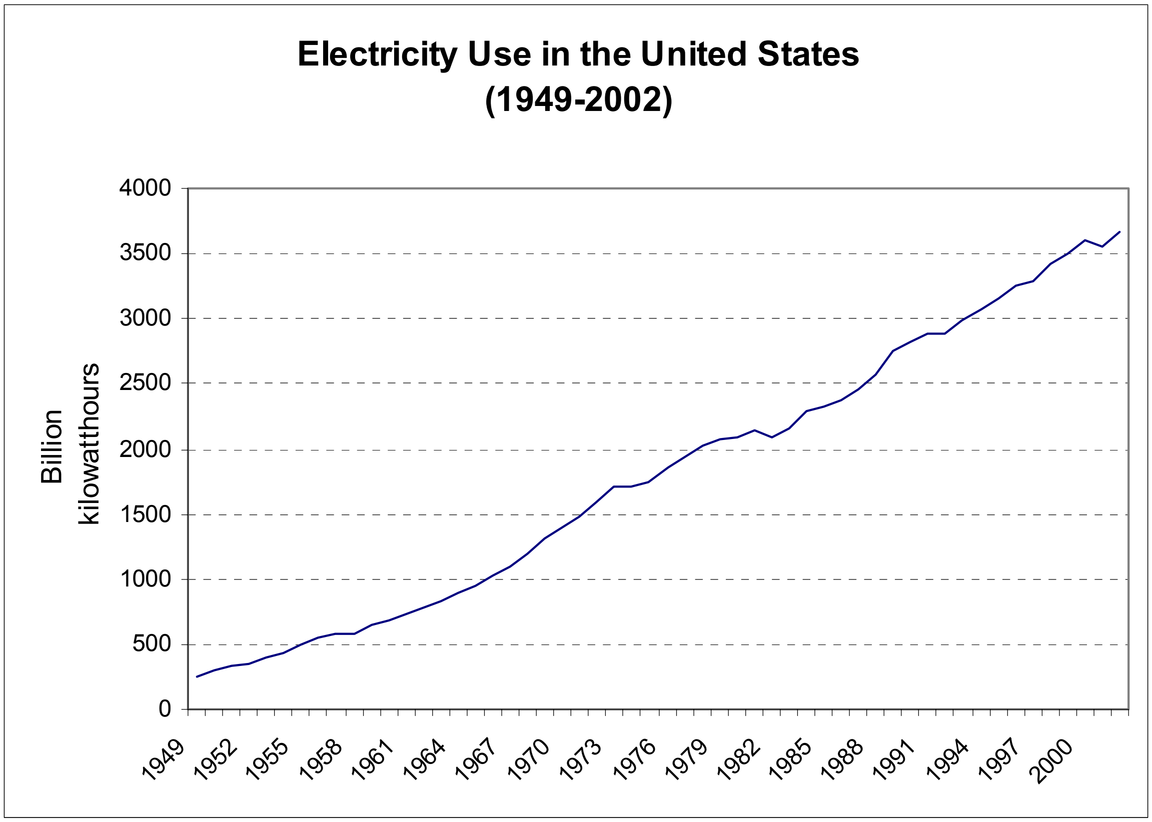
APPENDIX B. Estimating the Benefits of Preventing Electricity Interruptions by Lester B. Lave

Figure A-1



Source: Graphed from Energy Information Administration (EIA), U.S. Department of Energy, Annual Energy Review 2001, Energy Perspectives: Trends and Milestones 1949-2001; from R. Zimmerman and T. Horan, "“What are Digital Infrastructures” in R. Zimmerman and T. Horan, Digital Infrastructures (Routledge 2004: p. 8). Not for distribution or citation without the permission of the author and publisher.

Figure A-2



Source: Graphed from Energy Information Administration (EIA), U.S. Department of Energy, Annual Energy Review 2001, Energy Perspectives: Trends and Milestones 1949-2001; from R. Zimmerman and T. Horan, "“What are Digital Infrastructures” in R. Zimmerman and T. Horan, Digital Infrastructures (Routledge 2004: p. 8). Not for distribution or citation without the permission of the author and publisher.

