Energy Economics 89 (2020) 104756

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Economic consequence analysis of electric power infrastructure disruptions: General equilibrium approaches☆

Ian Sue Wing [a], Adam Z. Rose [b,c,*]

[a] Department of Earth and Environment, Boston University, United States of America
[b] Sol Price School of Public Policy, University of Southern California, United States of America
[c] Center for Risk and Economic Analysis of Terrorism Events, University of Southern California, United States of America

ARTICLE INFO

Article history:
Received 13 August 2018
Received in revised form 30 January 2020
Accepted 8 April 2020
Available online 6 May 2020

JEL classification:
C63
D58
L94
Q43
Q54
R13

Keywords:
Electricity disruptions
Analytical general equilibrium modeling
Reliability
Resilience

ABSTRACT

We develop a stylized two-sector analytical general equilibrium model that elucidates mechanisms of adjustment to widespread, long-duration electric power disruptions. Algebraic solutions illustrate the relative importance of resilience through producer and consumer input substitutability and mitigation investment in backup infrastructure capacity in moderating the economy-wide costs of outages. Simulations of the impacts of a two-week power outage on California's Bay Area economy using both the analytical model and a computational general equilibrium model yield welfare losses that are substantially smaller than stated-preference estimates of willingness to pay. Results highlight the role of resilience in moderating consequences of energy supply shocks.

1. Introduction

In electric power systems, 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" (National Research Council, 2017, p. 10).[1]

In this paper we investigate how mitigation and resilience measures affect the economic consequences of large-scale disruption to electric

☆ The work described in this study was funded by the Transmission Planning and Technical Assistance Division of the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

* Corresponding author at: Sol Price School of Public Policy, University of Southern California, United States of America.

E-mail address: adam.rose@usc.edu (A.Z. Rose).

[1] Dozens of definitions of resilience have been offered that emphasize multiple dimensions of the phenomenon. 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 (e.g., 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; Xie et al., 2018). Our emphasis here is on actions after the outage begins, which partially shifts inquiry away from a narrow focus on electricity suppliers toward consideration of the behavior of their downstream customers (see Section 2).

https://doi.org/10.1016/j.eneco.2020.104756
0140-9883/

power infrastructure. We do this by developing a parsimonious, analytically tractable and generalizable model of the economy-wide impacts of electricity service disruptions. We emphasize the differences between mitigation and resilience, in terms of the representation of these measures within an economic model, as well as their ultimate influence on the magnitude of impacts. Moreover, we show how their moderating influence depends on key characteristics of the measures themselves, and of the affected economy.

Electricity service providers take steps to increase the reliability of their systems through mitigation measures that reduce the frequency and magnitude of potential outages. Such measures include strengthening individual pieces of equipment and protecting system connectivity against natural disasters, technological accidents and terrorist attacks (Eto et al., 2012; National Research Council, 2017). At the same time, direct and indirect electricity customers pursue a range of measures to reduce production and consumption losses once the disruption begins, which Rose (2007, 2017) and others (e.g., Kajitani and Tatano, 2009; National Research Council, 2017) have characterized as "resilience". Some of these measures are inherent, in the sense that they exploit flexibility built into firms' production processes (e.g., the ability to substitute alternative power sources or the ability to shift operations to branch plants out of the affected zone) or households' consumption processes (e.g., the ability to reallocate activities over the course of the day to cope with periods of limited or no electricity supply). Some actions 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. A further strategy, more applicable to the electricity provider, is dynamic economic resilience, which refers to deliberate actions to accelerate the pace of restoration of electricity service.

Previous research by the authors has demonstrated methods for, and elucidated the broader economic consequences of, incorporating impact-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, 2017). Energy-focused CGE models are the workhorse of assessments of the broader economic consequences of shocks or disruptions to energy supplies. However, Sanstad (2016) 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 and their interlinkages—which drive the model's emergent behavior. While the calibration process is relatively straightforward for aggregates of electric generators with different technologies and/or fuels (Sue Wing and Balistreri, 2018), it is extremely challenging to resolve the use of inputs associated with components of the transmission and distribution grid. The network character of these distributed elements, and their interaction across space with geographically varying hazards, determine the initiating shocks from which economy-wide impacts ultimately arise.

