BUSINESS INTERRUPTION IMPACTS OF A TERRORIST ATTACK ON THE ELECTRIC POWER SYSTEM OF LOS ANGELES: CUSTOMER RESILIENCE TO A TOTAL BLACKOUT

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I. INTRODUCTION

Over the past forty years, the U.S. has witnessed some major urban and regional electricity blackouts that have plunged much of its citizenry into darkness and disrupted the surrounding economies.[1] Fortunately, these events have not lasted more than a couple of days, thus muting the damage and preventing possible accelerating effects due to panic or major economic dislocations. Although most of these blackouts were caused by factors other than terrorism, the terrorist threat is likely to become increasingly prominent for several reasons. First, unlike natural disasters or technical failures, which occur relatively randomly, terrorist attacks can be targeted to yield a maximum of damage. Second, electric power systems are relatively fragile and difficult to safeguard. With the exception of nuclear plants, no generating station, sub-station, transmission, or distribution lines have been constructed with an emphasis on protection from terrorism. Moreover, all of these components can be compromised by aircraft or ballistic mechanisms, and the network consists of millions of miles of power lines that defy constant surveillance. Third, the payoff from hitting the electric power system is rather large. Darkness can instill fear into the citizenry, spur crime, give cover to further terrorist activity, and damage the economy.

Estimation of economic impacts of power outages has become more prevalent in recent years. Most of the literature uses indirect measures or proxies of damage, such as equating the cost of outages with the cost of precautionary measures such as back-up generators. These and most other analyses have not included two factors that can significantly affect the impacts. The first is economic *resilience*, or the ability to mute the maximum impacts through inherent and adaptive responses at the level of the firm, industry (market), or regional economy. The second is *indirect* economic impacts, often referred to as multiplier or general equilibrium effects, which significantly increases the size of the damage as it ripples throughout the economy beyond those businesses whose electricity service is directly curtailed, though market resilience mutes these effects as well.

The purpose of this paper is to estimate the direct and indirect economic impacts of an extended electric power outage caused by a terrorist attack in a major U.S. city--Los Angeles, California. Several simulations are run relating to damage to various components of the electric power system. Given the ability to target maximum damage, the simulations involve a two-week period until the system is fully restored. The analysis extends beyond the approaches prevalent in the recent literature, which have omitted resilience and indirect effects. The simulations are performed with the use of a computable general equilibrium (CGE) model that addresses these often omitted factors and incorporates special features relating to terrorism. The CGE framework has been successfully applied to electricity and water disruptions from natural hazards (Rose and Guha, 2004; Rose and Liao, 2005), as well as from technical/regulatory failures (Rose et al., 2004), and has several advantages over other approaches in being applied to utility lifeline disruptions from terrorist attacks (Rose, 2005).

This paper does not address all of the economic impacts of an electric power outage but focuses on what is often termed business interruption and extends this to a counterpart "household interruption." We omit several considerations, such as the value of any lives lost, increased crime, psychological trauma, some infrastructure costs, and property damage. Various cost estimating factors (see Zimmerman et al., 2005a) might be used to complement our analysis. We have chosen to pursue the major cost component in depth and to do so with a formal analysis, rather than spread ourselves thin over the full range of impacts. The advantage of our approach is that it involves a model that has behavioral content, so that we can examine a range of responses to a power outage by individuals, businesses, and markets. This not only sharpens the estimates but helps identify ways to reduce losses in the future utilizing relatively low cost "non-structural" approaches such as market price rationing, information clearinghouses, and various types of substitutes for electricity and other inputs. Our model is also grounded in the specification of electricity generation, transmission, and distribution systems, which enhances its accuracy and also identifies appropriate mitigation and restoration options.

II. ECONOMIC IMPACTS

A. Partial Equilibrium Effects

Several approaches have been used to estimate the costs of electricity outages. Direct, or partial equilibrium, effects of outages manifest themselves in four major ways: lost sales, equipment damage or restart costs, spoilage of variable inputs, and idle labor costs. In addition, costs are incurred to reduce potential losses through the purchase of backup generators, permanent changes in production schedules, and utility capacity expansion to promote flexibility (Munasinghe and Gellerson, 1979). At the margin, the cost of outages should be equal to the cost of these adaptive responses. Hence, the most popular way of measuring electricity outage losses recently has been tabulating expenditures on back-up generation rather than measuring damages directly (Beenstock et al., 1997). Still, measurement of just a single coping tactic, or single type of damage, is likely to understate the direct dollar loss.

The marginal value of the loss of electricity is equivalent to the marginal value of electricity reliability (the obverse of the marginal adaptive response, or mitigation, noted earlier). This condition has been used to develop schemes to address the problem in the form of price discounts for interrupted service or premiums for priority service (see, e.g., Chao and Wilson, 1987; Doucet et al., 1996). If structured properly, these pricing provisions also serve as a proxy for the partial equilibrium effects of electricity outages, in addition to serving as an efficient rationing mechanism.

Many regions of the U.S. suffer power outages of as many as ten to thirty hours per year due to ordinary circumstances of engineering failures and severe storms. Simonoff et al. (2005) found that in recent years weather-related events have become more common and technical failures have become less so. One estimate of direct losses from electricity disruptions ranges from $1.50 to $7.50/kwh in the U.S. updated to 2005 dollars (see, e.g., Caves et al., 1992). The voltage disturbance blackouts of 1996, for example, are estimated to have cost California more than $1 billion in direct losses (Douglas, 2000). A more recent estimate of outage costs to business is as high as $50/kwh for some sectors. An application of such estimates placed the cost of the 2003 Northeast blackout at more than $6 billion (Graves and Wood, 2003). Zimmerman et al. (2005b), using a rather crude estimating factor (GDP per person times the number of people affected), estimate the cost at $5.6 billion. Both of these estimates, however, omit most of the various extenuating and mitigating factors addressed in this paper.

B. General Equilibrium Effects

In this paper, we utilize economic output losses (also adjusted to net, or value-added, terms and consequently translated into welfare measures) as a common denominator for both partial and general equilibrium (GE) effects. This even enables us to include some property damage and productivity losses into the measurement in addition to more conventional business interruption (Rose, 2004a). Overall, general equilibrium effects consist of several types. First is output loss to downstream customers of a disrupted firm through its inability to provide crucial inputs. This and the other GE effects noted below set off a chain reaction beyond the immediate or partial equilibrium effects (PE), in this case in terms of customers of firms who have had their electric power curtailed. Second is output loss to upstream suppliers of disrupted firms through the cancellation of orders for inputs. Again, this is transmitted through several rounds, though in this case in terms of suppliers. Third is output loss to all firms from decreased consumer spending associated with a decreased wage bill in firms directly affected by the electricity outage, as well as all other firms suffering negative GE effects. Fourth is output loss to all firms from decreased investment associated with decreased profits of firms suffering the electricity outage and other firms negatively impacted by GE effects. Fifth is output loss to all firms from cost (and price increases) from damaged equipment and other dislocations (including uncertainty) that result in productivity decreases in firms directly impacted.

The direct and indirect costs of electricity outages thus do not just take place during the period in which power is curtailed. Backup generators are purchased in anticipation of outages, and the carrying cost of increased inventories of critical materials are incurred over a longer period as well. Equipment damage, spoilage, and idle labor costs may translate immediately into lost profits, but they may not be passed through in the form of price increases until a later date. The same is true of electric utility cost and price increases that lag, even in a deregulated market. The three time periods, which we designate as *preparatory*, *crisis*, and *recovery*, will vary in length depending on the context. For example, the length of a preparatory period would depend on the level of expectations prior to such an attack. For estimation purposes, however, they may all be simulated simultaneously in cases where there are no significant dynamic (i.e., time-related) effects.