Figure A-3. Number of Electric Power Outage Incidents Over Time, U.S. 1990-2004: Annual Averages

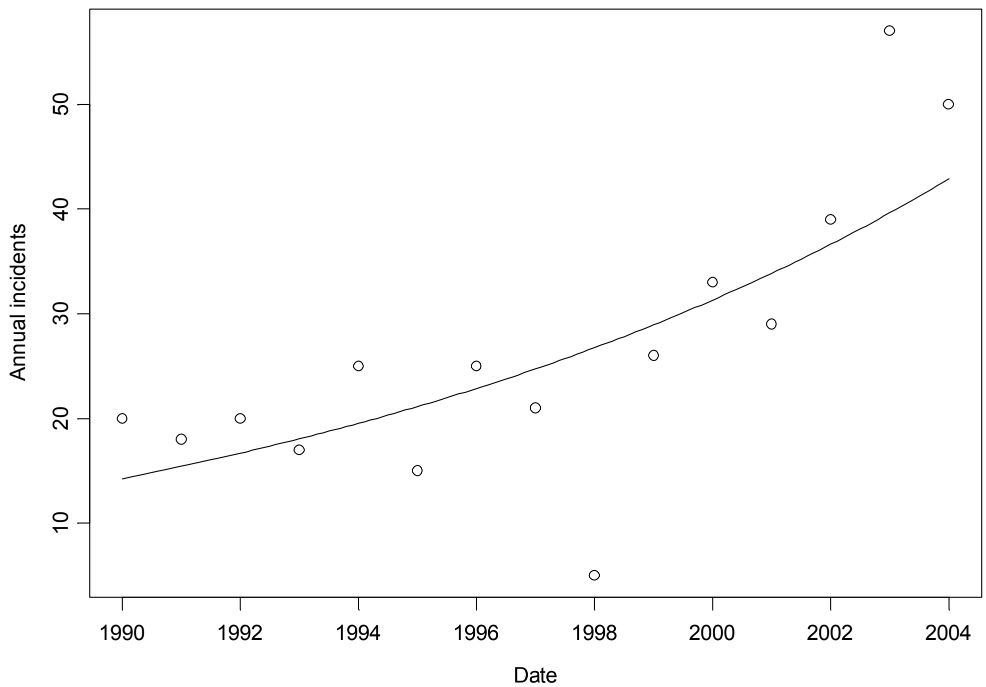


Figure A-4. Number of Electric Power Outage Incidents Over Time, U.S., 1990-2004: Seasonal Averages

