

economic consequence analysis of electric power infrastructure disruptions

an analytical general equilibrium approach

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Acronyms and Abbreviations

| | |
|--------|---|
| CA DOF | State of California Department of Finance |
| CAISO | California Independent System Operator |
| CGE | Computable general equilibrium |
| GE | General equilibrium |
| NRC | National Research Council |
| PE | Partial equilibrium |
| USEOP | United States Executive Office of the President |

1. Introduction

Electricity service providers take many steps to increase the reliability of their systems through mitigation measures that reduces the frequency and magnitude of potential outages. These measures include strengthening individual pieces of equipment and protecting system connectivity against natural disasters, technological accidents and terrorist attacks (NRC, 2017). At the same time, direct and indirect electricity customers pursue a range of measures to reduce their losses once the disruption begins, which Rose (2007, 2017a) and others (e.g., Kajitani and Tatano, 2009; NRC, 2017) have characterized as resilience. Some of these measures are inherent, or built into the production process, such as the ability to substitute other power sources or the ability to shift operations to branch plants out of the affected zone. Some require expenditures in advance of the disruption, such as the purchase of storage batteries and back-up generators to be used once an outage commences. Still other actions involve improvisation, or adaptive, resilience after the outage begins, such as conserving electricity at greater levels than previously thought possible, altering production processes, finding new suppliers of other critical inputs whose production has been disrupted by the outage, and recapturing lost production once electricity is restored. Yet another strategy, more applicable to the electricity provider is dynamic economic resilience, which refers to the acceleration of the pace of restoration of electricity service. The distinction between reliability, as promoted by mitigation, and resilience is poignantly stated in a recent NRC report: “Resilience is not the same as reliability. While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future” (NRC, 2017, p. 10).¹

In this paper we address three questions. First, we investigate the economy-wide impacts of a large-scale disruption to electric power infrastructure. Second, we ask what effect mitigation and resilience have on these impacts. Finally, we ask how the answers depend on key characteristics of the strategies and of the affected economy. Previous research by the authors has demonstrated the methods for, and elucidated the broader economic consequences of, incorporating these various risk reduction measures into multi-sector computational general equilibrium (CGE) models of economies affected by disasters (Rose et al., 2007; Sue Wing et al., 2016; Rose, 2017b). Energy-focused CGE models are the work-horse

¹ Dozens of definitions of resilience have been offered along several dimensions. One important distinction is between definitions that consider resilience to be any action that reduces risk (e.g., Bruneau et al., 2003; USEOP, 2013), including those taken before, during and after an unforeseen event such as a power outage, and those that use the term narrowly to include only actions taken after the event has commenced—acknowledging, however, that resilience is a process. The latter definition does not ignore pre-event actions in building resilience capacity, such as in the advance purchase of portable electricity generators, but notes that their implementation does not take place until after the outage has begun. This is in contrast to mitigation, which is pre-outage investment intended to make a system more resistant, robust or reliable (in standard engineering terminology) at the outset of the outage. Our definition simply chooses to focus on the basic etymological root of resilience, “to rebound”, and thus emphasizes system or business continuity in the static sense and recovery in the dynamic one (see also Greenberg et al., 2007; Wei et al., 2018). Note also that the emphasis on actions after the outage begins shifts some of the attention away from the utility (supplier) and in the direction of its customers (see Section 2).

of assessments of these broader economic consequences of shocks or disruptions to energy supplies. However, Sanstad (2015) identifies several shortcomings of previous applications of CGE modeling, including the need for advances in the theory, clarification of important concepts (e.g., energy conservation versus energy efficiency), and greater justifications for the parameter values of these models. It is now common for such models to combine top-down representations of economic activity with bottom-up detail in electricity generation technologies (see, e.g., Sue Wing, 2008). The resulting disaggregated representations of electric power supply need to be constructed using numerical calibration approaches that reconcile incommensurate data from economic accounts with engineering specifications of the discrete technology options whose interactions will drive the model's emergent behavior. While the calibration process is relatively straightforward for aggregates of electric generators with different technologies and/or fuels, it is extremely challenging to resolve the use of inputs associated with elements of the transmission and distribution grid because of their network (spatial) character.

This difficulty constitutes an important roadblock when investigation of disruption to electric power supply from natural hazards and potential terrorist threats necessitates representations of elements of the electric power system that are highly disaggregated. In particular, for any given downstream sector, power generated by multiple, geographically dispersed generators upstream is conveyed by multiple infrastructural assets to multiple electricity consuming entities located in different service territories. This fundamental network structure of supply-demand linkages—and the allocation of electric power flows to its various arcs, exists at geographic scales much finer than those at which economic models simulate markets (e.g., individual counties). In addition, multi-sectoral economic models are ill-equipped to represent the physical characteristics of power flows (e.g., Kirchhoff's laws). Such details are simulated with much greater fidelity by dedicated electricity sector techno-economic simulations such as optimal power flow, economic dispatch or capacity expansion simulations. Moreover, these types of models already exist and are routinely used by electricity system operators and balancing authorities, and it is relatively straightforward to use them to quantify: (a) the magnitude of disruption shocks—i.e., the extent of unserved load to various classes of customers, and (b) potential supply-side resilience measures—i.e., ability for various deliberate investments in slack capacity or costly interventions to manage the power system differently might be able reduce curtailments.

By contrast, explicit consideration of the foregoing details is rarely necessary for assessing the downstream economy-wide impacts of the supply disruptions that these models would simulate as emergent outcomes. The exception is the presence of strong feedbacks between downstream responses to electricity supply curtailment and fundamental technological drivers of the disruption. Yet, such feedbacks do not necessitate “hard” linkage (to say nothing of full integration) of multiple simulation models based on fundamentally different paradigms. Models can be “soft” coupled using emulation in conjunction with scenarios. In particular, one can envision the following three-step assessment process:

- (i) An optimal power flow model is used to simulate several scenarios of disruption while incorporating mitigation activities of varying cost and effectiveness.
- (ii) The simulation results are used to construct a reduced-form emulator of the envelope of

resilience options, their opportunity costs, and their benefits in terms of moderating the disruption (For recent efforts to construct reduced form emulators of economic models, see Chen et al., 2017; Rose et al., 2017.)

- (iii) The resulting vector of electricity supply curtailments, along with the response surface of mitigation and resilience tactics and their bottom-up opportunity costs, are used in conjunction with a multi-sector economic model to simulate the broader economic effects of power disruptions.

The rest of the paper is organized as follows. Section 2 summarizes prior research on the economic consequences of electricity outages, identifying key gaps in the existing literature. Motivated by these opportunities, Section 3 provides a detailed description of our methodological approach, introducing the analytical model which we solve, yielding our main results, and a numerical application of that model: a two-week disruption in Bay-Area electricity infrastructure that reduces the latter's annual capacity by 4%. Analytical and numerical modeling results are presented in Section 4. Section 5 concludes with a brief discussion of caveats to the analysis and fruitful opportunities for future research.

2. Insights from Prior Research

Nearly all of the early literature on the economic consequences electricity outages focused on standard economic impacts and ways to reduce the probability and magnitude of these events before they took place. As such, the major strategy was mitigation, which included such tactics as strengthening equipment, improving connectivity, development of parallel systems, and having back-up equipment in place. All of these tactics were essentially intended to enhance robustness/resistance of the electrical system from the initial shock.

Much of the early economics literature focused on partial equilibrium (PE) analyses of electricity providers or their customers. Except for a couple of studies of actual events, economy-wide losses were typically not analyzed until the 1990s. They were, and continue to this day, to be measured primarily with the common denominator of dollars in terms of gross output (sales revenue) or GDP. These economy-wide or general equilibrium (GE) effects are of several types (Rose et al., 2007), involving losses incurred by different actors:

- Direct customers of the electricity service provider.
There is some dispute over whether these are considered GE or PE losses. In essence, customers are the second major component of the electricity market in a PE sense, but much of the PE literature focuses only on the supply side.
- Downstream customers of disrupted firms, through their inability to source crucial inputs.
This and the other GE effects noted below set off a chain reaction beyond the PE effects.
- Upstream suppliers of disrupted firms, via cancellation of orders for inputs.
Here too, this is transmitted through multiple rounds of interaction, though in this case in terms of suppliers.