This challenge complicates investigation of the effects of electric power supply disruptions from natural hazards and potential terrorist threats. For a given downstream sector, power generated by multiple, geographically dispersed generators upstream is conveyed by multiple, spatially disaggregated infrastructural assets to multiple electricity consuming entities located in different service territories. This 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 capture the physical characteristics of power flows (e.g., Kirchhoff's laws). Details such as these are better captured by techno-economic simulations such as optimal power flow, economic dispatch or capacity expansion models. These types of models already exist and are routinely used by electricity system operators and balancing authorities, and it is comparatively straightforward to re-task 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.

We contend that explicit consideration of the foregoing details is rarely necessary to assess the downstream economy-wide impacts of the supply disruptions. Even where there are substantial feedbacks between downstream responses to electricity supply curtailment and the fundamental drivers of the disruption, one can envision "soft" coupling multiple simulation models based on fundamentally different paradigms using emulation in conjunction with scenarios. In particular,

(i) An optimal power flow model can be employed to simulate several scenarios of disruption while incorporating mitigation activities of varying cost and effectiveness.
(ii) The results of (i) can be 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 (see, e.g., Chen et al., 2018; Rose et al., 2017).
(iii) The vector of electricity supply curtailments and response surfaces of mitigation and resilience options and their bottom-up opportunity costs can be combined with a multi-sector economic model to assess the broader economic impacts of electric power disruptions.

The focus of the present study is step (iii). We demonstrate how the broader economic effects of stylized electricity supply curtailments may be captured using a two-sector analytical general equilibrium model that admits closed-form algebraic solutions. Within this reduced-form framework, we develop stylized representations of mitigation and resilience options, and characterize their moderating influence on economy-wide impacts. We show how the model's analytical skeleton may be fleshed out to provide practical economic insights by simulating a numerical case study of a two-week outage of electricity infrastructure in California's Bay Area that reduces the latter's capacity by 4%. Finally, to provide comparison and context, we develop and simulate an interregional CGE (ICGE) model of the California economy that resolves business interruption impacts across 46 sectors within the nine Bay-Area counties.

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. Section 3 provides a detailed description of our methodological approach, introducing both the analytical model and our numerical case study. The algebraic model's algebraic and numerical results are presented in Section 4, and impacts simulated by the more detailed ICGE model are summarized in Section 5. Section 6 concludes with a 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 of electricity outages characterized impacts in terms of residential, commercial and industrial willingness to pay (WTP) to avoid disruptions of various durations, and 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. With the exception 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, through different transmission pathways, as summarized by Table 1.

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 fixed-coefficients character, inability to capture substitution behavior content, and lack of consideration of prices and the effects of factor market adjustments on consumers' incomes. 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 the kinds of engineering and electricity market details necessary to credibly simulate the economic consequences of electricity disruptions.

The most recent modeling advances in this realm relate to various types of resilience defined in the previous section (Rose, 2007, 2009; Kajitani and Tatano, 2009). These papers shift the focus to the customer side, where substitution possibilities create many more opportunities for resilience that are by comparison much less costly. For example, the productivity-enhancing benefits of many energy conservation measures outweigh their costs, back-up generators are relatively inexpensive, as are outsourcing production to other facilities with excess capacity that have electricity service, and recapturing lost production at a later date via temporary overtime operation and extra shifts. While some of these measures require investments in physical planning or planning prior to the onset of an outage, many can simply be implemented if and when a disruption occurs. Moreover, downstream customers are also able to employ these measures, as well as temporarily draw down inventories, engage in input substitution, and replace domestically produced inputs that become scarce with similar commodities imported from outside the affected area. Rose and Liao (2005), Rose et al. (2007), Sue Wing et al. (2016), and Rose (2018) have shown how many of such resilience measures can be included in CGE models.[2]

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

Table 1
Partial and general equilibrium impacts of electricity service disruptions.