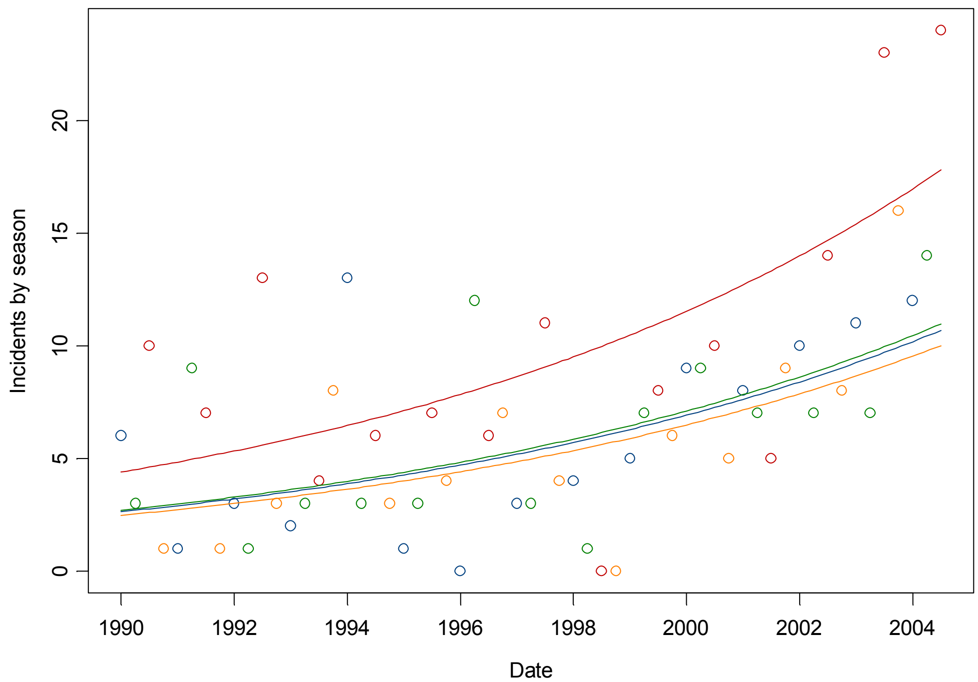
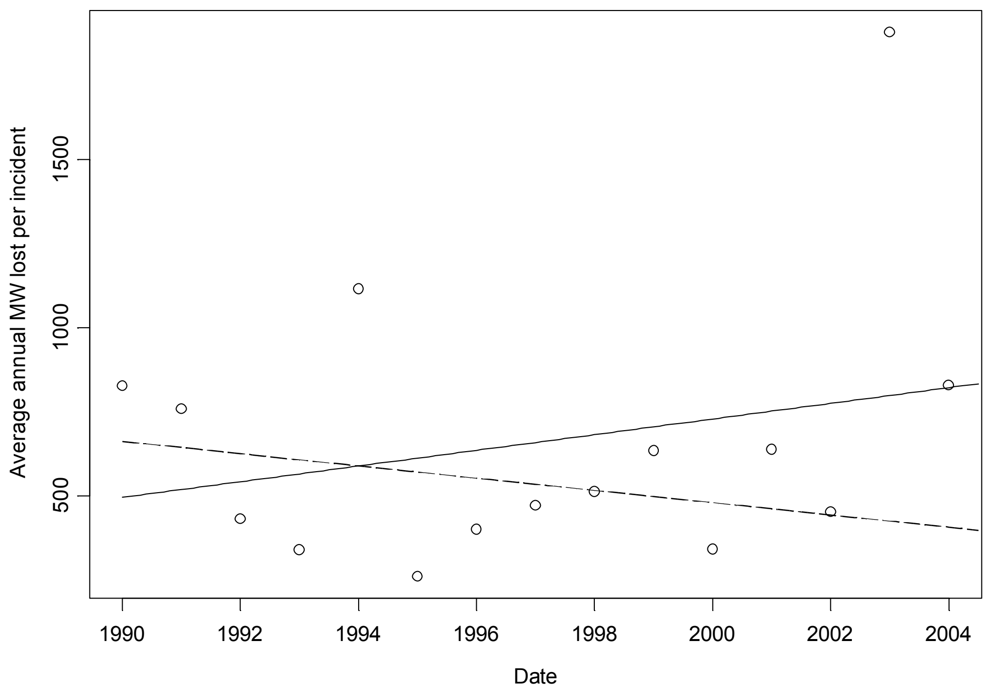
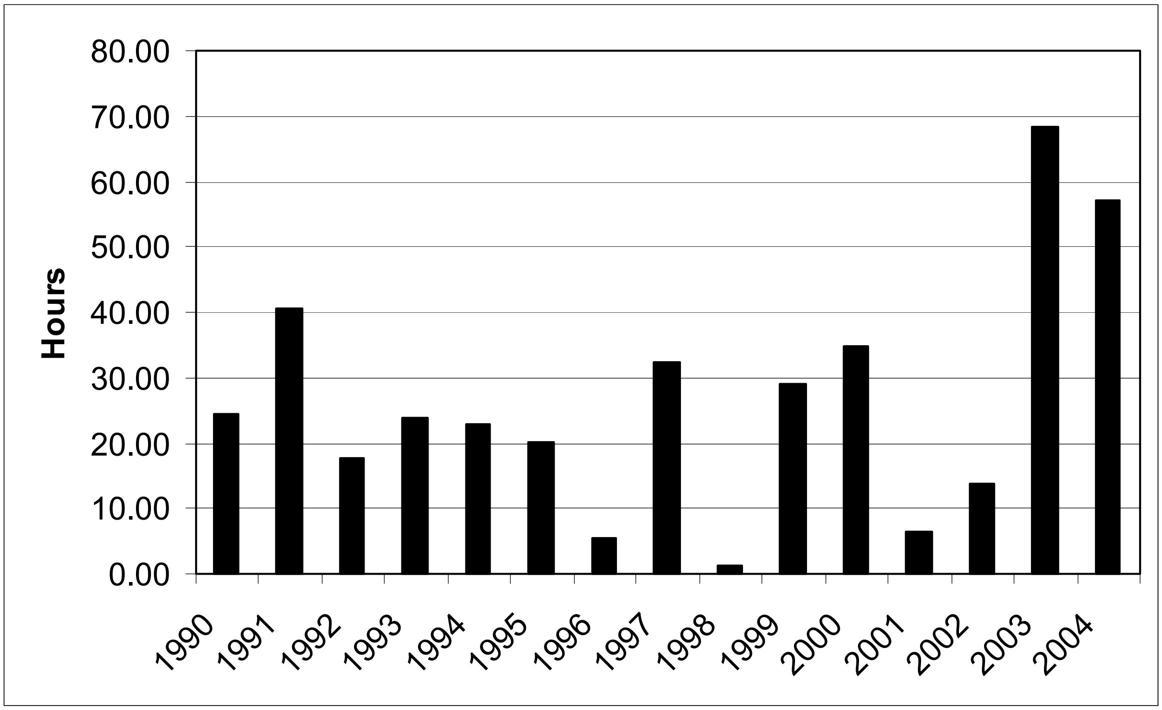