Note also that not all general equilibrium effects are negative. Some firms may benefit from the decreased prices associated with a shift in demand by other firms for various products. The analysis below indicates the existence of this possibility for several sectors, though the positive general equilibrium effects do not typically more than offset the negative partial equilibrium ones. In general, input-output (I-O) models are limited to uni-directional impacts, and, unless modified or used judiciously (see, e.g., Rose et al., 1997), exaggerate indirect effects as being equal to multiplier values (in the range of 2 to 3 times the direct effects for a city like Los Angeles). CGE models can incorporate a wide range of offsetting effects.

C. Resilience

In general *economic resilience* refers to the ability or capacity of a system to absorb or cushion itself against damage or loss (see, e.g., Holling, 1973; Perrings, 2001). A more general definition that incorporates dynamic considerations, including stability, is the ability of a system to recover from a severe shock. We also distinguish two types of resilience in each context:

Inherent--ability under normal circumstances (e.g., the ability of individual firms to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals).

Adaptive--ability in crisis situations due to ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations, or strengthening the market by providing information to match suppliers without customers to customers without suppliers).

Resilience emanates both from internal motivation and the stimulus of private or public policy decisions (Mileti, 1999). Also, resilience, as defined in this paper, refers to post-disaster conditions and response, which are distinguished from pre-disaster activities to reduce potential losses through mitigation (cf., Bruneau et al., 2003; Klein et al., 2003). In disaster research, resilience has been emphasized most by Tierney (1997) in terms of business coping behavior and community response, by Comfort (1999) in terms of non-linear adaptive response of organizations (broadly defined to include both the public and private sectors), and by Petak (2002) in terms of system performance. These concepts have been extended to practice. Disaster recovery and business continuity industries have sprung up that offer specialized services to help firms during various aspects of disasters, especially power outages (see, e.g., Salerno, 2003). Key services include the opportunity to outsource communication and information aspects of the business at an alternative site. There is also a growing realization of the broader context of the economic impacts, especially with the new emphasis on supply chain management. One company executive recently summarized the situation quite poignantly: "In short, companies have started to realize that they participate in a greater ecosystem—and that their IT systems are only as resilient as the firms that they rely on to stay in business" (Corcoran, 2003; p. 28). Experience with Y2K, 9/11, natural disasters, and technological/regulatory failures, as well as simulated drills, have sharpened utility industry and business resilience (Eckles, 2003). Similar activities of public agencies have improved community resilience.

Resilience can take place at three levels:

Microeconomic--individual behavior of firms, households, or organizations.

Mesoeconomic--economic sector, individual market, or cooperative group.

Macroeconomic--all individual units and markets combined, though the whole is not simply the sum of its parts, due to interactive effects of an economy.

Examples of individual resilience are well documented in the literature, as are examples of the operation of businesses and organizations. What is often less appreciated by disaster researchers outside economics and closely related disciplines is the inherent resilience of markets. Prices act as the "invisible hand" that can guide resources to their best allocation even in the aftermath of a disaster. Some pricing mechanisms have been established expressly to deal with such a situation, as in the case of non-interruptible service premia that enable customers to estimate the value of a continuous supply of electricity and to pay in advance for receiving priority service during an outage (Chao and Wilson, 1987).[2]

The price mechanism is a relatively costless way of redirecting goods and services. Price increases, though often viewed as "gouging," serve a useful purpose of reflecting highest value use, even in the broader social setting (see also Schuler, 2005). Moreover, if the allocation does violate principles of equity (fairness), the market allocations can be adjusted by income or material transfers to the needy.

Of course, markets are likely to be shocked by a major terrorist attack, in an analogous manner to buildings and humans. In this case, we have two alternatives for some or all of the economy: 1) substitute centralized decree or planning, though at a significantly higher cost of administration; 2) bolster the market, such as in improving information flows (e.g., the creation of an information clearing house to match customers without suppliers to suppliers without customers).

D. Empirical Insights

Will an X percent loss of electricity result in an X percent direct loss in economic activity for a given firm? The answer is definitely "no" given the presence of economic resilience. For the purpose at hand, we use as our measure of direct resilience, the deviation from the linear proportional relation between the percentage utility disruption and the percentage reduction in customer output (see Rose, 2004b). One of the most obvious resilience options for input supply interruptions in general is reliance on inventories. This has long made electricity outages especially problematic, since this product cannot typically be stored. However, the increasing severity of the problem has inspired ingenuity, such as the use of non-interruptible power supplies (capacitors) in computers (Douglas, 2000). Other resilience measures include various types of "distributed" generation (e.g., back-up generators), conservation, input substitution, and rescheduling of lost production. In many business enterprises, these measures are adequate to cushion the firm against some losses of a rather short or moderate duration.

Will a Y percent loss in direct output yield much larger general equilibrium losses? Here market-related adjustments suggest some muting of general equilibrium effects, if we measure market, or net general equilibrium, resilience as the deviation from the linear multiplier effect that would be generated from a simple input-output analysis of the outage (Rose, 2004b). Adjustments for lost output of goods and services other than electricity include inventories, conservation, input substitution, import substitution and production rescheduling at the level of the individual firm, and the rationing feature of pricing at the level of the market.

The number of studies that have estimated effects of utility service disruptions is rather sparse, especially if we consider only those that used customer lost output as the unit of measure and that have also included indirect (either ordinary multiplier or general equilibrium) effects. Tierney (1997), collected responses to a survey questionnaire from more than a thousand firms following the Northridge Earthquake, where the maximum electricity service disruption following this event was 8.3 percent and nearly all electricity service was restored within 24 hours. Tierney survey results indicated that direct output losses amounted to only 1.9 percent of a single day's output in Los Angeles County. A study by Rose and Lim (2002) of this same event used a simple simulation model that incorporated three resilience options to estimate direct losses at 0.42 percent and used a modified I-O model to estimate total region-wide losses of 0.55 percent. Although this study did not include the full range of resilience tactics as was inherent in the Tierney study, it is also likely that responses to the Tierney questionnaire under-reported the effects of production rescheduling, the major resilience response in the Rose and Lim study. A CGE analysis by Rose and Guha (2004) of the impacts of a hypothetical New Madrid Earthquake on the Memphis, Tennessee economy indicated that a 44.8 percent loss of electricity services would result in only a 2.3 percent loss of regional output; however, this model did not explicitly include resilience measures and was constrained from reducing major adaptation parameters, such as elasticities of substitution, to levels that truly reflected a very short-run crisis situation. A study by Rose and Liao (2005) for a hypothetical earthquake in Portland, Oregon, and for water rather than electricity utilities, incorporated engineering simulation estimates of PE losses into a CGE model. The first simulation, which represented a business-as-usual scenario, indicated that a 50.5 percent loss of utility services would result in a 33.7 percent PE loss, factoring in some resiliency measures. Further adjustment for production rescheduling reduces this to 5.7 percent. A second simulation, representing the case of $200 million capital expenditure initiative of replacing cast-iron pipes with modern materials, indicated that a 31 percent loss of utility services would result in a 21 percent PE loss in the region. Note that direct resilience declined following mitigation (direct output losses as a proportion of utility outage levels) increased, because mitigation reduces initial loss of service and hence ironically narrows the range of resilience options that can be brought into play.