Actor	Impact pathway	Type
Direct customers of the electricity service provider	Commercial and industrial customers: reduced production due to facility downtime, damage to equipment or loss of perishable work in process or finished goods inventory, residential customers: reduced well-being. Direct customers are the demand side of the electricity market in a partial equilibrium sense, yet much of the partial equilibrium literature focuses only on the supply side.	PE, GE
Downstream customers of disrupted firms	Reduced production and profit due to production foregone because of inability to source crucial inputs produced by directly impacted firms.	GE
Upstream suppliers of disrupted firms	Reduced production and profit due to cancellation of orders for inputs because of production delays/idling of capacity by directly impacted firms.	GE
Households	Reduced income because of decreased labor hiring, wage remuneration and dividends of firms directly affected by the electricity outage, as well as their downstream customers and upstream input suppliers.	GE
All firms	Decreased consumer spending associated with declines in household income.	GE
All firms	Decreased investment as a consequence of lower revenue/profit of firms directly affected by the electricity outage, as well as their downstream customers and upstream input suppliers	PE, GE
All firms and households	Reduced production and consumption activity due to general increases in prices because of scarcity.	GE

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

A major motivation for this study is illustrated in Fig. 1. Panel A shows the US Geologic Survey map of seismic hazard in California's nine-county Bay Area region, expressed as the peak ground acceleration with a 90% probability of not being exceeded in 50 years. Two parallel swaths of greatest earthquake hazard (90% probability of not experiencing ground acceleration > 100% of gravity) run southeast to northwest. The first, associated with the San Andreas fault, extends up the San Francisco peninsula to coastal Marin and Sonoma counties. The second, associated with the Calaveras, Hayward and Rodgers' Creek faults, extends through the Silicon Valley area of Santa Clara County, then follows

[2] 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.

the coastline of the East Bay and the border between Sonoma and Napa counties.

In 2017, the latest year for which data are available, the nine counties in the figure housed 2.3% of the US population and consumed 53.4 TWh of electricity, just under 1.5% of aggregate US demand. Of this total, 35% was residential, and 82% was accounted for by four counties: Santa Clara (32%), Alameda (21%), Contra Costa (18%) and San Francisco (11%). Forty-six percent of the Bay Area's electricity consumption was generated locally, with 90% of domestic supply coming from Contra Costa (45%), Sonoma (21%), Santa Clara (14%) and Solano (12%) counties. Panel B shows the distribution of electricity infrastructure connecting supply and demand across region. San Mateo, Santa Clara and Alameda in particular have a high concentration of generation units, substations and high-voltage transmission lines in close proximity to the aforementioned high-hazard areas. Additional infrastructure is concentrated in areas of lower, but still significant, hazard, around southern, eastern and western shores of Suisun Bay (Marin, Napa and Contra Costa counties), and along the eastern boundary of Sonoma county.

This risk of ground motion suggests that a major earthquake centered in any of the high-hazard zones of this region will likely cause severe damage to multiple components of the Bay Area electricity grid over a wide geographic extent. The precise pattern of damage to network components, and the consequent duration and geographic extent of electricity disruption, will depend on the magnitude, depth and location of the earthquake itself, and the resulting realization of ground motion. Even if spatially-detailed earthquake scenarios are available, characterization of power disruptions requires: engineering calculations of network elements' ability to withstand the resulting shock, as well as estimating the subsequent redundancy and resilience of the system. These imponderables are precisely the kind of detail we want to avoid getting bogged down in. By contrast, we focus on the mechanisms by which geographically widespread, long time-duration electricity service disruptions exert their economic impacts. Instead, we abstract from these specifics to consider the simplified scenario of a 14-day power outage across the five southern Bay Area counties where the spatial intersection of electricity infrastructure and seismic risk is largest.