Figure A-5. Megawatts Lost in Electric Power Outages Over Time, U.S., 1990-2004



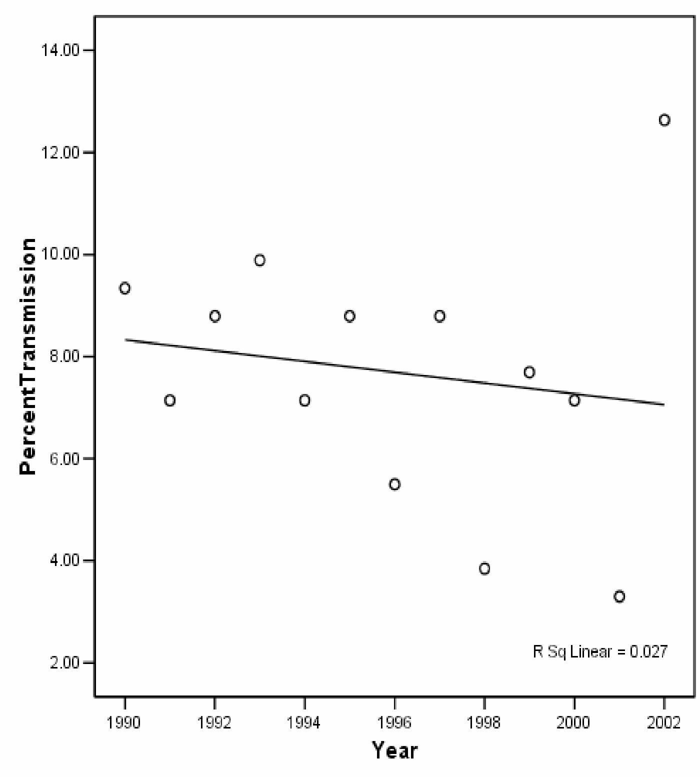
Notes:
The solid line is all events.
Dashed line eliminates the outlier, which is the August 14, 2003 blackout.
See Report 3 for a finer division of events by time and detailed statistical significance analyses.

Figure A-6. Average Duration, U.S. and Canada, 1990-2004
(U.S. DOE Database)



Source: New York University Critical Infrastructure Project, CREATE

Figure A-7. Change in Component Share of Total Events: Transmission Components, Linear curve-fit, U.S. and Canada, 1990-2002



APPENDIX B. Background paper on a review of alternative approaches for identifying interconnections between electric power and other sectors and the benefits of preventing outages.

Estimating the Benefits of Preventing Electricity Interruptions

Lester B. Lave
Carnegie Mellon University
November 30, 2004 (revised 5-22-05)

Introduction

The electricity sector is vital to the US economy and life styles of Americans. It is also vulnerable to terrorist attack since there are tens of thousands of unguardable transmission towers and thousands of generators and substations. Natural hazards, accidents, and operations mistakes are currently responsible for about four power interruptions per year for consumers. A terrorist attack could cause a cascading blackout, such as August 14, 2003, that put 50 million people in the dark. An attack could knock out much of the power to a city such as New York for a year or more.

Even a casual inquiry into the blackouts of 1965, 1977, and 2003 makes it clear that there were large losses and that society has a large stake in preventing their reoccurrence. Blackouts pose risks to health and safety, result in dumping large amounts of raw sewage that damage the environment, and generally endanger public health. The economy all but stopped during the outages and estimated losses were $4 to 12 billion dollars for the 2003 blackout.

The Value of Electricity to the Economy

A first way to examine the cost to the nation of a power failure is to observe that the electricity sector sold $270 billion of power in 2003, about 2.4% of GDP (U.S Energy Information Agency, U.S. Department of Commerce (BEA website)). Thus, the economic loss could be approximated as $740 million dollars per day for a nation-wide power outage.

This first approximation is deficient in that electricity is required to provide lighting and heat for buildings, communication and electronics, much of our transportation, and much of our manufacturing. Since the incremental cost of producing and delivering a kilowatt-hour (KWh) is about 8.9 cents to residential customers and 5.1 cents to large industrial customers, the value to the economy of an additional KWh is about 5-8 cents (http://www.eia.doe.gov/cneaf/electricity/page/at_a_glance/sales_tabs.html). But the value of the first few KWh is much greater. A few KWh each month would provide some lighting and power a radio and telephone; a few more KWh would run a fan allowing a natural gas or oil furnace to heat the house. A few more KWh would power a television. Residential customers would be willing to pay a great deal more for the first KWh, but less for each successive KWh until they got to current usage levels where the willingness to pay would be about 8 cents per KWh.

As another example, the first customers paid Edison the equivalent of more than $5 (in 2004 dollars) per KWh in 1884 in order to have electric lighting. It seems unlikely that they would have paid this amount to use an electric can opener, although at 8 cents per KWh, an electric can opener is an affordable luxury. Someone paying $50 per month for cable television would surely be willing to pay that much for the electricity to power the television (about 25 cents per KWh).