- All firms, via decreased consumer spending associated with a decreased wages and dividends of firms directly affected by the electricity outage, as well as all other firms suffering negative GE effects.
- All firms, via decreased investment associated with decreased profits of firms suffering the electricity outage and other firms negatively impacted by GE effects.
- All firms, from cost (and ensuing price) increases from damaged equipment and other dislocations (including uncertainty) that reduce the productivity of directly impacted firms.²

Sanstad (2016) and others have reviewed various modeling approaches to estimating the economy-wide (typically at the regional level) impacts of electricity outages. The general leaning of these assessments is that CGE models are the preferred approach. Input-output (I-O) models are limited by their inherent linearity, lack of behavioral content and absence of considerations of prices and markets. CGE models are able to maintain the best features of I-O models—sectoral detail and ability to trace interdependencies—while overcoming these limitations. Macroeconometric models are especially adept at forecasting, but often lack the detail needed in this area of inquiry and are less able than CGE models to accommodate engineering data.

The most recent advances in modeling the economic consequences of electricity disruptions relates to various types of resilience defined in the previous section (Rose, 2007, 2009; Kajitani and Tatano, 2008). The focus here shifts to the customer side, since there are so many more tactics available, and they are much less costly. For example, a good deal of conservation more than pays for itself (energy efficiency), back-up generators are relatively inexpensive, shifting production to other facilities that have electricity as well as excess capacity is relatively inexpensive, as is recapturing lost production at a later date by working overtime and extra shifts. Moreover, most of these tactics need not be put in place before the outage, but can simply be implemented on an as-needed basis once an outage occurs. These and other resilience tactics are available to downstream customers as well, with the others including use of inventories, input substitution, and relying more on imported goods from other regions or countries. Rose and Liao (2005), Rose et al. (2007), Sue Wing et al. (2016), and Rose (2018) have shown how various resilience tactics can be included in CGE models. For example, conservation can be included by changing the productivity parameter of a production function, while inherent input substitution and import substitution are an automatic aspect to this modeling approach, and adaptive input substitution and import substitution can be modeled by altering the input substitution elasticities and Armington elasticities, respectively. Several other resilience tactics, such as distributed generation and storage batteries, can be modeled by simply reducing the electricity supply disruption in the first place or by applying the production recapture factor to the initial results.

Several studies have measured the economic consequences of major electricity outages as summarized in NRC (2017): the New England-East Canada Blackout of 1998 (\$4 billion), the Northeast Blackout of

² Various other types of effects are often referred to as indirect, such as those relating to health and safety. This terminology and the lack of attention to these types of effects, is not to denigrate them but simply to note that they are beyond the scope of this paper.

2003 (\$4 to \$10 billion), and SuperStorm Sandy in 2013 (\$14 to \$26 billion). We note that most of these studies did not explicitly model or estimate most types of resilience on either the supplier or customer sites. Studies that have explicitly modeled various types of resilience include: the 1994 Northridge Earthquake (Rose and Lim, 2002), the 2002 Southern California rolling blackouts (Rose et al., 2005), and a hypothetical two-week shutdown of the Los Angeles (City) Department of Water and Power electricity system due to a terrorist attack (Rose et al., 2007). These studies all found that resilience substantially moderates losses, though the latter is likely to be overstated because the effects of potential rather than actual implementation of resilience tactics are quantified.

Few studies have examined the impacts of long-term electricity outages. This phenomenon would best be addressed by a dynamic CGE modeling approach. It would also place greater emphasis on dynamic economic resilience, which Rose (2009, 2017) defines as investment in repair and reconstruction so as to recover at an accelerated pace and decrease the duration of the outage in order to reduce losses. Of course, repair and reconstruction efforts are also important for shorter outages, and a good deal of literature has been developed to optimize restoration patterns, both to restore electricity and to achieve various societal goals with respect to customer priorities (see, e.g., Çağnan et al., 2006). Finally, we note that Rose (2009) has examined how resilience changes over time, with some tactics (e.g., Draconian conservation, inventories/storage) eroding and others (e.g., input substitution and technological improvisation) increasing.

3. Methods

Our approach explicitly recognizes that the economic effects of power disruptions depend critically on the geographically localized upstream topology of the affected electricity generation, transmission and distribution network, as well as the downstream structural and resilience characteristics of the economy that this network serves. This circumstance complicates broad assessment of blackouts in two ways: it limits our ability to develop general insights, threatening to make any conclusions context-specific, and it increases the fixed cost of undertaking numerical analyses by necessitating substantial investments in data development and calibration to capture the specific local and/or regional characteristics of electric power systems and the electricity-using economy. Our strategy for surmounting these obstacles is to set up and solve an analytical model that abstracts from realistic detail to capture the essence of the broader economic impacts in a manner that is simple, compelling, and easily adapted to a wide range of circumstances that can potentially arise in specific geographic locales.

3.1 An Analytical General Equilibrium Model

Our brutal abstraction is to reduce the supply side of the economy to two broad sectoral groupings, electric power and the rest of the economy, indexed by $j = \{E, N\}$, respectively. Output of the electric power sector is indicated by q_E , and its price by p_E . Electricity production requires the input of generation, transmission and distribution infrastructure capital. Denoted k , this input is assumed to be a fixed factor with rate of return r . Electricity production also depends on the input of a composite

factor, indicated by z_E . The factor is mobile among sectors, is in perfectly inelastic aggregate supply and has a ruling price w . Output of the much larger rest-of-economy sector is indicated by q_N , and has a price p_N . Rest-of-economy production relies on intermediate inputs of electricity, x , and inputs of the composite factor, z_N . Production is assumed to be of the constant elasticity of substitution (CES) variety, in electric power and the rest of the economy parameterized by technical coefficients α and β and elasticities of substitution σ_E and σ_N , respectively. Infrastructure capital in the power sector and electricity in the rest of economy are assumed to be necessary inputs, implying that $\sigma_E, \sigma_N \in (0,1]$. Electricity supply satisfies N 's intermediate demand as well as the demands final of final consumers, denoted by c . Households also consume the entire rest-of-economy output. Households derive utility, u , from consumption of c and q_N and are endowed with CES preferences, parameterized by the technical coefficient ϕ and elasticity of substitution σ_U . Both inputs are assumed to be necessary, implying that $\sigma_U \in (0,1]$. The variables, parameters and equations of the model are summarized in Table 1.