The results of the several studies, using several alternative methods, indicate that direct (PE) business resilience is quite high and that results of analyses that included this factor would be between 77 percent and 95 percent lower than for analyses that neglected it (e.g., a purely linear model). GE effects are presented are a moderate increase over PE effects, ranging from an additional 22 percent to 43 percent. The I-O model of the Rose-Lim (2002) study did not allow for ordinary multiplier effects, because of assumed adequacy of inventories for goods other than electricity for the 36-hour outage period, and thus considered only "bottleneck effects" (see the discussion below). Interestingly, the first simulation by Rose and Liao (2005) yielded general equilibrium effects on the order of 22 percent of direct effects, and the second simulation yielded general equilibrium effects 43 percent as great as direct effects. This means that mitigation not only lowered direct business resilience (though of course overall vulnerability was much reduced) but also made the regional economy as a whole less resilient, thus offsetting some of this strategy's benefits.

Thus, in this group of studies direct resilience is a stronger force on the downside than are general equilibrium effects on the upside.[3] These two sets of effects do not cancel each other out, and a study that omitted both is still likely to significantly overestimate the effect that a terrorist attack on a utility lifeline has on the overall economy.

III. CHARACTERISTICS OF ELECTRIC POWER OUTAGES

A. General Considerations

Terrorist attacks can damage the various components of an electric power system, each with a different implication for the surrounding economy. At the most fundamental level, this involves destroying a generating plant, which reduces the supply of electricity. However, most large cities are serviced by more than one generating station. Moreover, many cities are not necessarily serviced by the nearest power plant, but rather electricity enters a transmission network grid from which deliveries are parceled out to different locations, with an increasing reliance on markets and pricing considerations for these allocations.

Thus, probably the most effective way of targeting the reduction of the availability of electricity in a given area is the destruction of large transmission lines that directly feed a given regional economy (see also Zimmerman et al., 2005, who found that 60 percent of all terrorist attacks attempt to disable transmission systems). This will lead to an across-the-board reduction of electricity availability to all customers in a large geographic area, including many moderately sized cities.

The next level of the system is the receiving station, which converts the high voltage electricity to lower levels for the next stage of transmission. The voltage is then further reduced at receiving stations, which are typically serviced by one of more transmission lines, the hubs for local distribution networks (see, e.g., Shinozuka and Chang, 2004). Each receiving station's service territory is often referred to as an Electric Power Service Area, or EPSA. Destruction of a receiving station would also reduce electricity availability equally proportionally to all customers within an EPSA. This, however, will not result in equal proportional cutback for all sectors in a city, since economic activity is not randomly or uniformly distributed within it. For example, some EPSAs service industrial centers, while others service primarily residential or commercial customers. Thus, to model the economic impacts of an attack on this component, and all down-stream components of the system, it is necessary to have an economic model with some spatial attributes. This is also the case for the simulation of the impacts of an attack on a power plant or transmission line servicing a large city that is also serviced by several alternatives.

Below the level of the receiving station, there are more local distribution stations that further reduce the voltage, as well as local distribution lines that feed neighborhoods and that are hooked-up to individual customers. Except for various strategic locations, this lowest level of the system is not likely to be the focus of a terrorist attack.

In most cases, damage to components of the electric power system result in a shut-off of power rather than a reduction in its quantity. An exception would be if sabotage of a receiving station reduced but did not entirely destroy its capacity, and where decision-makers decide to ration the remaining electricity by initiating a series of rolling blackouts (where customers in a given area have their electricity curtailed for some pre-announced number of hours each day). Thus, unlike a water system, where customers can received reduced service flows, the electric power case is typically an "all or nothing" proposition. Moreover, it is often easier for businesses to work around a rolling blackout, as long as it is pre-announced, rather than a quantity reduction. This can be done by a combination of rescheduling production or minimizing the intrusion on customers where business is time-sensitive (e.g., cutting off power to restaurants at non-meal hours).[4]

The all or nothing aspect of most electric power disruptions makes them a bit more complicated in the context of regional economic modeling. There is a distinct difference in a non-linear model between the following two cases:

A. 20 percent of the customers have a 100 percent outage
B. 100 percent of the customers have a 20 percent outage

Case B is the most straightforward approach in the context of a CGE model. It serves as a linear approximation of circumstances reflected in most actual cases, with the error depending on the extent of non-linearities in the production function.

Another consideration in evaluating the economic impact of utility outages is the temporal and spatial pattern of system recovery. In the case where multiple transmission lines, substations, receiving stations or distribution lines are down, power can be restored so as to minimize the disruption by sequencing restoration to favor customers who put the electricity to highest value use (see, e.g., Rose et al., 1997; Davidson and Cagnan, 2004). Moreover, this use would reflect not only the direct value to the electricity user but also the value to its suppliers and customers, thus adding to the list of advantages of using some form of applied general equilibrium modeling. Although many utilities and municipalities have a customer prioritization list, it is not clear that the primary objective is to reduce regional economic impacts, but rather to maintain health and safety. This is reflected in priorities usually given to hospitals, police and fire protection, as well as residential customers in general. Moreover, restoration crews are frequently dispatched according to cost-engineering considerations (e.g., priority is accorded to the substation that can be returned to service most quickly or cheaply).[5]

One of the major factors in evaluating the economic impacts of utility lifeline outages is resilience, or the ability of an individual, organization (e.g., business) or institution (e.g., market) to cushion itself against maximum losses (see, e.g., Rose, 2004b; Rose and Liao, 2005). This is done by implementing various inherent or adaptive coping measures for adjustment or adjustments, rather than passively carrying out business as usual. Some examples of resilient responses for dealing with electricity disruptions include:

- Conservation--utilizing less electricity per unit of output
- Fuel substitution--utilizing some other fuel
- Back-up power--utilizing an alternative source of generation
- Production rescheduling--making up lost production at a later date
- Electricity importance--utilizing the portion of a business that has no need for electricity

For the case of electricity disruptions, conservation is a limited option because of the all or nothing nature of the situation. Fuel substitution can be implemented by using a stand-by boiler to generate heat. Other input substitution involves using capital, labor or materials instead of energy. This is also relevant to households, as in the substitution of brawn for household appliances such as electric can openers. While such examples might at first appear trivial, it is important to note the important role of households as consumers of this product. In Los Angeles County in 2002, for example, households represented 33 percent of total demand for electricity. Moreover, lost time or inconvenience for households does have a value and can be measured (see, e.g., Rose and Oladosu, 2005).[6] Back-up power refers to the use of on-site (decentralized) generation. It includes both self-contained (often emergency) generators or dedicated small power plants. The former are rather ubiquitous in LA County because of experiences with earthquakes and regulatory dislocations, while the latter are confined to large factories or institutions. Production rescheduling is one of the most powerful options, even for an outage as long as two weeks, and is applicable to all sectors whose output is not time sensitive and that are not operating 24/7 at full capacity. "Electricity importance" (ATC, 1991) is an adjustment for those aspects of production that do not require electricity (e.g., crop growing and delivery services), and is thus a limited option for outages of short duration. All of these factors are important in designing simulations for the regional economic impact of a major power outage caused by a terrorist attack.