Of course, the economic effects of a Bay Area power disruption will depend critically on the geographic distribution of ground shaking, the upstream topology of the electricity generation, transmission and distribution assets in the most severely affected locations, as well as the downstream structural and resilience characteristics of the economy that the distribution network serves. But this circumstance complicates broad assessment of blackouts in two ways. First, it militates against the development of general insights by threatening to make conclusions specific to the context of the initiating natural hazard and affected electricity grid. Second, it increases the fixed cost of analysis by necessitating substantial investments in data development, model building and calibration to capture the particular spatially-disaggregated characteristics of the shock, affected electric power assets and the downstream electricity-using economy. In light of these complications, our strategy is to circumvent these obstacles entirely by setting up and solving 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. In the process we illustrate just how much analytical progress can be made using a stylized, parsimonious approach.

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 sector-specific fixed factor with rate of return r. Electricity production also depends on the input of a composite factor, z_E, which is mobile among sectors, is in perfectly inelastic aggregate supply and has a ruling price w. Output of the 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

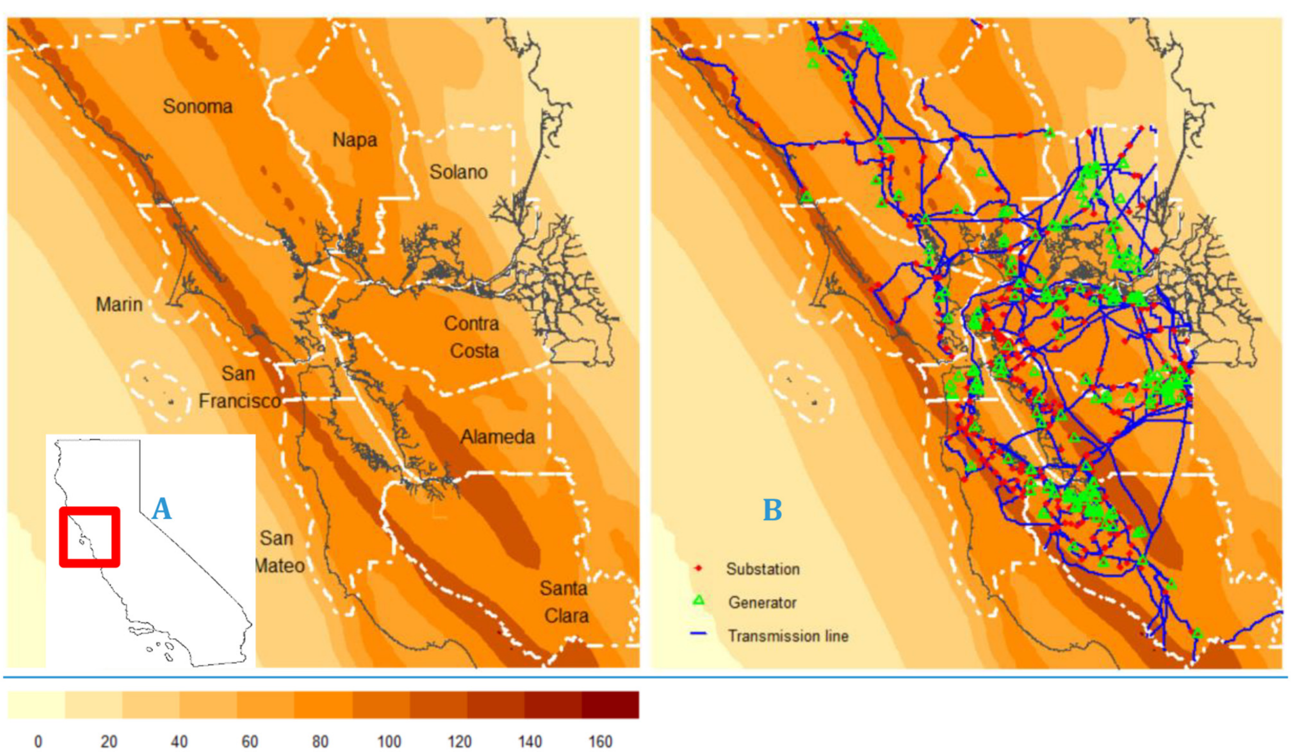

Fig. 1. California's Bay Area: seismic hazards and electricity infrastructure.