Similarly, commercial, and industrial customers would pay a great deal for the first KWh and successively less for additional KWh. For example, a few KWh per month would provide lighting and enable an office or store to be open. Another way to look at this is that an office worker in New York costs a company perhaps $100,000 per year in salary, benefits, and rent. Without electricity that office worker produces no output. Surely the company would be willing to pay thousands of dollars for the tens of KWh required to provide lighting, heat, and power to run a computer or other device to enable that office worker to produce output. Thus, a company would be willing to pay hundreds to thousands of dollars per KWh for the first KWh. Manhattan and other large cities could not function without traffic lights. The alternative to traffic lights is to have a policeman at each intersection, costing perhaps $500,000 per year per intersection. The electricity for the traffic lights costs perhaps $800 per year, indicating that the city would be willing to pay perhaps 500 times more KWh for the electricity to power traffic lights.

Economists describe this notion as "consumer surplus" and estimate it as the area under the demand schedule. Econometric studies estimate that residential customers would cut their electricity consumption by about 2% if electricity prices rose 10%. If we assume that customers would be willing to pay $6 for the first KWh and that the demand schedule is a straight line to the current consumption of 3,600 terrawatt hours at 7.6 cents per KWh, the consumer surplus is about $12 trillion, the same amount as current GDP.

Another way to estimate consumer surplus is to use the estimated price elasticity. Short-run elasticities are estimated to be -.1 to -.3 (Patrick, R. and F. Wolak, 2001. "Estimating the Customer-Level Demand for Electricity Under Real-Time Market Prices," NBER Working Paper, ftp://zia.stanford.edu/pub/papers/rtppap.pdf) while long run price elasticities are estimated to be -.7 to -1.0 reflecting the many opportunities to use electricity more efficiently (Halvorsen B. and B. Larsen, 2001. "The Flexibility of Household Electricity Demand Over Time," Resource and Energy Economics 23:1). A short-run elasticity of -.1 gives an estimate comparable to GDP.

These simple calculations give some idea of the effect on the economy if electricity were not available, but both these approaches underestimate the value to the economy of electricity. In the short-run, almost every aspect of the economy and of consumer activities is dependent on electricity, as was made evident by the August 14 blackout. If that blackout had lasted for a year, many people would have died, there would be disease outbreaks due to untreated sewage, and economic activity essentially would have stopped. Even if we had a decade to prepare for a world without electricity, the effects would be devastating; GDP would be reduced almost to zero. As a reality check, think of what would happen to GDP without electricity. We would have no electronics or no communication; we would have to return to gaslights and candles, as well as steam engines rather than electric motors. Even after some time to adjust, GDP would be reduced to a small fraction of what it is today. Alternatively, think of an average American family. Without electricity, they would have no light, heat, radio or television, no telephone, no refrigerator, and perhaps no way to cook if they have electronic ignition for their stove, rather than a pilot light. Would that family be willing to pay $6 per KWh to get electric lighting? Light from a compact fluorescent light (that is equivalent to a 100 watt incandescent bulb) currently costs 2/10 of a cent per hour. Would most customers be willing to spend 12 cents per hour ($6/KWh) to light their houses? As another reality check, consumers are willing to spend more than $100 per KWh for portable power, such as batteries for a flashlight or portable radio or toy.

During current operations, almost seven times a year, the electricity supply is interrupted for the average customer. LaCommare and Eto (2004) estimate the cost of short-term power interruptions in the USA by pulling together 24 independent customer surveys concerning the cost of interruptions. While the averages vary from year to year, the annual number of interruptions greater than 5 minutes is about 1.3, about 110 minutes are without power, and there are about 5.5 interruptions of less than 5 minutes. The estimated annual cost of these interruptions is $79 billion, with a one standard deviation confidence interval of $22-$135 billion. The vast majority of the cost is due to momentary interruptions: $52 billion, with $26 billion for the sustained interruptions. The vast majority of costs are borne by the commercial sector: $57 billion, with industry bearing costs of $20.4 billion and residential customers bearing costs of only $1.5 billion. They estimate the costs of a momentary interruption to be $5.85 for a residential customer, $1,230 for a commercial customer, and $23,097 for an industrial customer. The costs of a 60 minute interruption are $6.90, $1,859, and $59,983, respectively. Thus, for residential and commercial customers, the vast majority of the cost comes from even a momentary disruption. For industrial customers, the longer interruption is more expensive, but not nearly in proportion to the time of lost power. Thus, unless the duration of the blackout extends far beyond 60 minutes, utilities should focus on reducing the number of momentary outages.