Table 1. THE ANALYTICAL GENERAL EQUILIBRIUM MODEL

| A. Variables | | | | | | | |
|--------------|------------------------|------------------------|----------------------------|--------------------|------------------------|-----------|------------|
| | Electric sector Output | Rest of economy output | Electricity infrastructure | Electricity demand | Composite factor | Utility | Mitigation |
| Quantity | \hat{q}_E | \hat{q}_N | \hat{k}^* | \hat{c}, \hat{x} | \hat{z}_E, \hat{z}_N | \hat{u} | \hat{b} |
| Price | \hat{p}_E | \hat{p}_N | \hat{r} | | \hat{w} | | |

| B. parameters | | | | | | | |
|---------------|--|------------|---|--|--|--|--|
| α | Electricity sector infrastructure output elasticity | σ_E | Electricity sector elasticity of substitution | | | | |
| β | Rest-of-economy sector electricity output elasticity | σ_N | Rest-of-economy elasticity of substitution | | | | |
| λ | Electricity sector share of aggregate factor supply | σ_C | Consumption elasticity of substitution | | | | |
| γ | Household share of aggregate electricity supply | ξ | Power sector backup share of infrastructure | | | | |
| ϕ | Household electricity share of total expenditure | δ | Power sector backup share of factor input | | | | |
| | | η | Factor-to-backup transformation elasticity | | | | |

| C. Model equations | | | | | | | |
|--|--|--|--|---|------|--|--|
| Outage model with inherent resilience only | | | | | | | |
| Electric power sector production function | | | | $\hat{q}_E = \alpha \hat{k}^* + (1 - \alpha) \hat{z}_E$ | (1) | | |
| Rest-of-economy sector production function | | | | $\hat{q}_N = \beta \hat{x} + (1 - \beta) \hat{z}_N$ | (2) | | |
| Electric power sector zero profit condition | | | | $\hat{p}_E + \hat{q}_E = \alpha(\hat{r} + \hat{k}^*) + (1 - \alpha)(\hat{w} + \hat{z}_E)$ | (3) | | |
| Rest-of-economy sector zero profit condition | | | | $\hat{p}_N + \hat{q}_N = \beta(\hat{p}_E + \hat{x}) + (1 - \beta)(\hat{w} + \hat{z}_N)$ | (4) | | |
| Elasticity of substitution in electricity production | | | | $\hat{k}^* - \hat{z}_E = -\sigma_E(\hat{r} - \hat{w})$ | (5) | | |
| Elasticity of substitution in rest-of-economy production | | | | $x - \hat{z}_N = -\sigma_N(\hat{p}_E - \hat{w})$ | (6) | | |
| Household utility function | | | | $\hat{u} = \phi \hat{c} + (1 - \phi) \hat{q}_N$ | (7) | | |
| Elasticity of substitution in final consumption | | | | $\hat{c} - \hat{q}_N = -\sigma_C(\hat{p}_E - \hat{p}_N)$ | (8) | | |
| Electricity supply-demand balance | | | | $\hat{q}_E = \gamma \hat{c} + (1 - \gamma) \hat{x}$ | (9) | | |
| Composite factor supply-demand balance | | | | $\lambda \hat{z}_E + (1 - \lambda) \hat{z}_N = 0$ | (10) | | |
| Alternative model with inherent and adaptive resilience | | | | | | | |
| Electric power sector production function | | | | $\hat{q}_E = \alpha(\hat{k} + \xi \hat{b}) + (1 - \alpha) \left(\hat{z}_E - \frac{\delta}{\eta} \hat{b} \right)$ | (1') | | |

Following Fullerton and Metcalf (2002) and Lanzi and Sue Wing (2013), the model of the economy is posed as a system of log-linear equations in which a “hat” over a variable represents its logarithmic differential (e.g., $\hat{x} = d \log x / x$), which can be interpreted as a fractional change from an initial equilibrium level. On the supply side of the economy, producer behavior is captured by three sets of equations: production functions (1)-(2), associated free-entry conditions guaranteeing zero economic profit with perfectly competitive supply (3)-(4), and the definition of producers’ input substitution possibilities (5)-(6). The demand side of the economy is represented by two equations, households’ utility function (7) and the definition of their elasticity of substitution (8). The supply and the demand side of the economy are linked by the markets for electricity and rest-of-economy output. Producers are linked to each other via input competition for fixed endowment of the composite factor. These constraints are captured by the supply-demand balance conditions (9) and (10), respectively.

We assume that the economy is initially in equilibrium. The model’s system of algebraic equations account for the economy-wide consequences of electricity supply interruptions through the channel of a secular adverse shock to infrastructure capital, with the expected percentage loss in fixed factor capacity given by $\hat{k}^* = \mathbb{E}[\hat{k}] < 0$. The solution to the algebraic system gives the expected economic consequences of a blackout. The system is made up of the ten equations (1)-(10) in eleven unknowns $\{\hat{q}_E, \hat{c}, \hat{x}, \hat{p}_E, \hat{q}_N, \hat{p}_N, \hat{z}_E, \hat{z}_N, \hat{w}, \hat{r}, \hat{u}\}$. To close the model we treat the composite factor as the numeraire commodity using the normalization $\hat{w} = 0$, which we include as an additional equation. This approximation is valid where the value of electric power production ($p_E q_E$) is much smaller than that of the rest of the economy ($p_N q_N$), which for regions in the United States is almost always true. In this situation factor markets and prices will only be modestly impacted even in the event of a severe shock to electricity infrastructure. This result is a system with as many equations as unknowns, in which closed-form algebraic solutions for the latter can easily be obtained as functions of the shock, \hat{k}^* .

Notwithstanding the model’s abstract character, it has many advantages. Its solution is simple, in the sense that although the unknown variables are generally complicated algebraic combinations of the underlying parameters, the fundamental linearity of eqs. (1)-(10) guarantee that the resulting expressions are linear functions of the initiating shock. The simple insight is that the combinations of parameters whose values might differ according to the specific domain of any individual study can be thought of as elasticities whose magnitudes (and, potentially, signs) will vary with the specific circumstances of the shock and the impacted economy. The model’s simplicity and genericity enable it to be flexibly parameterized to capture a broad range of economies at various geographic scales. This in turn facilitates the expeditious creation of zeroth-order estimates of business interruption losses from disruptions of different magnitudes. Moreover, doing so decouples economic consequence analysis from detailed electric power system modeling, expediting assessment by enabling the two investigations to proceed in parallel and have their results combined.

The model’s algebraic framework also enables us to explore the implications of inherent resilience and

mitigation. On the supply side, inherent resilience is determined by the opportunities to substitute the composite factor for damaged infrastructure capacity in E and for scarce electricity in N , determined by the values of σ_E and σ_N . Symmetrically, on the demand side inherent resilience arises out of consumers' ability to substitute other goods and services for electricity as the latter's supply is curtailed, which is captured by the value of σ_U . Turning to mitigation, power producers will attempt to offset the negative economic impacts of blackouts via deliberate investments in backup generation, transmission and distribution capacity, indicated generically by b . While inherent resilience is assumed to be a costless property of the benchmark economy embodied in the elasticity of substitution parameters, mitigation via backup investments incurs an opportunity cost.

We assume that the backup technology can be produced by investing a portion, z_E^{Backup} , of the factor input to the electricity sector. The net quantity of the factor available to produce power,

$$z_E^{Net} = z_E - z_E^{Backup}$$

can be expressed in log differential form as

$$\frac{z_E^{Net}}{z_E} \left(\frac{dz_E^{Net}}{z_E^{Net}} \right) = \left(\frac{dz_E}{z_E} \right) - \frac{z_E^{Backup}}{z_E} \left(\frac{dz_E^{Backup}}{z_E^{Backup}} \right)$$

This investment yields backup capacity according to the elasticity of transformation, η :

$$db = \frac{\partial b}{\partial z_E^{Backup}} dz_E^{Backup} \Rightarrow \frac{dz_E^{Backup}}{z_E^{Backup}} = \underbrace{\left(\frac{\partial b}{\partial z_E^{Backup}} / \frac{b}{z_E^{Backup}} \right)^{-1}}_{\eta} \frac{db}{b} \Rightarrow \hat{z}_E^{Backup} = \frac{1}{\eta} \hat{b}$$

We exploit the simplifying assumption that the magnitude of backup investment is small compared to the overall quantity of factor input ($z_E^{Backup}/z_E = \delta \ll 1$). The result is the approximation

$$\hat{z}_E^{Net} \approx \hat{z}_E - \delta \hat{z}_E^{Backup} \approx \hat{z}_E - \frac{\delta}{\eta} \hat{b} \quad (11)$$

which we substitute into the second terms on the right-hand side of eq. (1) and the left-hand side of eq. (5). The backup technology provides the benefit of extra infrastructure capacity

$$k^{Net} = k + b$$

which in log differential form is given by

$$\frac{k^{Net}}{k} \left(\frac{dk^{Net}}{k^{Net}} \right) = \frac{dk}{k} + \frac{b}{k} \left(\frac{dk}{k} \right)$$

Assuming that the benchmark quantity of the backup technology constitutes a small fraction of conventional capacity ($b/k = \xi \ll 1$), we obtain the approximation

$$\hat{k}^{Net} \approx \hat{k} + \xi \hat{b} \quad (12)$$

which we substitute into the first term on the right-hand side of (1) and the left-hand side of (5).