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 σ_E, $\sigma_N \in (0,1]$. Electricity supply satisfies N's intermediate demand as well as household demands final consumption of electricity, 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 2.

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: sectoral 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 demand sides 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 the fixed endowment of the composite factor. Households and downstream firms are linked through their competition for the electricity sector's output. 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 capacity loss 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 Eqs. (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 at the scale of United States regions 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 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 particular characteristics 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 a variety of geographic scales. This in turn facilitates the expeditious creation of zeroth-order estimates of business interruption losses from disruptions of different magnitudes. It does so by enabling the economic consequence analysis to be decoupled from detailed electric power system modeling, which expedites assessment by enabling the two investigations to proceed in parallel and have their results subsequently 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,

$$z_E^{Net} = z_E - z_E^{Backup} \tag{11}$$

can be expressed in log differential form as

$$\frac{z_E^{Net}}{z_E}\left(\frac{dz_E^{Net}}{z_E^{Net}}\right) = \left(\frac{dz_E}{z_E}\right) - \frac{z_E^{Backup}}{z_E}\left(\frac{dz_E^{Backup}}{z_E^{Backup}}\right) \tag{12}$$

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

$$db = \frac{\partial b}{\partial z_E^{Backup}} dz_E^{Backup} \Rightarrow \frac{dz_E^{Backup}}{z_E^{Backup}} = \underbrace{\left(\frac{\partial b}{\partial z_E^{Backup}} \Big/ \frac{b}{z_E^{Backup}}\right)^{-1}}_{\eta} \frac{db}{b} \Rightarrow \hat{z}_E^{Backup} = \frac{1}{\eta}\hat{b} \tag{13}$$

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

$$\hat{z}_E^{Net} \approx \hat{z}_E - \delta \hat{z}_E^{Backup} \approx \hat{z}_E - \frac{\delta}{\eta}\hat{b} \tag{14}$$

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

$$k^{Net} = k + b \tag{15}$$

which in log differential form is given by

$$\frac{k^{Net}}{k}\left(\frac{dk^{Net}}{k^{Net}}\right) = \frac{dk}{k} + \frac{b}{k}\left(\frac{db}{b}\right) \tag{16}$$

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

$$\hat{k}^{Net} \approx \hat{k} + \xi \hat{b} \tag{17}$$

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 2, augmenting the model to incorporate inherent resilience yields the new system of Eqs. (1′), (2)–(4), (5′) and (6)–(10). The number of equations is the same as before, but the addition of the variable, $\hat{b}$, 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

Table 2
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	$\hat{q}_E = \alpha(\hat{k} + \xi\hat{b}) + (1-\alpha)(\hat{z}_E - \frac{\delta}{\eta}\hat{b})$	(1′)
Elasticity of substitution in electricity production	$(\hat{k} + \xi\hat{b}) - (\hat{z}_E - \frac{\delta}{\eta}\hat{b}) = -\sigma_E(\hat{r} - \hat{w})$	(5′)

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 insights, we 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, Santa Clara). 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 a 6-month post-earthquake recovery period, similar patterns of disruption and restoration translate into integrated power supply curtailments 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 IMPLAN. These are summarized in Table 3. Electric power production is highly capital intensive, with inputs of capital accounting for 42% of the sector's output. We assume that the total value of various kinds of infrastructure accounts for one quarter of this amount, which suggests that the infrastructure cost share and output elasticity is just over 10%. As the Bay Area is the hub of California's 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%. Even so, households' electricity spending is only 1.4% of their total expenditure, 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 only 0.6%.

Our model's highly aggregate and stylized character means that the parameters that determine the opportunity cost and penetration of the backup technology will necessarily have a less rigorous empirical basis. 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

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

Table 3
Parameters of the numerical model.