Identifying Vulnerable Sectors

Natural hazards, accidents, and mistakes cause many blackouts. These blackouts are costly to many sectors. An important question is which sectors are most directly dependent on electricity. Which sectors would be hurt the most by a blackout? A first way of answering the question is to examine which sectors have backup generation. Customers willing to pay for backup generation reveal that they would lose a great deal if the power went off. Hospitals, airports, financial networks, internet operators, many factories and nursing homes, radio and television broadcasters, some police and fire stations, some farms, telephone companies and others have backup generators. The cost of a 5-15 KW generator is about $300-1,000 per KW or about $36-120 per KW per year. If a customer expected to lose power for three hours per year, with a major blackout every decade lasting 20 hours, the cost of backup power would be $7-24 per KWh, 100-300 times the price of electricity. Alternatively, assume that a customer expected to lose power six a year for less than 5 minutes. If so, buying a backup generation means that this customer is willing to pay $6-20 to prevent an interruption. Thus, customers that have small backup generators reveal their value of preventing blackouts to be the equivalent of more than twice GDP.

An alternative to these gross calculations is a more detailed look at each sector and industry. What is the cost to the steel industry of a power failure? To the factories making microprocessors? The answers may seem a bit surprising. The cost to hospitals, television stations, microprocessor factories and others with backup generation would be essentially zero. These customers have already paid to be protected. The amount that they have spent on backup generation is a lower bound to their cost of a power outage.

For industries that have not purchased backup generators, the cost of a blackout might be as small as sending workers home and making up the work later or losing all the work in progress, as for a steel mill that has to dump all the molten iron because it cannot operate its basic oxygen furnace and continuous caster. We could evaluate each industry, but that would be a time consuming, expensive task.

For the whole economy, we could estimate the cost of disruptions as the sum of the annual cost of installed backup generators plus the additional cost above this level for those customers with backup generation plus the cost of disruption for customers that don't have back up generators. A rough way of doing this would be to assume that the cost of disruption is a straight line defined by two points: Zero hours of disruption has a cost of zero and 3 hours of disruption have a cost equal to that of having the current number of backup generators.

An Input-Output Approach

A model that might give an answer to the question of the most vulnerable sector is the U.S. Input-Output (IO) table, 500-sector representation of the economy (W. Leontief, Input-Output Analysis, Oxford University Press, 1966).. While these Department of Commerce data give a detailed picture of the US economy that is useful for many purposes, it is not useful for estimating the cost of a power outage.

As devised by Wasily Leontief, the key assumption in IO analysis is that the production function takes a "fixed coefficients" form: $Y = \min(a1X1, a2X2, a3X3, \ldots anXn)$ where Y in the output and the Xi are inputs (energy, raw materials, labor, etc.). For a particularly simply product, the production function might be: $Y = \min(0.5X1, 4X2)$. The function can be thought of as a recipe where half a unit of X1 is combined with four units of X2 to product a unit of output. This function allows no flexibility or substitution. For example, if only two units of X2 are available, only half a unit of Y is produced, even if half a unit of X1 is available. Similarly, if no X1 (or X2) is available, no output can be produced, even if there is a large amount of X2 (X1) available. Think about making water. The production function is min(2H,O). A molecule of water is H_2O. If there are 10 hydrogen atoms and 5 oxygen atoms, we can make 5 molecules of water. But if we had 8 hydrogen atoms and 5 oxygen atoms, we could make only 4 molecules of water, with one oxygen atom left over.

This production function means that input-input analysis is not useful for determining which sectors would be affected most critically by an electricity interruption (or by the interruption of any other sector in the economy). The I-O matrix would show which sectors purchase electricity (nearly all). The production function would imply that production in each of these sectors would stop if electricity supply were interrupted. It makes no difference whether electricity is a major cost of a sector (aluminum) or a minor cost (trucking); as long as a sector purchases any electricity, the I-O model implies that production would cease if electricity delivery were interrupted.

Intuitively, it seems that interrupting electricity supply would have a greater effect on aluminum than on trucking, but this intuition is not borne out by the I-O model. If the trucks could not be refueled because the service station fuel pumps weren't working, operations would cease.

This property of the I-O model applies not just to electricity, but also to any input. Any sector that purchased gasoline, diesel fuel, coal, natural gas, or some component would cease production if the supply of that input were interrupted, according to the I-O model. Thus, the I-O model is not a helpful guide for the Department of Homeland Security in knowing which sectors are most critical and, equally, provide no information to terrorists to know which sector to target.