B. Simulation Parameters

Our simulations pertain a total electric power outage, as where all transmission lines are destroyed. This, as well as the other simulations, is expected to have a duration of two weeks. However, only this case will affect the entire County. As such, all sectors will be affected equally at first. As transmission lines are repaired, sectoral differentials are in fact applicable, since only remaining portions of the County will be without power.

We also assume recovery will take 2 weeks (see Zimmerman et al., 2005a) and will be sequential, with priority given to the transmission lines in terms of their contribution to the regional economy. Thus recovery will not be linear but in fact accelerated. However, we will invoke our linear approximation to the determination of the percentage of customers affected by each transmission line. Resilience options for businesses will include all of the options described in the previous sub-section.

Implicitly, our analysis assumes the following:

- No advance warning of the terrorist attack
- No rolling blackouts to deal with disruption
- No splicing of power lines across EPSAs
- Linear approximation of reduction in individual service
- Inapplicability of some resilience considerations

We also invoke important assumptions regarding the price of electricity. In our simulations, we keep the electricity price constant because of the massive nature of the outage and the need for as much economic stability as possible.

IV. THE ROLE OF UTILITIES IN LA COUNTY

Los Angeles County has one of the largest regional economies in the U.S. In 2002, total economic output in the County was about $652 billion, consisting of 57 percent net value-added (roughly equivalent to Gross Regional Product), 39 percent intermediate inputs (including imports), and about 4 percent indirect taxes. Exports from the County amounted to about $194 billion, 81 percent of which are shipped to the rest of the U.S., and 19 percent of which are shipped overseas. Seventy-four percent of the imports into the LA County economy comes from the rest of the U.S. Household income amounted to about $301 billion (MIG, 2005). The economy is highly developed, as exemplified by strong interdependencies between sectors, the prominence of manufacturing and service sectors, and a relatively high level of regional self sufficiency.

Electricity is a major driver of the LA County economy both as an output and an input. In 2002, Private Electric Utilities (Southern California Edison, or SCE) sales were $3.5 billion, and State and Local Electric Utilities (primarily Los Angeles Department of Water and Power, or LADWP) sales were $2.8 billion. Residential customers represented 35.3 percent of SCE's total sales, and 28.3 percent of LADWP's total sales in dollar terms in 2002. Hence, failure to consider impacts of an electricity disruption on the household sector would grossly understate regional economic impacts.

In 2000 and 2001, Los Angeles, as well as several other parts of the state suffered a series of blackouts, due primarily to poorly designed deregulation, weather conditions both within and outside the State, volatile natural gas prices, and lagging capacity expansion of both generating and transmission systems.

Some casual observers have suggested the California rolling blackouts impacts were rather minimal. Economists with the U.S. Treasury, the San Francisco Federal Reserve Bank, and a major investment firm interviewed by Berry (2001) generally downplayed the situation in the aftermath of outages in 2000. Part of the reason is that firms had preventative measures in place, such as backup generators and spatially dispersed facilities, in part due to the State's susceptibility to earthquakes. They noted the consumers were insulated against accompanying price increases by the continued regulation of retail electricity prices, though they emphasized the absorption of losses by utility stockholders and debt holders. Those interviewed concluded that the firms being affected were minor in the context of the overall California economy but warned that persistent outages could affect business and consumer attitudes and hence behavior.

In contrast, a survey by the National Federation of Independent Business (NFIB, 2001) found that over half of small businesses experiencing blackouts in California in January, 2001, had to curtail operations. Of these, 34.2% lost sales, averaging about 6.3% of their January sales total. Moreover, the Study indicated significant indirect effects. For example, 15.2% of businesses in California as a whole, and 10.5% in the Los Angeles area, noted that shipments or services to them were delayed because of a blackout affecting someone else. Also, 13.7% in California and 7.7% in LA lost sales "because customers directly impacted by a blackout either could not reach them or were otherwise preoccupied." California firms experiencing blackouts estimated that indirect effects cost them 16.9% of sales, more than double the direct effects, probably due in part to the fact that direct electricity customers often had prior warning, while indirect effects apply to goods and services, whose producers were likely unaware of the timing of the outages. A significant number of firms suffered long-term effects, e.g., 13.6% curbed new hiring or delayed investments. Also, 12.8% of firms in California and 13.3% in the LA area responded that "the electricity problem has forced me to take concrete steps exploring the possibility of moving my business out of California." The above includes both planned and unplanned outages. A simulation analysis by Rose et al. (2004) of pre-announced rolling blackouts estimated the economic impacts as much more modest than the NFIB study. This is likely due to the advance warning context of the former study, a condition that will not be present for a terrorist attack.

V. THE LA CGE MODEL

CGE analysis is the state-of-the-art in regional economic modeling, especially for impact and policy analysis (Partridge and Rickman, 1998). It is defined as a multi-market simulation model based on the simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (see, e.g., Shoven and Whalley, 1992). The CGE formulation incorporates many of the best features of other popular model forms, but without many of their limitations (Rose, 1995). The basic CGE model has been shown to represent an excellent framework for analyzing natural hazard impacts and policy responses, including disruptions of utility lifeline services (Brookshire and McKee, 1992; Rose and Guha, 2004; Rose et al., 2004; Rose and Liao, 2005). To date, however, a CGE model has not been applied to a terrorist attack, even though several features of this approach are ideally suited to this context (Rose, 2005).[7]

A. Model Specification

We constructed a static, regional CGE model of the LA County economy consisting of 33 producing sectors. The sector classification was designed to highlight the sensitivity of production processes to water and electricity availability. Institutions in the model are households, government, and external agents. There are nine household income groups and two categories each of government (State/Local and Federal) and external agents (Rest of the U.S. and Rest of the world). Major features of the model are:

1. Production

The top level consists of substitution possibilities among a capital-labor-energy-material (KLEM) aggregate. Production activities are specified as constant-returns-to-scale, nested constant elasticity of substitution (CES) functions. The next level reflects the choice of a material inputs aggregate (in terms of fixed coefficients) and a capital-energy-labor input combination. On the third level, the capital-labor-energy combination is made up of labor and a capital-energy combination. On the fourth level, the capital-energy combination is made up of capital and energy aggregates. In order to capture the role of electricity more explicitly, we include an energy sub-nest consisting of fuels and electricity. Fuel use is a CES function of petroleum and gas, while overall electricity use is derived as a Leontief (fixed coefficient) aggregation of private electric utilities and state/local electric utilities.

2. Supply and Trade of Goods and Services

We specify transactions between the LA County and the two external sectors in the model using the Armington function for imports and the constant elasticity of transformation function for exports. The former is specified as a CES function to reflect imperfect substitution between domestic goods and competitive imports in demand. The latter is also a CES function that reflects the revenue-maximizing distribution of domestic output between exports and domestic markets, respectively. Regional export and import prices are based on exogenous external prices plus percentage taxes and tariffs (for the Rest of the World sector) to reflect the open nature of the LA County economy.

3. Income Allocation, Final Demand, and Investment

Incomes from labor and capital employment in the economy are shared among institutions after the following deductions are made. Governments collect profit taxes on capital and employer-paid social security taxes on labor income, while industries deduct depreciation charges and retained earnings before paying capital incomes. The remaining incomes are then distributed to households and external agents according to fixed shares. Institutions also receive inter-institutional transfers, such as subsidies, social security, and income taxes.