As shown in Table 1, augmenting the model to incorporate adaptive resilience yields the new system of equations (1'),(2)-(4),(5') and (6)-(10). The number of equations is the same as before, but there is the additional variable, \hat{b} , which makes the system under-determined. We therefore use the model to explore how undertaking different levels of backup investment can moderate or exacerbate the adverse consequences of an infrastructure shock, elucidate the economic consequences of various combinations of \hat{b} and \hat{k} . A particular advantage of our simple analytical framework is that it enables us to solve for the level of backup capital that can minimize disruption of operational infrastructure ($\hat{k}^{Net} \rightarrow 0$), the electricity supply ($\hat{q}_E \rightarrow 0$) or welfare losses ($\hat{u} \rightarrow 0$) for a given expected curtailment of infrastructure capacity. As we go on to illustrate, these criteria have different economic consequences.

3.2 Numerical Application: A Two-Week Power Outage in California's Bay Area

As is common in theoretical studies, the model's algebraic solutions can be challenging to interpret, especially in cases where the responses of key variables cannot be unambiguously signed, with the result that their direction of change depends on the parameters. To obtain additional insight, we therefore numerically calibrate and simulate the model in an experiment that showcases its capabilities for assessing the economic consequences of a shock to infrastructure. Our application is the impact of a 14-day disruption of electricity infrastructure in five counties of California's Bay Area (Alameda, Contra Costa, San Francisco, San Mateo). Using the simple assumption of constant daily average electricity load, this interruption can be interpreted as a 4% reduction in the region's annual electricity supply capacity ($\hat{k}^* = -0.04$).³ This shock is quite extreme. To put it in context, in the US Geological Survey's HayWired earthquake scenario, ground shaking, liquefaction, and subsequent fires and landslides trigger immediate loss of power for 95% of customers in Alameda, with restoration of service to 83% of customers within 7 days. Over the 6-month post-earthquake period, similar patterns of disruption and recovery translate into integrated power supply losses of 3.9% in Alameda, 2.7% in Santa Clara, 2.5% in Contra Costa, 1.8% in San Mateo, and 1.3% in San Francisco (Sue Wing et al, 2018).

Values for the economic parameters in Table 1 were calculated by aggregating social accounting matrices for the five counties for the year 2012, constructed by the Minnesota IMPLAN Group. These are summarized in Table 2. Electric power production is highly capital intensive, with inputs of capital

³ The scenario characterizes the physical impacts and economic consequences of a rupture of the Hayward Fault—see Detweiler and Wein (2017).

accounting for 42% of the sector’s output. We assume that the total value of various kinds of infrastructure account for one quarter of this amount, which suggests an infrastructure share cum output elasticity of just over 10%. As the Bay Area is a major hub of the digital economy, downstream production activity served by the power sector is not only large by comparison—accounting for 99.6% of the demand for the region’s endowment of primary factors, it is also responsible for the bulk of the demand for electricity, accounting for 81% of supply in contrast to the residential sector’s 19%. In terms of households’ expenditure, electricity makes up 1.4%, with the remainder allocated to consumption of the output of industries in the rest-of-economy aggregate. Relative to other inputs to downstream production, intermediate electricity plays an even smaller role, with a sectoral cost share of 0.6%.

Table 2. PARAMETERS OF THE NUMERICAL MODEL

| α | λ | β | γ | ϕ | ξ | η | δ |
|----------|-----------|----------|----------|----------|-------|----------|----------|
| 0.104512 | 0.004106 | 0.004995 | 0.19208 | 0.014424 | 0.15 | 0.5-1.25 | 0.02 |

Our model’s highly aggregate and stylized character means that the parameters that determine the opportunity cost and penetration of the backup technology will of necessity be less rigorously empirically grounded. We assume that the backup technology’s share of infrastructure capacity in the baseline equilibrium is 15%, the same as the operating reserve margin required by the California Independent System Operator (CAISO). The elasticity of transformation between primary factors and reserve generation, transmission and distribution capacity, as well as the benchmark share of the power sector’s factor hiring allocated to provide these services, are both more speculative. For the elasticity parameter we assume that, on one hand, power producers would be unwilling to sink resources into the backup technology if such investment were not sufficiently productive (i.e., of sufficient capacity to moderate the cost of adverse shocks), and, on the other hand, that if such investments were highly productive firms would pursue them to such an extent as to render regulation unnecessary. This in turn suggests that η is neither highly inelastic nor highly elastic. Accordingly, we consider values in the range $\eta \in [0.5, 1.25]$ to be plausible. We calibrate the share based on the values of the remaining parameters. The assumption that the benchmark prices of infrastructure and the composite factor do not differ appreciably leads to the approximations $k/q_E \approx \alpha$ and $z_E/q_E \approx 1 - \alpha$. We further assume that the productivity elasticity of backup investment is near unitary ($\eta \approx 1$), which allows us to express the latter as $z_E^{Backup} \approx b$. Combining our approximations with the definition of the share leads to

$$\delta = \frac{z_E^{Backup}/q_E}{z_E/q_E} \approx \frac{\alpha}{1 - \alpha} \frac{z_E^{Backup}}{k} \approx \frac{\alpha}{1 - \alpha} \frac{b}{k} = \frac{\alpha}{1 - \alpha} \xi$$

which yields a plausible value of 0.0167. We round this result to 2%, which represents an upper bound, given the uncertainties inherent in our calibration procedure.

We treat the elasticities of substitution as exogenous parameters whose values are simply assumed. At the regional scale of our investigation, infrastructure capital is a necessary input to mains electricity

supply, and power is a necessary input to both firms and households, which suggests that the values of all elasticities are less than unity. The extreme technological difficulty of using other productive inputs to substitute for infrastructure capacity in power generation, transmission and distribution suggests that the inputs to the electricity sector are complements ($\sigma_E \ll 1$). Accordingly, for our model simulations we consider low and high values for that sector's elasticity of substitution, $\sigma_E = \{0.01, 0.25\}$. By contrast, firms and households both possess myriad opportunities to substitute other inputs for mains electricity supply in response to supply curtailments and/or price increases. We therefore consider substitution elasticities in the range $\sigma_N, \sigma_U \in [0.25, 1]$.

4. Results

4.1 No Substitution

We begin by considering the extreme case where economic actors do not engage in substitution. Although admittedly unrealistic, we note that this corresponds to the implicit assumptions underlying PE studies that treat prices, power sector output demands and/or inputs supplies as fixed. The infrastructure disruption has straightforward economic consequences. If power producers do not react to infrastructure curtailment by adjusting their factor usage, then the quantity of output declines according to the product of the infrastructure output elasticity and the shock. Downstream, if neither intermediate nor final consumers alter their demands for inputs of factors and the rest-of-economy good (respectively), as the electricity supply declines, their electricity demands will decline by the same percentage amount as the fall in supply. Accordingly, we have

$$\hat{q}_E = \hat{x} = \hat{c} = \alpha \hat{k}^* < 0 \quad (13)$$

while downstream output in the rest of the economy is reduced by the amount

$$\hat{q}_N = \alpha \beta \hat{k}^* < 0 \quad (14)$$

triggering a welfare decline of

$$\hat{u} = \alpha(\phi + (1 - \phi)\beta)\hat{k}^* < 0 \quad (15)$$

With these responses our numerical parameterization implies that the impacts of a two-week infrastructure disruption are modest: a slight decline in electricity supply and demand (0.4%), negligible reduction in rest-of-economy output (0.002%), and a small welfare loss (0.19%).