A Computable General Equilibrium Approach

To provide insight into the costs to a sector of an electricity interruption or shortage, a production function must recognize the ability to substitute on input for another. These more general production functions could be accommodated in a computable general equilibrium (CGE) model. Unfortunately, computational difficulties limit CGE models to perhaps two-dozen sectors. Even here, the model would require estimates of the flexibility of generation in terms of substituting fuels for each of the sectors; I know of no economy data of this sort on each sector. I conclude that the CGE models have something to offer, but are not going to give direct answers to the question. What is needed are, for example, direct data on the substitutability among fuels for each power plant. Given these data for each sector, a good first order estimate could be made, although the estimate would not encompass all the indirect effects that would come from a CGE model. For example, 32% of the generating plants in Texas have dual fuel capability.

Survivability: Protecting the Mission

Natural hazards, accidents, poor management, or terrorists could disrupt the supply of any input or product in the economy. One way to think about this is to focus on protecting the mission, rather than predicting the supply of a particular input. This could be done in a number of ways. To keep the cost of such an interruption low, businesses and consumers can take the following steps. First, make sure that there is sufficient spare capacity in each sector that losing a single generator, transmission line, port, highway, or factory would not reduce the ability to produce the current bundle of goods and services that make up GDP. Second, maintain inventories of supplies at the customer sufficient to handle expected disruptions, e.g., coal at electricity generating plant or supplies of water in your home. Third, maintain inventories at the producer sufficient to handle expected disruptions, e.g., coal at the mine or canned goods at the food processor. Fourth,
design the production process to be flexible with respect to inputs, e.g., a generation plant than can burn both goal and natural gas. Fifth, maintain parallel delivery mechanisms, e.g., additional ports or highways or transmission lines that could handle the traffic if one highway or port or transmission line is closed. Sixth, maintain several suppliers with different owners in different locations, e.g., flu vaccine produced in different places with sufficient capacity to meet demand if one plant fails.

The cost to the economy of an interruption caused by a natural hazard, strike, accident, or terrorist attack depends on the extent to which the six mechanisms named above are able to allow the mission to survive.   For example, the US has multiple seaports and a vast interstate highway system that provides a great deal of flexibility in routing. Closing a single port or highway would be an inconvenience and have short-term costs related to the size of the facility being closed, but the ability to substitute another port or route would mean that the long-term costs were much lower.

However, the US economy has been moving in a direction that makes it more vulnerable to interrupting the mission. For example, longer supply chains, as in importing manufactured goods, lowers the flexibility of the system and reduces the ability to respond quickly. Similarly, much of manufacturing has moved to a "just in time" system where there is less than a day of inventory at the plant. Almost all of the new electricity generation capacity built since 1990 has been fueled by natural gas, with essentially no inventory at the plant. Giving a plant the ability to burn alternative fuels makes it less efficient. Deregulating the electricity industry has put a huge premium on cost reduction, resulting in few new plants being flexibly fueled. Similarly, deregulation has led to each generating company seeking to build plants that have the lowest cost. Under regulation, utilities sought to have a diverse supply of fuels so that an interruption in one fuel supply would not lead to a disruption in electricity supply. Deregulation means that generators have little incentive to build a higher cost plant in order to have a diverse fuel supply. When a price cap is imposed on generators, as FERC and the independent systems operators have done, this has the effect of removing any incentive to have a diverse fuel supply. Without the price cap, a generating company might be willing to take a gamble that, although this higher cost plant would operate only a small proportion of the time, when the other plants were unable to supply power, it would get a large enough price for its power to make this an attractive investment. With a price cap, the small number of hours of operation means that the plant could never pay back the investment.

This movement away from fuel diversity, fuel flexibility, and having sufficient inventories not only has costs to the economy, it also increases the threats to public health and safety. For example, a city without traffic lights is a city where emergency vehicles will be totally or at least partially blocked for putting out a fire, interrupting a criminal act, or giving emergency medical assistant to someone who is injured or suffering a heart attack. The cost to residents and businesses of having the streets be grid locked is large. It also provide a tempting scenario for terrorists: First shut down the electricity supply and then, when the streets are grid locked set a fire or explosion in major buildings.

Survivability of the Electricity Sector

I can apply these concepts to the electricity sector. The current fuel mix is 50% coal, 20% nuclear, 15% natural gas, 6% hydroelectric, 3% oil, and 6% other. In general, coal plants maintain lower coal inventories than they did in previous years. Nuclear plants have adequate fuel supplies so that the interruption of a shipment of fuel rods by a few days should not be a difficulty. Hydroelectric generation has its inventory behind the dam. That inventory can fall to low levels if there is inadequate precipitation. If the dam failed due to a structural problem or sabotage, there would likely be a devastating flood that would be worse than the power interruption. Natural gas turbines are vulnerable to supply interruptions since they maintain essentially no inventory. In this sense, moving toward greater dependence on natural gas makes the nation more vulnerable.