α	Electricity sector infrastructure output elasticity	0.104512
β	Rest-of-economy sector electricity output elasticity	0.004995
γ	Electricity sector share of aggregate factor supply	0.192080
λ	Household share of aggregate electricity supply	0.004106
ϕ	Household electricity share of total expenditure	0.014424
ξ	Power sector backup share of infrastructure	0.15
δ	Power sector backup share of factor input	0.02
η	Factor-to-backup transformation elasticity	0.5–1.25

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

$$\delta = \frac{z_E^{Backup}/q_E}{z_E/q_E} \approx \frac{\alpha}{1-\alpha}\frac{z_E^{Backup}}{k} \approx \frac{\alpha}{1-\alpha}\frac{b}{k} = \frac{\alpha}{1-\alpha}\xi \tag{18}$$

which yields a plausible value of 0.0167. We round this result to 2%, which represents an upper bound, given our unavoidably approximate calibration procedure.[4]

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 electricity supplied from the grid, and power is a necessary input to both firms and households, which suggests that the values of all elasticities are at most unity. The extreme technological difficulty of using other productive inputs as large-scale substitutes for infrastructure capacity in power generation, transmission and distribution suggests that the inputs to the electricity sector are relative 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 σ_N, $\sigma_U \in [0.25,1]$.

3.3. A computational general equilibrium modeling comparison

A model as highly stylized as the one in Section 3.1 is too simplified to be useful for detailed policy analysis. Nevertheless, our central argument is that such a parsimonious approach can yield effects whose sign and magnitude are plausible, and constitute zeroth-order estimates of the economy-wide impacts of electric power disruptions, and the moderating effects of generic resilience. To demonstrate this point we compare our numerical results from Section 3.1 with the output of a highly detailed 18-region, 46-sector interregional CGE (ICGE) model of the California economy that resolves producer and consumer behavior in the nine Bay Area counties (the five counties above plus Marin, Napa, Solano and Sonoma) and the rest of the state. A detailed description of the model is given in an appendix to the paper.

Each sector is modeled as representative firm that produces a single good or service from inputs of labor, capital and intermediate commodities that are combined according a nested CES technology. Households in each county are grouped into representative consumers in nine distinct income classes. Each consumer is modeled as a representative agent with CES preferences and a constant marginal propensity to save and invest out of income. The government is modeled in a simplified fashion, with the passive role of collecting taxes from industries, passing on some of the resulting revenue to households as lump-sum transfers, and purchasing commodities to create a composite government good which is consumed by the households. Counties are modeled as open economies that trade with other regions, the rest of the U.S. and the rest of the world according to the Armington specification that treats imports from other regions as imperfect substitutes for goods produced domestically. The model computes the prices and quantities of goods and factors that equalize supply and demand in all markets in the economy, subject to constraints on the external balance of payments.

The ICGE model includes three factors of production: labor, general capital and electricity transmission and distribution (T&D) capital, all of which are owned by the households and rented out to the firms in exchange for factor income. Given the short time-duration of the shock in comparison to the annual period over which the model's benchmark social accounting matrices are defined, both types of capital are treated as intersectorally immobile. In every sector, and for each aggregate household grouping, we further assume a Leontief relationship between T&D capital and intermediate and final demands (respectively) for electric power. This specification enables electricity service curtailment to be modeled in the same way as the analytical model: a uniform 4% reduction in the economy's endowments of sector-specific T&D capital (and, for consumers, similar reductions in the productivity of household-specific T&D capital) across the five Bay-Area counties. The key difference is that backup T&D options are not represented, owing to the extensive data requirements necessary to specify them with any realism, and the large uncertainties in their characteristics and distribution across sectors and affected counties. In the absence of the moderating influence of backup capacity, the outage reduces the supply of electric power to industries and households, which increases the marginal cost of goods production differentially according to sectors' electricity intensity, in affected counties. This in turn induces changes in household income, substitution of non-electric inputs for electricity in affected counties, and adjustments in imports and exports among counties. The accompanying changes in household welfare, sectoral value added and county GDP capture the economy-wide impacts of the electricity supply disruption that can be expected in the presence of inherent resilience due to input substitution.