4.2 Inherent Resilience Via Input Substitution

In the more realistic situation where producers and consumers do engage in substitution, the results change dramatically. We begin by defining the quantity

$$\mathcal{D}_0 = (1 - \alpha(1 - \lambda))\sigma_E + \alpha(1 - \lambda)(1 - \gamma(1 - \beta))\sigma_N + \alpha(1 - \lambda)\gamma(1 - \beta)\sigma_U > 0$$

which plays the role of the denominator of the algebraic expressions of variable changes and is unambiguously positive. The impact on power supply is unambiguously negative, as before,

$$\hat{q}_E = \alpha\{\lambda\sigma_E + (1 - \lambda)(1 - \gamma(1 - \beta))\sigma_N + (1 - \lambda)\gamma(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} < 0 \quad (16)$$

but here it is smaller in magnitude.⁴ A second unambiguous impact is an increase in the electricity price,

$$\hat{p}_E = -\alpha\mathcal{D}_0^{-1}\hat{k} > 0 \quad (17)$$

The impact on intermediate electricity use depends on the values of the parameters

$$\hat{x} = \alpha\{\lambda\sigma_E + (1 - \lambda(1 - \gamma(1 - \beta)))\sigma_N - \gamma\lambda(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \quad (18)$$

The outcome depends on the competition for power between intermediate and final demands, which is determined by the relative magnitudes of the elasticities of substitution. For curtailment of demand by downstream firms, the restriction on the parameters is

$$\sigma_U < \frac{1}{\gamma(1 - \beta)}\sigma_E + \frac{1 - \lambda(1 - \gamma(1 - \beta))}{\gamma\lambda(1 - \beta)}\sigma_N$$

suggesting that households' elasticity of substitution between residential electric power and rest-of-economy output must not be "too large". If electric power and downstream producers' outputs are both necessary goods, the inequality above will be satisfied if the elasticities of substitution among inputs to the producing sectors are sufficiently large that their weighted sum on the right-hand side above exceeds unity.⁵

The sign of impacts on downstream economic output, residential electricity use and welfare are all ambiguous as well:

$$\hat{c} = \alpha\{\lambda\sigma_E + (\beta - \lambda(1 - \gamma(1 - \beta)))\sigma_N + (1 - \gamma\lambda)(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \quad (19)$$

$$\hat{q}_N = \alpha\{\lambda\sigma_E + (\beta - \lambda(1 - \gamma(1 - \beta)))\sigma_N - \gamma\lambda(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \quad (20)$$

$$\hat{u} = \alpha\{\lambda\sigma_E + (\beta - \lambda(1 - \gamma(1 - \beta)))\sigma_N + (\phi - \gamma\lambda)(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \quad (21)$$

⁴ The numerator and denominator have identical second and third terms. The magnitude of the impact on the power sector is less negative because the magnitude of the first term in the denominator, $(1 - \alpha(1 - \lambda))\sigma_E$, exceeds that of the first term in the numerator, $\alpha\lambda\sigma_E$.

⁵ Note that the weights on σ_E and σ_N are strictly positive.

For these impacts to be negative, the main restriction on the parameter values that they share is that the output elasticity of electricity in downstream production exceeds the share of the factor endowment accounted for the power sector:

$$\beta > \lambda \frac{1 - \gamma}{1 - \gamma\lambda}$$

Additional restrictions are, for welfare (21), the sufficient condition, $\phi > \gamma\lambda$, and, for rest-of-economy output (20), the sufficient condition

$$\sigma_U < \frac{1}{\gamma(1 - \beta)}\sigma_E + \frac{\beta - \lambda(1 - \gamma(1 - \beta))}{\gamma\lambda(1 - \beta)}\sigma_N$$

The essence of substitution's moderating effect is that producers (consumers) are able to use relatively larger quantities of factor (rest-of-economy) inputs in an attempt to compensate for declines in the quantities of inputs of infrastructure or electricity. By eqs. (5), (6) and (8), the extent to which actors adjust along these margins depends on the values of the elasticities of substitution, in conjunction with general equilibrium feedback effects on prices that induce relative price changes. For the power sector, the potential for adjustment is indicated by setting $\hat{q}_E = 0$ in (1) and simplifying to obtain

$$\begin{aligned} -\frac{dz_E}{dk} &= -\left(\frac{z_E/q_E}{k/q_E}\right)\left(\frac{dz_E/dk}{z_E/k}\right) \approx \frac{\alpha - 1}{\alpha} \frac{\hat{z}_E}{\hat{k}^*} \\ &= (1 - \alpha)(1 - \lambda)\{\sigma_E - (1 - \gamma(1 - \beta))\sigma_N - \gamma(1 - \beta)\sigma_U\}\mathcal{D}_0^{-1} \end{aligned} \quad (22)$$

which is positive so long as the factor-infrastructure elasticity of substitution is sufficiently large, i.e.,

$$\sigma_E > (1 - \gamma(1 - \beta))\sigma_N + \gamma(1 - \beta)\sigma_U$$

Applying similar mathematical arguments to eqs. (2) and (7) yield the potential adjustment by downstream producers and consumers as

$$-\frac{dz_N}{dx} \approx \frac{\beta - 1}{\beta} \frac{\hat{z}_N}{\hat{x}} = \frac{\beta - 1}{\beta} \left\{ \frac{\lambda\sigma_E - \lambda(1 - \gamma(1 - \beta))\sigma_N - \gamma\lambda(1 - \beta)\sigma_U}{\lambda\sigma_E + (1 - \lambda(1 - \gamma(1 - \beta)))\sigma_N - \gamma\lambda(1 - \beta)\sigma_U} \right\} \quad (23)$$

$$-\frac{dq_N}{dc} \approx \frac{\phi - 1}{\phi} \frac{\hat{q}_N}{\hat{c}} = \frac{\phi - 1}{\phi} \left\{ \frac{\lambda\sigma_E + (\beta - \lambda(1 - \gamma(1 - \beta)))\sigma_N - \gamma\lambda(1 - \beta)\sigma_U}{\lambda\sigma_E + (\beta - \lambda(1 - \gamma(1 - \beta)))\sigma_N + (1 - \lambda\gamma)(1 - \beta)\sigma_U} \right\} \quad (24)$$

Respectively, these expressions' signs are positive for $\sigma_N > 0$ and $\sigma_U > 0$, and are negative only in the limiting situations where electricity is strictly complementary to use of the factor in the case of

producers, or rest-of-economy output in the case of consumers. The important implication is that estimates of the economic consequences of outages should account for the tendency of the rest of the