In some parts of the country, there is a large amount of generating capacity beyond that needed to meet peak demand. This additional capacity means that the loss of an individual plant would have no long-term consequences. If the system is being operated properly, losing an individual plant should have no short-term consequences since the system is operated for an "N – 1" contingency, meaning that any single component could be lost without causing a disruption. However, at times of peak demand, such as 6 PM on an August afternoon, some areas do not have adequate capacity to operate on an N – 1 basis. In particular, when demand is high, Manhattan is vulnerable to the loss of a transmission line or substation. Building additional transmission lines, substations, and generating plants in the city could remedy this.

Providing backup generator at critical facilities could protect them again power failure. However, these units have to be tested regularly to ensure reliability.

Another approach to ensuring greater survivability is to have more of the generation in small units located at or close to the customer. This "distributed generation" breaks up generation into much smaller units so that the loss of a generator has little cost. The distributed nature of generation means that loss of a transmission line (or even a distribution line) would not cause a power interruption. Finally, having generation be local means greater reliability even for customers who don't have these generators. Since the generators lower the demand, the pressure on distant generating units and transmission is lowered. Whatever the current capacity, building distributed generation would mean that the loss of one or more central generators or one or more transmission lines would be less likely to cause a blackout.

A final example of survivability is changing the system so that a loss of power would not be devastating. For example, traffic lights could be changed to light emitting diodes, lowering electricity use by 90%. These LEDs could function for a day after power was interrupted. Similarly, elevators could be modified sot that they could descend to the next floor in the even of a power failure. No electricity is required for descent.

What Was the Cost of the August 14 Blackout?

A power outage can lead to injuries because people cannot see where they are going, because it encourages crime, or because people try to do things that cause injury. The outage can lead to public health problems because potable water is no longer available, because spoiled food is eaten, or because untreated sewage forms pools in the street. The lack of refrigeration can cause medicine to spoil and prevent people from getting needed medicine and treatment. If the outage is long enough, all perishable food spoils.

Without electricity, essentially all economic activity stops. Some estimates of the cost of August 14 tabulate the number of lost days of production. This is almost certainly an overestimate of the cost, since workers tend to work harder and be more productive when the power returns. If necessary, workers can put in overtime to make up the lost production. However, if the blackout shut a parts factory which led to shutting an assembly line, the cost of shutting the assembly line in an location that was not blacked out could be much higher than shutting the parts factory.

A range of estimates has been made about the cost of the August 14 blackout, from about $4 to $12 billion. In looking at the material on which the estimates are based, it is clear that they are “guesstimates” rather than scientific estimates. They are based on spotty reports of costs from some companies and consumers. There is no audit of the reports and the companies reporting are not a random sample of all companies. Clearly, the “true” costs could be somewhat higher or much lower.

Conclusions and Lessons

A first estimate of the cost of a prolonged power interruption, both in terms of lost production and losses to consumers, is the size of GDP. An input-output model is not useful for setting sectoral estimates of these costs, not is it helpful in identifying which sectors are most vulnerable to power interruptions. At least initially, a blackout causes an almost complete suspension of economic activity and loss of some goods in process and inventories.

Natural hazards, accidents, poor management, or terrorists could disrupt the supply of any input or product in the economy. To keep the cost of such an interruption low, businesses and consumers can take the following steps.

1, Make sure that there is sufficient spare capacity in each sector that losing a single generator, transmission line, port, highway, or factory would not reduce the ability to produce the current bundle of goods and services that make up GDP.

2. Maintain inventories of supplies at the customer sufficient to handle expected disruptions, e.g., coal at electricity generating plant or supplies of water in your home.

3. Maintain inventories at the producer sufficient to handle expected disruptions, e.g., coal at the mine or canned goods at the food processor.

4. Design the production process to be flexible with respect to inputs, e.g., a generation plant than can burn both goal and natural gas.

5. Maintain parallel delivery mechanisms, e.g., additional ports or highways or transmission lines that could handle the traffic if one highway or port or transmission line is closed.

6. Maintain several suppliers with different owners in different locations, e.g., flu vaccine produced in different places with sufficient capacity to meet demand if one plant fails.

Unfortunately, the economy seems to be moving toward lessening the protection inherent in these six ways of protecting against natural hazards, accidents, management mistakes, and terrorists. As the economy becomes more tightly integrated with just-in-time delivery and the general elimination of inventories and flexibly fueled plants in order to lower cost, we make ourselves more vulnerable to a host of disruptions. Reversing these trends in the economy will not be easy or costless.

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