Households' production and consumption of goods and services are modeled using Cobb-Douglas expenditure functions.[8] Government consumption is specified as a Leontief expenditure function. Income elasticities are unity for both households and government, and price elasticities are one for households but less than one for governments. Savings by households and governments are fixed proportions of disposable income, while external savings balance out this account. Households, government, and external entities also borrow from the capital account. Net savings by institutions, plus depreciation charges and retained earnings, are used to finance investment in capital goods. Investment in individual capital goods categories is a fixed proportion of total investment funding.

4. Equilibrium/Disequilibrium Conditions

Equilibrium conditions balance supply and demand in goods and services markets. Capital endowments in the economy are fixed to reflect the short-run nature of our simulations. In the labor market, the Keynesian closure rule is used to allow for unemployment even in equilibrium. This disequilibrium condition prevents the muting of impacts inherent in the forcing of an equilibrium by the application of the Neoclassical closure rule (zero unemployment equilibrium).

Disequilibrium is introduced into the model in several other ways (see, e.g., Rose et al., 2004; Rose and Liao, 2005). Most important are constraints on utility service supplies resulting from a terrorist attack. This causes a shift away from an efficient equilibrium to a second-best world. Because some electricity rates in LA County are rigid (LADWP has still not opted to have its electricity prices deregulated), utility service markets cannot adjust in the usual manner. Price adjustment lags because regulation keeps prices constant at pre-attack levels, which does not allow markets to clear under what would otherwise be increasing price pressure from shortages. The model solves for the excess demand and with an opportunity cost loss for utility companies.

Another source of disequilibrium stems from temporary imbalances in trade and financial flows in and out of the County. An increased demand for imports will likely be required to offset the reduced production within the County. Trade imbalances are not as serious in a sub-national setting as at the international level, since they do not affect currency values. Moreover, lags in outside aid and insurance payments to pay for imports (or pay for intra-county products) can readily be handled by lags in the payments and expenditure of wages and capital-related income, as well as in tax revenues.

Finally, the model can incorporate fiscal imbalances. This would include debt, as well as other options (increased taxes, user fees or outside aid) to fund mitigation, and deficit spending to fund recovery and reconstruction. These various alternatives are likely to have significantly different impacts on the regional economy. An infusion of outside aid will translate into an unfettered boon, and the economy might expand or contract depending on shifts in spending from one stream to another (fewer consumer goods and more public services from tax increases, or shifts from ordinary consumer expenditures to repair and reconstruction expenditures).

B. Model Construction

1. Utility Data

A major amount of the data for the model are taken from the detailed 2002 Social Accounting Matrix (SAM) for LA County, derived from the Impact Planning and Analysis (IMPLAN) database (MIG, 2005).[9] The IMPLAN data base uses a non-survey approach to down-scale national and state economy indicators (output, income, employment) to the county level. Hence, it is important to verify the IMPLAN figures in key sectors for small area I-O tables. The reconciliation of the data between region-specific sources and the IMPLAN data base are presented in Rose et al. (2005).

Elasticities of substitution for regionally produced inputs and for imports were based on a synthesis of the literature (Oladosu, 2000; and Rose and Liao, 2005),[10] and other major parameters were specified during the model calibration process. Spatial data on economic activity and the electric power network are discussed in the following section.

Note that the various types of resilience are incorporated into the model by modifying key CES production function parameters. Various methods will be used as explained in more detail in Rose et al. (2004) and Rose and Liao (2005).

VI. ELECTRICITY OUTAGE SIMULATIONS

A. Model Refinements

Although the basic LA CGE model includes fundamental economic aspects of the production and consumption of electricity, it lacks two important dimensions. The first relates to engineering considerations of generation, transmission, and distribution. These affect the extent of possible outages, the resultant flow of electricity to various customers, and patterns of recovery. The second relates to the spatial dimensions of the electricity system. This helps pinpoint the direct effect on customers of various types, capturing differentials that arise because economic activity is not uniformly distributed geographically throughout the LA County economy.

The first dimension is included by working with staff of LADWP and SCE to identify electricity system characteristics unique to the two main providers in the County, as well as general characteristics relating to electrical engineering. The second is incorporated through GIS overlays of system components and economic activity. In essence, this amounts to specifying the sectoral employment composition by place of work onto an EPSA map.[11] At this point, the work has been completed for the 20 EPSAs in the LADWP service area. Data are specified for the overall SCE service area within Los Angeles County but not for any individual EPSAs, so a direct proportioning method is used.

Essentially, adding these dimensions enables us to specify constraints on electricity availability to each sector of the model and to simulate reasonable recovery patterns. These patterns can be entered into the model as sectoral electricity constraint changes over time.

Below we summarize some assumptions and refinements related to our simulation case of a terrorist attack that causes a total electric power outage in LA County. In this case, all customers are initially cut off from service, so conservation is a limited resilience option. Some companies are also able to maintain some economic activity, because of the "electricity importance" consideration--some parts of companies are not dependent on electricity for their operation (e.g., delivery services). However, based on data obtained from a variety of sources, we assume that a significant percentage of economic activity in the area was serviced by electricity generation on site (e.g., co-generation or back-up generators), though this varies significantly across sectors. Thus, a centralized electricity system can be characterized as "blacked-out," and yet some customers within its service territory are directly unaffected. Other direct responses include substituting other factors of production for electricity and conservation. Production rescheduling, which takes place at a later date, should be deducted from the initial reduction in production so as not to overestimate the impacts of a terrorist attack. There is often a cost of rescheduling, such as paying overtime work or the carrying cost of capital, though sufficient information was not available to estimate these costs. However, initial inquiries indicate that they are relatively minor.

With respect to *indirect* effects, all of the above adjustments are possible for suppliers and customers, both within and outside the EPSA, of those companies initially disrupted by the terrorist attack on the sub-station. Companies within the County but outside the EPSA need not make the direct effect adjustments, but they do need to cope with the reduced supplies of goods and services from those companies whose production was curtailed within the EPSA. Note, however, that lack of availability of these products is really not the issue. Although the price of electricity in this case is held constant because LADWP has not yet opted for deregulation, the price of all other goods and services can adjust through the market mechanism, therefore representing a type of "price-rationing" in this case. Even firms that have inventories of the products in short supply will also bid up prices because of their concerns over inventory holdings; hence, it is not necessary to explicitly include inventory holdings in the calculation. The one exception would be if that product's output were reduced to zero and with no possibility of obtaining it through importation from domestic or foreign sources. However, this is highly unlikely in the case of an outage of a single sub-station, and may be unlikely for all but the most specialized products in the world.

Other adjustments are made in the analysis. For example, since LA County is part of a large consolidated metropolitan area with much economic activity in close physical proximity, it is not unreasonable to increase the possibilities of substituting imports for goods whose production has been curtailed in the County. Increased transportation costs penalties in this case are likely to be minimal because of the short distances involved.