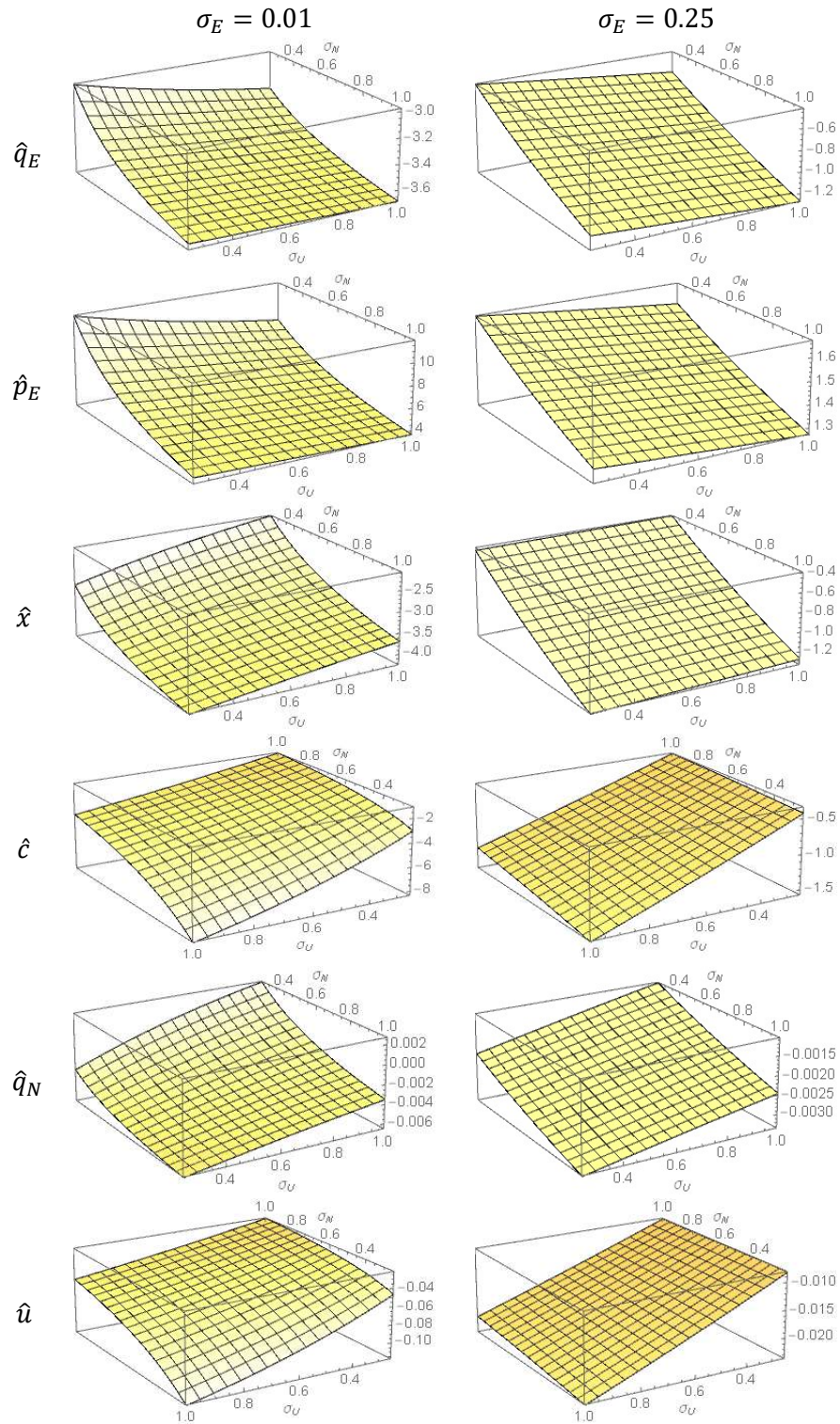


Figure 1. IMPACTS OF A TWO-WEEK ELECTRICITY INFRASTRUCTURE DISRUPTION ON THE BAY AREA ECONOMY: INHERENT RESILIENCE (% change in the value of each variable from its baseline level)

economy to exploit any opportunity to replace relatively scarce and expensive power with other inputs that are relatively abundant, and cheaper.

Figure 1 illustrates the net effects of these forces in our Bay Area disruption scenario. The response surfaces make clear that while the impacts on variables' percentage changes may be linear in the initiating shock, they are nonlinear in the parameters. There are unambiguously negative impacts on electricity supply (between -3.6% and -0.6%), intermediate and final electricity demands (-4% to -0.4% and -8% to -0.5%), and welfare (-0.1% to -0.01%). Electricity power becomes unambiguously more expensive (1.3% to greater than 10%), while the output of the rest of the economy contracts or expands slightly depending on the combination of substitution elasticity values (between -0.06% and 0.002%). With the exception of the electricity price, increases in the scope for producer and consumer substitution shrink the absolute percentage magnitude of economic consequences. Under many parameter combinations, this results in impacts that are smaller than the initiating shock. Not surprisingly, this is overwhelmingly true for electric power producers' ability to substitute factors for infrastructure: the larger the value of σ_E the more the impacts shrink toward zero, and become linear in the parameters. For the supply of, price of, and intermediate demand for, power, as well as rest-of-economy output, the second strongest determinant of the response to a disruption is the rest of the economy's elasticity of substitution, whereas for final electricity demand and utility, this role is played by the household elasticity of substitution. The results for \hat{u} indicate that the economy-wide benefit of substitution is to moderate the welfare cost of the shock by at least an order of magnitude.

4.3 Mitigation

The counterfactual equilibrium of the model with backup investment is algebraically too complex to yield clear analytical insights. Notwithstanding, it allows us to solve for changes in the quantity of backup capacity that satisfy different criteria. We consider three cases. The first is the investment that minimizes the loss of infrastructure capacity, which by (12) simply follows the fixed rule

$$\hat{b}^{K0} = \hat{b}|_{\hat{k}^{Net}=0} = -\xi^{-1}\hat{k}^*$$

The second is the investment that minimizes power supply disruption, which we find by setting $\hat{q}_E = 0$ and solving for \hat{b} as a function of the parameters:⁶

$$\hat{b}^{E0} = \hat{b}|_{\hat{q}_E=0} = -\alpha\eta\{\lambda\sigma_E + (1-\lambda)(\gamma(1-\beta)\sigma_U + (1-\gamma(1-\beta))\sigma_N)\}\mathcal{D}_1^{-1}\hat{k}^*$$

⁶ In the polar case of no substitution, power producers do not adjust their gross factor input, and reduce their net factor input by an amount that exactly offsets their allocation of resource to backup investment. The effect of mitigation is therefore to simply replace \hat{k}^* with $\hat{k}^* + \xi\hat{b}$ in eqs. (13)-(15), in the event of which the optimal backup is simply $\hat{b} = \hat{b}^{K0}$.

Similarly, the third is investment that minimizes welfare loss, which we find by setting $\hat{u} = 0$ and solving for \hat{b} :

$$\hat{b}^{U0} = \hat{b}|_{\hat{u}=0} = \alpha\eta\{\lambda\sigma_E - \lambda(\gamma(1 - \beta)\sigma_U + (1 - \gamma(1 - \beta))\sigma_N) + \beta\sigma_N + (1 - \beta)\phi\sigma_U\}\mathcal{D}_2^{-1}\hat{k}^*$$

Here, the denominators \mathcal{D}_1 and \mathcal{D}_2 are complicated functions of the parameters.

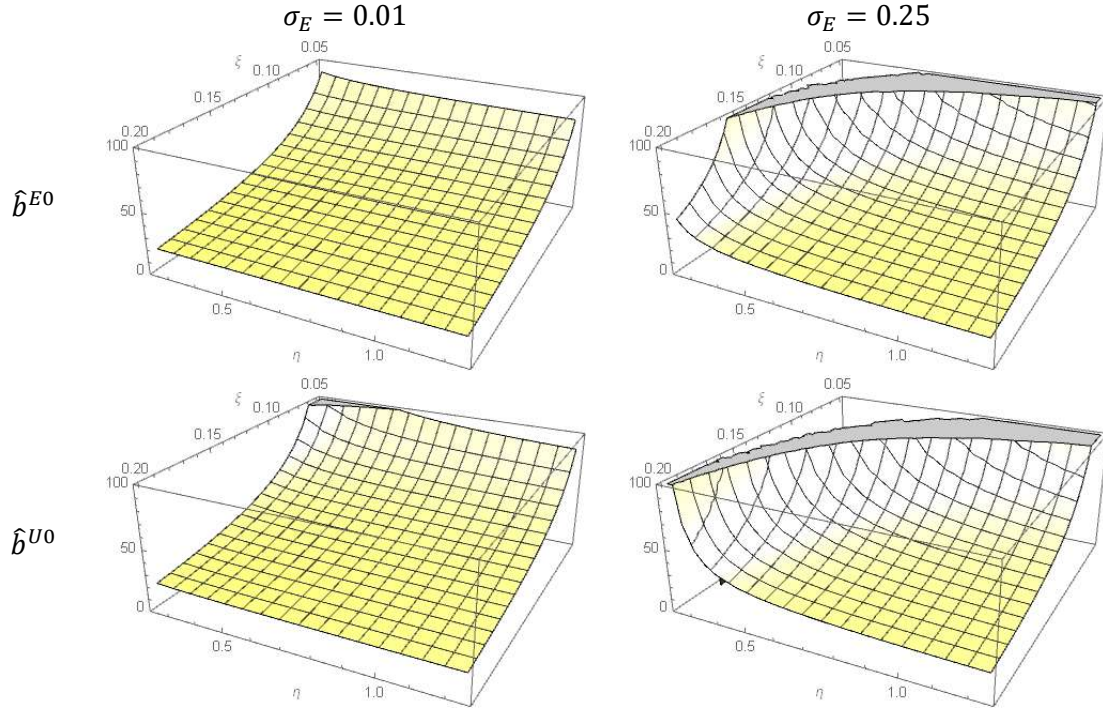


Figure 2. ENERGY SUPPLY DISRUPTION MINIMIZING AND OPTIMAL BACKUP TECHNOLOGY PENETRATION (% change in backup capacity from its baseline level)