In Table 1, we summarize various parameter and electricity availability constraint adjustments in the basic CGE model for our simulations. Many of the assumptions and adjustments are based on limited information; therefore we will perform sensitivity tests on them. We note first an initial adjustment to convert our CGE model from a long-run equilibrium tool to reflect conditions in the very short-run (two week electricity outage durations). This involves reducing the substitution elasticities between all input combinations by 90 percent of their initial values.[12] The only other major adjustment worth considering, other than disequilibrium conditions mentioned in the previous section, is the possibility of price change

TABLE 1. RESILIENCE PARAMETER CHANGES

Type	Parameter	Data	Modification (practical)	Modification (ideal)
Inherent Electricity Substitution	σ	see text	none	none
Adaptive Electricity Substitution	$\sigma\uparrow$	assumption	increase σ by 10% for all sectors	increase σ by Y_j% for each sector j
Inherent Factor Substitution	σ_{EX}	see text	none	none
Adaptive Factor Substitution	$\sigma_{EX}{}^{a}\uparrow$	assumption	increase σ_{EX} by 10% for all inputs	increase σ_{EX} by Y_i% for input i
Inventories	n.a.[b]	—	—	values for each input i in each sector j
Electricity Conservation	$A_{ELE}\downarrow$	assumption	decrease A_{ELE} by 5% for all sectors	increase A_{ELE} by Y_j% for sector j
Electricity Importance	A_{ELE}	ATC (1991)	loosen electricity constraints	decrease A_{ELE} by Y_j% for each sector j
Alternative Generation	σ_{EK} or A_{ELE}	see text	loosen electricity constraints	decrease A_{ELE} by Y_j% for each sector j
Production Rescheduling	ΔZ	FEMA (1997); Rose & Lim (2002)	multiplicative factor for each sector	multiplicative factor for each sector

[a] Elasticity of substitution between energy and non-energy inputs (X).

[b] Refers to inventory (storage) of all inputs. Not included in model at this time (storage of electricity very limited).

[c] Electricity-specific technology factor.

lags. However these are complex conceptually, and we have no information on which to base them empirically, so we have omitted them at this point.

Several countervailing factors to the more rigid economic structure just noted are presented in Table 1, representing individual and market resilience.[13] Unlike other inputs, conservation of electricity, when it is completely shut off, is a very limited option, so we have included only a 5 percent level in our base case, implemented by adjustment of the electricity input productivity term. A 10 percent level of conservation is simulated in our sensitivity tests. In the case of indirect, or general equilibrium, effects, we invoke the same parameters.[14]

Increased interfuel substitution is a potential response and we model it by increasing substitution elasticities relating to energy types by 10 percent in our base case.[15] Sensitivity tests alter the parameter by zero and 20 percent. We utilize the same parameter adjustments for interfuel substitution in the indirect calculations of the model. As noted before, other factors of production can also be substituted for energy, so we invoke similar parameter increases for substitution between these factors in the direct and indirect portions of the model.

Inventories (customer storage) is not a major option in the case of electricity. Also, we lack the modeling capability and data to factor in other types of inventories, so we have omitted this consideration for now. This will bias our results a bit toward the upper bound.

Electricity importance differs by sector, ranging from low levels of 30 percent in various transportation related sectors to 100 percent in various in Manufacturing sectors. We have no basis for establishing an “importance factor” for goods other than electricity as inputs.

On-site alternatives to centralized electricity delivery from LADWP and SCE cover values ranging from 10 percent in most sectors to 50 percent in sectors with very large firms (e.g., Petroleum Refining), sensitive production processes (e.g., Semi-conductors), or where implementation is relatively easy (e.g., Security Brokers). We invoke sensitivity tests of plus and minus 25 percent of these values for both direct effects and indirect effects.

Production rescheduling also differs by sector, with very high rates for those sectors whose deliveries are not time sensitive (e.g., Durable Manufacturing) and low rates for those whose are (e.g., Hotels and Restaurants). We also assume that a 2-week outage will not cause any permanent change in customer-supplier relationships. This resilience adjustment enters the model at both direct and indirect levels of analysis. As in the case of electricity importance, production rescheduling factors are considered reasonably accurate, and therefore sensitivity tests are not required.

Finally, the price of electricity is fixed (see the discussion above). However, the price of all other goods is allowed to adjust to market conditions.[16]

B. Results

The initial results of our simulations are presented below. These results represent the impacts on the entire Los Angeles County economy and on individual sectors.

The results for a total electricity blackout in Los Angeles County, with only inherent resilience associated with normal input and import substitution and, without any adaptive resilience adjustments, can be quickly summarized. To begin, we have reduced direct delivery of electricity to all sectors by 99 percent as an approximation of a total blackout (reduction by 100 percent involves some division by zero in the model and cannot be computed at this time). The difference between the 99 percent service curtailment and the direct (or partial equilibrium, PE) impacts represent inherent resilience, which is less than 1.2 percent in all sectors except private transportation. Indirect (general equilibrium, GE, minus PE) impacts are very low because the economy is nearly shut down, and there is not much remaining economic activity to be impacted (see also Cochrane, 1997). The total, or GE, impact is a reduction of economic activity of 93.6 percent, which translates into $20.5 billion, compared to base year gross output of $539.7 billion. The economic loss thus represents 3.8 percent of one year's output in LA County. A basic I-O model would yield a result of 100% loss of output, because it omits all resilience (even inherent substitution). In this case too, there would be no standard multiplier effects of two to three times this amount, however, because there is so little remaining economic activity to be impacted. Hence, inherent resilience in our model is approximately 5.4 percent (99-93.6) according to metrics developed by Rose (2004b).[17]

Table 2 summarizes the results when several additional types of resilience are included. In this case, the 99 percent curtailment of centralized electricity services results in only a 47.9 percent decrease in direct output once sectoral production functions are recalibrated. Aside from Private and Public Utilities themselves, the sectors taking the greatest hit are Other Durable Manufacturing, Wholesale Trade, and Mining. The sectors least affected are Agriculture, Government, and various types of Transportation. Indirect effects add another 11.4 percent loss, with the largest impacts on Local Public Transportation, Computer Services, and Gas Utilities. The implicit multiplier is thus 1.238 [(11.4+59.3)÷59.3] reflecting offsetting general equilibrium factors (primarily adjustments to price changes) in contrast to the I-O, or linear model, multiplier of about 2.5 increase over direct effects.

The total general equilibrium loss is a reduction of 59.3 percent, or $13.0 billion, but this does not include sizeable production rescheduling opportunities, which range from 30-99 percent across sectors. These reduce the sub-total general equilibrium losses by an additional $10.2 billion, or 78.2 percent, to $2.8 billion.[18] Hence, the total disruption is only a reduction of 12.9 percent of two weeks of economic activity, if we incorporate rescheduling actions into the post-disruption period. The sectors hit hardest in absolute terms (see the last column of Table 2) are Entertainment, Business Services, and Health and Social Services.

The relative influence of five resilience factors is presented in Table 3, including the partial equilibrium and general equilibrium effects of each. Production rescheduling aside, the results indicate that conservation is the resilience factor with the weakest direct influence, and that "electricity importance" is the one with the strongest direct influence. When indirect effects are considered, alternative generation has the greatest potential to cushion losses. However, the total 28.1 percent (99-70.9) resilience this option provides is still much lower than the potential of production rescheduling of 78.2 percent [(59.3-13)÷59.3].[19]

TABLE 2. ECONOMIC IMPACTS OF A TOTAL ELECTRICITY BLACKOUT IN LOS ANGELES COUNTY

(includes all resilience adjustments)

Sector	Electricity Input		Output	Output Change during 2-Week Electricity Outage				
	Baseline (million $)	Direct Disruptions (%)	Baseline (million $)	Recalibrated Direct (%) (Partial Equilibrium, PE)	Indirect (%) (GE-PE)	Total (%) (General Equilibrium, GE)	Total Loss (million $)	Total Adj for Rescheduling
1. Agriculture	5.8	99	1398	-2.4	-7.3	-9.7	-5	-1
2. Mining	22.6	99	2589	-73.2	-1.6	-74.8	-74	-1
3. Construction	33.0	99	28770	-18.7	-29.9	-48.6	-538	-27
4. Food Processing	88.5	99	14744	-56.5	-8.6	-65.1	-369	-18
5. Petroleum Refining	59.5	99	11404	-29.7	-25.1	-54.8	-240	-2
6. Other Non-Durable Mfg	341.1	99	33435	-71.2	-2.8	-73.9	-951	-48
7. Primary Metals	75.1	99	3192	-30.1	-17.8	-48.0	-59	-1
8. Semiconductors	8.3	99	1133	-38.3	-7.8	-46.0	-20	0
9. Other Durable Mfg	430.7	99	63364	-73.1	-4.6	-77.7	-1894	-19
10. Local Private Transportation	0.7	99	1039	0.0	-11.4	-11.4	-5	-4
11. Other Transportation	55.5	99	21407	-5.2	-32.1	-37.2	-306	-214
12. Communications	25.5	99	15674	-23.3	-7.2	-30.6	-184	-111
13. Private Electric Utilities	0.1	99	2349	-99.0	0.0	-99.0	-89	-22
14. Gas Utilities	4.3	99	4738	-22.9	-35.3	-58.2	-106	-27
15. Water Utilities	3.0	99	381	-55.5	-2.5	-57.9	-8	-1
16. Sanitary Services	0.3	99	1149	-62.6	-1.6	-64.1	-28	-3
17. Wholesale Trade	136.2	99	35676	-73.0	-0.2	-73.2	-1004	-10
18. Retail Trade	168.5	99	27761	-66.1	-8.5	-74.6	-797	-159
19. Real Estate	197.6	99	31230	-73.0	-3.9	-76.8	-923	-92
20. Banking & Credit	30.0	99	19759	-21.7	-11.2	-32.9	-250	-25
21. Security Brokers	3.4	99	8153	-14.6	-15.4	-30.0	-94	-9
22. Insurance	4.5	99	11733	-66.6	-5.4	-72.0	-325	-33
23. Hotels & Restaurants	162.6	99	14383	-43.3	-21.9	-65.2	-361	-144
24. Personal Services	30.7	99	4301	-69.1	-2.2	-71.3	-118	-47
25. Business Services	134.2	99	59026	-70.0	-3.1	-73.1	-1660	-498
26. Computer Services	5.4	99	6035	-11.7	-39.9	-51.6	-120	-72
27. Entertainment	256.4	99	39098	-57.0	-10.2	-67.1	-1010	-707
28. Education	13.9	99	5015	-54.2	-31.2	-85.4	-165	-2
29. Health & Social Services	118.7	99	30138	-42.7	-32.2	-74.9	-869	-434
30. State & Local Electric Utilities	0.0	99	2425	-99.0	0.0	-99.0	-92	-23
31. Local Public Transportation	41.6	99	1254	-9.1	-54.5	-63.5	-31	-21
32. Other Government	116.6	99	36916	-5.0	-17.1	-22.1	-314	-63
Total	2573.9	99	539668	-47.9	-11.4	-59.3	-13010	-2839

TABLE 3. RELATIVE PROMINENCE OF RESILIENCE ADJUSTMENTS

Resilience Factor	PE Effect	GE Effect
Adaptive Elec. Substitution	-92.1	-93.5
Electricity Conservation	-92.9	-93.5
Electricity Importance	-70.3	-83.9
Alternative Generation	-70.9	-78.6
Production Rescheduling	-19.6	-21.9
Total	9.4	13.0

The combined effects of all resilience options to lower the potential negative impacts of a total electricity blackout in Los Angeles County is 86 percent (99-13). This far exceeds the 23.8 percent (11.4÷47.9) increase in impacts due to indirect effects. As in previous studies, this indicates that resilience is a much greater force than general equilibrium effects.

Note also that we can now measure inherent and adaptive resilience. Actually, electricity importance might be considered an inherent resilience factor since it is imbedded in the economic structure. Thus, if we add this to the inherent resilience of electricity and other factor substitution, total inherent resilience is 20.5 (5.4+15.1). Adaptive resilience, including its corresponding general equilibrium effects, is 65.5 percent (99-20.5-13).[20, 21]

How do these results compare with results of other recent studies of the regional economic impacts of power outages caused by terrorist attacks? With respects to our estimates in the absence of resilience, they are nearly exactly the same as the recent estimates by Lave et al. (2005) for New York City. Our estimates for Los Angeles translate into \$1.465 billion per day. However, this is stated in gross output terms and must be multiplied by 0.60 for an estimate of \$878 million per day in net (value added of gross regional product) terms. This then translates into about \$89 per day. Making an adjustment for economic growth and inflation between base year of our model and 2005, gives us an estimate very close to the \$112 per person per day on the Lave et al. study. At the same time, this study by Lave et al. does not measure the effects of resilience.[22] Thus, our estimate including resilience are more than 80 percent lower than this counterpart study.

VII. CONCLUSIONS

This paper summarizes the development and application of a computable general disequilibrium model to estimate the business interruption impacts of the terrorist attack on the electricity power system serving Los Angeles County. The model has been especially designed to incorporate engineering and spatial aspects of the electric power system in the context of the regional economy, to reflect the several types of disequilibria that an electric power disruption will bring about, to include the various inherent and adaptive resilience responses at the individual, market, and economy-wide levels, and to capture both partial and general equilibrium effects. The simulation of a two-week total electricity blackout in LA County amounts to a business interruption loss of $20.5 billion without any resilience adjustment and $2.8 billion with the inclusion of several types of resilience, most prominently the rescheduling (recapture) of production after electric service is restored. The results indicate that inherent aspects of the electricity-economy relationship (e.g., interfuel substitution) and adaptive behavioral responses (e.g., conservation, on-site electricity generation) can reduce the potential disruption impacts by 86 percent.

We emphasize two caveats of our analysis. First, many of our resilience factors are rough estimates, and more empirical work is needed to refine them. However, our model serves the useful purpose of identifying the many important considerations affecting the impacts and the relative sensitivity of the results to these various factors. This provides a guide to setting priorities for further conceptual and empirical research. Second, we have measured only one, although likely the major, aspect of electricity disruption—business interruption. This result can be supplemented by crude estimating factors of household impacts, property damage, and casualties. Our next priority is to extend the model to estimate household impacts, given the sizeable portion of the market represented by this customer group.

One final conclusion has a great bearing on future policy and is especially poignant in light of Hurricane Katrina. In the aftermath of the September 11 terrorist attacks, no politician wanted to admit that the government couldn't protect us from a major threat. Likewise, in the case of utility outages, no matter what the cause, we have looked to utilities to protect us. This paper has indicated how customers can protect themselves and contribute to the national war on terrorism by enhancing resilience to disasters in general. It has identified several ways this can be accomplished and the relative effectiveness of each type of resilience response at the individual, market, and regional economy levels. There is a strong indication that people learn from disaster experiences, and that options implemented for one type of disaster apply to others (e.g., purchase of back-up electric generators in the aftermath of the Northridge Earthquake). Thus, there is some cause for optimism that resilience to disasters will increase over time.

ENDNOTES

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[1] These include the New York City blackout of 1977, the East Coast blackout of 1982, a Los Angeles blackout following the Northridge Earthquake in 1994, two Western States blackouts in 1996, and the Northeast States blackouts in 1965, 1967, and 2003, the latter affecting 50 million people.