To understand the implications of these expressions we numerically parameterize them using values from Table 1. Focusing on the role played by our technology parameters, we evaluate \hat{b}^{E0} and \hat{b}^{U0} at representative values of the elasticities of substitution ($\sigma_N = 0.5, \sigma_U = 0.75$) while varying the factor elasticity of backup transformation and the baseline share of backup capacity. The results, shown in Figure 2, highlight the nonlinear response of backup investment to these parameters. Under either criterion, the optimal level of investment is for all practical purposes invariant over a wide range of combinations of η and ξ . The analytical solutions that underlie the figure indicate that in this region, the elasticities of the response of backup capacity to the shock range from -6.6 to -7.2, which closely parallel the value of the infrastructure disruption minimizing elasticity, above ($1/\xi = 6.7$). These responses correspond to increases in backup capacity of around 27%.

As either the productivity of factors diverted to backup capacity additions or the baseline share of backup capacity decline, the investment response becomes exponentially more sensitive, with values of

η below 0.4 and ξ below 0.1 inducing increases in backup infrastructure of more than double their baseline level. This behavior is more sensitive to the pre-existing level of backup technology, which is not surprising considering that the model solutions are interpreted as percentage changes, and ξ indicates the base off of which that change is calculated. For even smaller values of the two parameters, the increase in the elasticity of \hat{b}^{E0} and \hat{b}^{U0} to the shock is asymptotic, which suggests that there is no feasible way to satisfy their respective criteria given how much additional backup capacity needs to be added to the small installed base, and/or the quantity of resources that must be diverted to this effort, due to the low productivity of the investment transformation technology. Particularly noteworthy is the fact that such a problem arises when it is possible for power producers to directly substitute factor inputs for specialized infrastructure capital ($\sigma_E = 0.25$). Conversely, with strict input complementarity ($\sigma_E \rightarrow 0$), deliberate investment in backup capacity is the sole margin on which electric power producers are able to adjust to maintain baseline levels of supply. The range of values of the parameter at which modest is correspondingly broadened.

We close by assessing the consequences of the shock under both uncertainty of the substitution parameters and mitigation investment in backup capacity. In the counterfactual equilibrium with mitigation, each of the variables takes the form $\mathcal{F}\hat{k} + \mathcal{G}\hat{b}$, where \mathcal{F} and \mathcal{G} are functions of the parameters that are algebraically too complex to yield clear insights. We therefore focus on the numerical solutions to the model with backup investment set at the levels \hat{b}^{K0} , \hat{b}^{E0} and \hat{b}^{U0} , above. Table 3 reports the median and range of values of the variables calculated under 32 different combinations of the substitution elasticities, fixing the technology parameters at representative values ($\eta = \{0.5, 0.75\}$, ξ and δ as in Table 1). Across scenarios there are modest differences in the median level of investment, from 27% to 33% (27% to 41%) when backup investment is more (less) productive. Compared to the impacts in section 4.2, backup capacity has a substantial moderating influence on the responses of both electricity prices, downstream quantities of electricity inputs and economic output, and consumers' welfare. In particular, despite the fact that the welfare losses in the absence of mitigation are small, the net effect of backup capacity expansion is to further reduce them by up to an order of magnitude. However, for a given baseline backup capacity, the magnitude of these benefits depends critically on the productivity of the factors of production that power producers divert toward its expansion. At the low productivity optimum, the warranted level of capacity can more than double under the worst-case combination of our substitution elasticities.

Finally, the results emphasize that although the magnitude of investments that minimize losses of infrastructure capacity and output might be similar in magnitude, they nonetheless incur welfare losses. The reason is that neither measure fully internalizes the opportunity cost of the factors that must be diverted from alternative productive uses in the process of making such investments. Even in the stylized environment of the present model where factor prices are assumed to be constant, the reallocation of factors among industries will give rise to general equilibrium effects that induce broader changes in commodity prices, supplies and demands.

Table 3. EFFECTS OF BACKUP CAPACITY INVESTMENT ON THE CONSEQUENCES OF INFRASTRUCTURE DISRUPTION (median % change in the quantity of each variable from its baseline level, minimum and maximum values in square braces)

| \hat{b} | \hat{q}_E | \hat{p}_E | \hat{x} | \hat{q}_N | \hat{c} | \hat{u} |
|---|----------------|------------------|------------------|-------------------|------------------|-------------------|
| Inherent resilience via substitution only | | | | | | |
| — | -2.1 | 2.7 | -1.7 | -0.0025 | -1.4 | -0.023 |
| — | [-3.7,-0.42] | [1.3,12] | [-4.2,-0.39] | [-0.0065,0.0027] | [-8.3,-0.34] | [-0.12,-0.0081] |
| Backup investment that minimizes infrastructure disruption ($\hat{b} = \hat{b}^{K0}$) | | | | | | |
| $\eta = 0.5$ | | | | | | |
| 27 | -0.083 | 0.24 | -0.083 | -0.0044 | -0.096 | -0.0059 |
| — | [-0.37,-0.035] | [0.039,0.48] | [-0.39,-0.026] | [-0.0048,-0.0041] | [-0.45,-0.015] | [-0.011,-0.0046] |
| $\eta = 0.75$ | | | | | | |
| 27 | -0.034 | 0.098 | -0.034 | -0.0029 | -0.039 | -0.0035 |
| — | [-0.15,-0.015] | [0.015,0.19] | [-0.16,-0.011] | [-0.0031,-0.0028] | [-0.19,-0.007] | [-0.0055,-0.003] |
| Backup investment that minimizes electricity supply disruption ($\hat{b} = \hat{b}^{E0}$) | | | | | | |
| $\eta = 0.5$ | | | | | | |
| 32 | — | -0.0079 | 0 | -0.0049 | 0 | -0.0048 |
| [27,38] | — | [-0.022,-0.0044] | [-0.002,0.0009] | [-0.0054,-0.0044] | [-0.0038,0.0083] | [-0.0054,-0.0043] |
| $\eta = 0.75$ | | | | | | |
| 29 | — | -0.0048 | 0 | -0.003 | 0 | -0.0029 |
| [27,30] | — | [-0.012,-0.0029] | [-0.0011,0.0005] | [-0.0031,-0.0029] | [-0.0022,0.0047] | [-0.003-0.0028] |
| Backup investment that minimizes welfare loss ($\hat{b} = \hat{b}^{U0}$) | | | | | | |
| $\eta = 0.5$ | | | | | | |
| 41 | 0.37 | -0.63 | 0.37 | -0.0055 | 0.38 | — |
| [28,110] | [0.12,2.2] | [-3.3,-0.31] | [.076,2.6] | [-0.012,-0.0039] | [0.27,0.81] | — |
| $\eta = 0.75$ | | | | | | |
| 33 | 0.21 | -0.34 | 0.21 | -0.0031 | 0.21 | — |
| [27,48] | [0.081,0.68] | [-1,-0.2] | [0.05,0.79] | [-0.0036,-0.0024] | [0.16,0.25] | — |

5. Discussion and Conclusions

We have developed a simple analytical general equilibrium model of the economy-wide impacts of electricity infrastructure disruptions. The model's counterfactual equilibria throw into sharp relief two key factors. The first is the role of substitution as an inherent resilience mechanism, which gives rise to changes in commodity prices and quantities, and concomitant reductions in welfare, that are much smaller in magnitude than the initiating shock. The second is the ability for deliberate investments in mitigation to further dampen the consequent price and quantity changes, and ultimate welfare losses.