[2] Rose and Benavides (1999) have identified a potential flaw in non-interruptible service premia in a general equilibrium context because a given firm considers only its own benefits from continued service and not the benefits to its suppliers and customers (see also Rose et al., 2004).

[3] This is reinforced mathematically by the fact that business resilience is applied to the direct effect, which serves as the base for the market effect. That is, a 90 percent decrease in direct economic impacts due to resilience also reduces the general equilibrium impacts in absolute (though not in percentage) terms. However, a reduction in general equilibrium effects does not reduce individual business resilience.

[4] A study by Rose et al. (2004) indicated that a regional economy can be highly resilient to rolling blackouts of short duration. However, the context of the study was the mismanaged implementation of electricity deregulation, and is less applicable to a targeted and unannounced, and hence likely much more damaging, context of a terrorist attack.

[5] Note that the rationing of scarce utility lifeline services need not be accomplished by flipping technological switches. This can be accomplished by decree, as in requiring the various customers curtail demand, or through the marketplace by allowing a price increase to guide demand to its highest value use.

[6] This response is similar to fuel substitution, since the back-up generators use fuel oil. It is separated here because of the additional capital expense over the case of pure interfuel substitution (where additional capital expense is minimal). Note also aspects of substitution of labor for energy as in hauling material by hand or dolly versus conveyor belt (see also the discussion of household responses below).

[7] These advantages include the ability to model: multi-sector distinctions that facilitate the identification of specific targets; the ability to model individual behavior (including bounded rationality); market behavior (including the optimal rationing feature of the price system); both stock (property damage) and flow (business interruption) losses; non-market considerations associated with use of infrastructure services, iconic values such as national parks, and household activities such as additional time and inconvenience from utility outages; resilience to terrorist attacks; inclusion of the recovery process; economic disequilibria relating to critical input availabilities, labor markets, government budgets, and trade balances; macroeconomic repercussions in the form of general equilibrium effects; the distribution of impacts across socioeconomic groups; the spatial diffusion of economic impacts, though this adds great complexity to the model; and mitigation and its economic impacts. With respect to modeling considerations, CGE is operational (and in real time), can be constructed with readily available data, and is relatively low cost.

[8] Work is underway to upgrade this model component through the specification of household production functions, which allow for the assessment of the value of lost time and inconvenience (see Rose and Oladosu, 2005).

[9] The IMPLAN system consists of an extensive data base of economic data, algorithms for generating regional input-output tables and social accounting matrices, and algorithms for performing impact analysis. IMPLAN is the most widely used database for generating regional I-O models and SAMs in the U.S.

[10] Sources of these elasticities include: Prywes (1986), Deardoff and Stern (1986), Reinert and Roland-Holst (1992), Li (1994), and McKibbin and Wilcoxen (1998).

[11] This involves assigning employment data by census tract to the EPSA in which it is located (see French, 1998; Rose and Lim, 2002). Various adjustments are needed for the location of employment for sectors such as agriculture and utilities (based on firm-specific data) because employment addresses are often assigned to a headquarters rather than a job site (e.g., a sub-station).

[12] The elasticity of substitution captures the ease of adjustment between input combinations in relation to changes in input price ratios. Such adjustment is easier for a longer time frame and visa versa. The elasticities in the basic model are first specified for a "short-run" timeframe (1-2 years) and are then reduced to reflect a very short timeframe of our analysis. Unfortunately, we are not aware of any studies that have estimated elasticities for a kind of "very short run" that we consider. Because electricity disruptions are hard constraints on electricity availability and because electricity prices need to be held fixed in some cases (reflecting institutional limitations or policy advantages) in future simulations, the reduced elasticities prevent unrealistic substitutions of other inputs for utility services. Only empirical estimation of very short-run elasticities would enable us to assess the implications of our approach to the accuracy of the results.

[13] We have incorporated sectoral differentials into the analysis, but we were not able to include other major differences in the response by firms. For example, major differences exist between the ability of small and large businesses to cope with power outages, as well as other ramifications of terrorist attacks. Small businesses are especially vulnerable to power outages. A recent survey by Emerson (2004) indicate that 62 percent of small businesses do not have any type of back-up power. Also, 75 percent say that electrical power outages are a threat to their business, but only 22 percent feel very prepared to deal with an outage. The majority of these firms are interested in adapting back-up power technology used by large businesses. The August 2003 blackout stimulated greater interest by small businesses in alternative power sources; in fact, Emerson reports that an additional 3 percent (200,000 small businesses) purchased back-up power technology after the event.

[14] Conservation of other inputs is possible, but, since we have no information on which to base this, we have omitted this consideration.

[15] The existing substitution possibilities represent "inherent" resilience, and the increased substitution possibilities (increased elasticity of substitution values) represent "adaptive" resilience.

[16] Note that we confine our measurement of economic impacts to Los Angles County. Of course these impacts radiate to neighboring counties, as well as the nation as a whole, through price and quantity effects in various markets. The majority of these effects will take place within the boundaries of an "economic trading area," a region in which the majority of firms do their majority of business with other firms in the area. In this case, the trading area is more likely to be the five-county Southern California Association of Governments (SCAG) Region. Still, LA County will contain nearly all of the direct impacts and the majority of indirect ones.

Note also that, aside from the geographically spreading negative impacts, areas outside the disaster site are likely to incur positive benefits. Examples would be using branch plants, out-sourcing critical aspects of businesses, and businesses in other areas producing goods now in short supply in the region hit by the terrorist attack. The sum total of all of these impacts needs to be considered to yield the net impacts to the nation as a whole.

[17] There is, however, one resilience factor (inherent substitution of electricity and other inputs) and another at the market and regional economy levels (price changes, except for electricity) that are imbedded in the model and cannot easily be excluded. However, below we do compare our results with those of a basic input-output model, which would exclude these considerations, in order to identify the contribution of inherent resilience.

[18] Production rescheduling has been separated because it is the dominant resilience factor, and because it does not require any significant modeling refinements—it is simply a multiplicative factor.

[19] We also test the effects of nonlinearities and interaction effects in the model. Here we examine whether the whole of resilience is greater than the sum of its parts. We compare the simple sum of these options separately with the results of incorporating them into the model all at once. The difference between the two estimates represents a combination of interactions effects and nonlinearities in our CGE model. In terms of PE effects, the results are nearly the same. However, the results do differ significantly with the addition of GE effects.

[20] General equilibrium effects should probably be subtracted from the adaptive resilience estimate because they represent the inherent resilience of the price system. This will be done at a later date.

[21] We acknowledge some problems with our model that are in the process of being corrected. First, we are not yet able to simulate the impact of an electricity disruption to households. This is being rectified by reformulating the household portion of the model from a lineal expenditure system to a set of household production functions (see Rose and Oladosu, 2005). This will enable us to estimate non-market effects associated with "inconvenience" and the use of household time, as well as their general equilibrium consequences. It will also enable us to calculate welfare measures, such as equivalent and compensating variation for all effects of electricity disruptions. Note that the inability to measure the household effects has little influence on our estimate of business interruption, though it would likely have a very significant effect on broader measures of impacts, since households purchased 33 percent of the electricity in Los Angeles County in 2002.

[22] The Lave et al. study does provide an excellent discussion of resilience opportunities but on the supplier (utility side) of the market rather than the customer side, as is the focus of our study. As noted in endnote X, we would refer to these measures as "mitigation," since they reduce the probability of system failure, rather than reducing the consequences of failure (our definition of static resilience).

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