Additional insights were developed via a numerical case study investigating the consequences of a two-week electricity infrastructure outage in California's Bay Area. Inherent resilience and mitigation drive a wedge between the initiating shock and the actual reduction in electricity supply. With substitution alone, power output declines between -3.7% and -0.42%, the electricity price increases by 3% to 12%, and intermediate and residential electricity use fall by -4.2% to -0.39% and . Mitigating these impacts by expanding backup infrastructure capacity can reduce these effects by as much as two orders of magnitude, and even nullify the loss in welfare.

In percentage terms the ultimate welfare impacts are small, ranging from -0.19% assuming no substitution whatsoever to -0.0081%

The measure of welfare impact used here is a more theoretically consistent indicator of the economy-wide burden of disruptions than commonly-used partial equilibrium measures of cost. To put our results in context, we treat the change in utility as percentage equivalent variation, which we then multiply by the combined annual personal income of our affected counties (\$537 Bn in 2016). With no substitution, this suggests a worst-case nominal economy-wide net cost of \$1 Bn, which is reduced to \$123-644 M by inherent resilience due to substitution, \$19-30 M with additional infrastructure capacity-preserving backup investment, and \$15-16 M with supply-preserving investment. By contrast, applying an average \$2/hour long-duration residential outage cost (e.g., Sullivan et al, 2015: Table 5-7) to the 2.2 million households in our affected Bay Area counties (CA DOF, 2017) yields a cost of our disruption scenario of \$1.5 Bn in the residential sector alone! Disparities such as these points to the need for research to reconcile costs derived from general equilibrium frameworks of the kind developed here with bottom-up, partial equilibrium estimates of willingness to pay.

Turning to the supply side, it is more difficult to quantify what our results mean in terms of the direct cost to power producers entailed in expanding backup capacity by the percentage amounts in Table 3. This points to what is perhaps the most important limitation of this study: its stylized, highly simplified character that requires additional research to be rendered consistent with the physical reality of the power system. The latter is particularly relevant for our mitigation results, which rely on the artifice of a monolithic backup technology. Detailed engineering and/or power system simulation studies to elaborate the constituents of this black box, the manner in which their interactions determine backup performance, and their operational and investment demands for different inputs—particularly capital, can yield much needed empirical constraints on the values of the key uncertain parameters ξ , δ and η .

Lastly, we take pains to acknowledge caveats to our economic model itself. A key omission is that it ignores the income effects associated with changes in factor prices driven by shifts in the marginal productivities of both the power sector infrastructure fixed factor and the intersectorally mobile generic factor. In a regional economic system such price changes tend to be dampened by factor movements across the regions' boundaries, and we have eschewed explicit representation of these economic processes for the sake of keeping the analysis simple and tractable. Our choices in this regard also raise concerns that the model is insufficiently detailed in terms of the number of electricity using sectors it represents, and, particularly, its omission of intermediate inputs to production, to be useful for policy analysis. Furthermore, the model's static character precludes its application to elucidate the role of general equilibrium interactions in the dynamics of recovery from power disruption events, and how they might influence the relative cost, effectiveness and desirability of different backup technology options. All of the foregoing limitations can be expeditiously addressed through a program of research to develop dynamic multi-sectoral (and perhaps additionally, multi-regional) CGE simulations and couple them with techno-economic power system models. But in advance of such efforts, the type of model developed here is sufficiently simple and flexible that it can be easily adapted to a broad range of situations at a variety of geographic scales to provide first-order insights on the economic consequences of long-term power disruptions.

6. References

- Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., and D. Von Winterfeldt. "A Framework to Quantitatively Assess and Enhance Seismic Resilience of Communities." *Earthquake Spectra* 19 (2003): 733–52.
- Çağnan, Z., Davidson, R., and S. Guikema. "Post-Earthquake Restoration Planning for Los Angeles Electric Power." *Earthquake Spectra* 22(3) (2006): 589-608.
- Detweiler, S.T. and A. Wein (eds.) *The HayWired Earthquake Scenario*. Earthquake hazards: U.S. Geological Survey Scientific Investigations Report No. 2017-5013 (<https://doi.org/10.3133/sir20175013v1>), 2017.
- Eto, J. H., LaCommare, K. H., Larsen, P., Todd, A., and E. Fisher. *An Examination of Temporal Trends in Electricity Reliability Based on Reports from US Electric Utilities*. LBNL-5268E, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US), 2012.
- Fullerton, D. and G. Metcalf. "Tax Incidence." *Handbook of Public Economics* Vol. 4 (2002): 1787-1872.
- Greenberg, M., Mantell N., Lahr, M., Felder F., and R. Zimmerman. "Short and Intermediate Economic Impacts of a Terrorist-Initiated Loss of Electric Power: Case Study of New Jersey." *Energy Policy* 35 (2007): 722-733.
- National Research Council. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: National Academies Press, 2017.
- Rose, A. "Economic Resilience to Natural and Man-Made Disasters: Multidisciplinary Origins and Contextual Dimensions." *Environmental Hazards* 7 (2007): 383-398.
- Rose, A. *Economic Resilience to Disasters*. Community and Regional Resilience Institute Report No. 8, Oak Ridge National Laboratory, Oak Ridge, TN, 2009.
- Rose, A. Benefit-Cost Analysis of Economic Resilience Actions, in S. Cutter (ed.) *Oxford Research Encyclopedia of Natural Hazard Science*, New York: Oxford, 2007.
- Rose, A. "Incorporating Cyber Resilience into Computable General Equilibrium Models," in Y. Okuyama and A. Rose (eds.), *Modeling Spatial and Economic Impacts of Disasters*, Heidelberg: Springer, 2018.
- Rose, A. and S. Liao. "Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions." *Journal of Regional Science* 45(1) (2005): 75-112.

Rose, A., Oladosu G., and S. Liao. "Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout." *Risk Analysis* 27(3) (2007a), 513-31.

Rose, A., Oladosu G., and D. Salvino. "Economic Impacts of Electricity Outages in Los Angeles: The Importance of Resilience and General Equilibrium Effects." In M. A. Crew and M. Spiegel (eds.), *Obtaining the Best from Regulation and Competition*. Springer Science, 2005.

Sanstad, A. *Regional Economic Modeling of Electricity Supply Disruptions: A Review and Directions for Future Research*, Report No. LBNL- 1004426, Lawrence Berkeley National Laboratory, 2016.

(CA DOF) State of California, Department of Finance, *E-5 Population and Housing Estimates for Cities, Counties and the State*–January 1, 2011- 2017. Sacramento, California, May 2017.

Sue Wing, Ian. (2008). "The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technology Detail in a Social Accounting Framework." *Energy Economics* 30 (2008): 547-573.

Sue Wing, I., D. Wei, A. Rose and A. Wein. *Economic Impacts of the HayWired Earthquake Scenario*. Report to the US Geological Survey, 2018.

Sullivan, M.J, J. Schellenberg and M. Blundell, *Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States*, Report No. LBNL-6941E, Lawrence Berkeley National Laboratory, 2015.

(USEOP) United States Executive Office of the President. *Presidential Policy Directive – Critical Infrastructure Security and Resilience*. White House press release, February 12, 2013.