4. Analytical model results

4.1. No substitution

We begin by investigating the extreme case where economic actors do not engage in substitution. Although admittedly unrealistic, we note that this corresponds to the assumptions implicit in 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

[4] In the Fullerton-Metcalf log-linear specification of producer and consumer behavior, output and input elasticities are the same as the cost and expenditure shares. We therefore compute the values of these coefficients as cost or expenditure shares using the IMPLAN county-level input-output accounts based on this well-known precedent. The key behavioral parameters relating to resilience are elasticities of substitution. Our highly stylized model's computational efficiency enables us to evaluate the effects of many combinations of these parameters on the equilibrium of the economy, as a way of assessing the consequences of uncertain input substitutability. Accordingly, the numerical findings in Table 3 report the mean and range of values that are the result of a broad search over combinations of elasticity parameter values. This can also be thought of as a sensitivity test of the elasticity values.

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

$$\hat{q}_E = \hat{x} = \hat{c} = \alpha\hat{k}^* < 0 \tag{19}$$

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

$$\hat{q}_N = \alpha\beta\hat{k}^* < 0 \tag{20}$$

triggering a welfare decline of

$$\hat{u} = \alpha(\phi + (1-\phi)\beta)\hat{k}^* < 0 \tag{21}$$

A key feature of our log-linear setup is that the magnitude of the initiating shock always exceeds the changes in sectoral output and welfare in percentage terms. This result stems from the fact that the benchmark value of electricity infrastructure is smaller than the output of the power sector and downstream production and consumption.[5] Consequently, when expressed on the same annual percentage basis as the shock, 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 (0.13%). Eqs. (19)–(21) trace these small effect sizes to electricity's small share of households' expenditure, and, particularly, downstream firms' costs on an annual basis.

4.2. Inherent resilience via input substitution

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

$$\begin{aligned}\mathcal{D}_0 = {} & (1-\alpha(1-\lambda))\sigma_E + \alpha(1-\lambda)(1-\gamma(1-\beta))\sigma_N \\ & + \alpha(1-\lambda)\gamma(1-\beta)\sigma_U > 0\end{aligned} \tag{22}$$

which plays the role of the denominator of the algebraic expressions of variable changes. This parameter is a convex combination of the producer and consumer elasticities of substitution in which the weights are combinations of the cost and expenditure shares and is unambiguously positive. The impact on power supply is unambiguously negative, as before,

$$\hat{q}_E = \alpha\{\lambda\sigma_E + (1-\lambda)(1-\gamma(1-\beta))\sigma_N + (1-\lambda)\gamma(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} < 0 \tag{23}$$

but here it is smaller in magnitude.[6] A second unambiguous impact is an increase in the electricity price,

$$\hat{p}_E = -\alpha\mathcal{D}_0^{-1}\hat{k} > 0 \tag{24}$$

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

$$\hat{x} = \alpha\{\lambda\sigma_E + (1-\lambda(1-\gamma(1-\beta)))\sigma_N - \gamma\lambda(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \tag{25}$$

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

$$\sigma_U < \frac{1}{\gamma(1-\beta)}\sigma_E + \frac{1-\lambda(1-\gamma(1-\beta))}{\gamma\lambda(1-\beta)}\sigma_N \tag{26}$$

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.[7]

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

$$\hat{c} = \alpha\{\lambda\sigma_E + (\beta-\lambda(1-\gamma(1-\beta)))\sigma_N + (1-\gamma\lambda)(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \tag{27}$$

$$\hat{q}_N = \alpha\{\lambda\sigma_E + (\beta-\lambda(1-\gamma(1-\beta)))\sigma_N - \gamma\lambda(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \tag{28}$$

$$\hat{u} = \alpha\{\lambda\sigma_E + (\beta-\lambda(1-\gamma(1-\beta)))\sigma_N + (\phi-\gamma\lambda)(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\hat{k} \tag{29}$$

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:

$$\beta > \lambda\frac{1-\gamma}{1-\gamma\lambda} \tag{30}$$

Additional restrictions are, for welfare (Eq. (29)), the sufficient condition, $\phi > \gamma\lambda$, and, for rest-of-economy output (Eq. (28)), the sufficient condition

$$\sigma_U < \frac{1}{\gamma(1-\beta)}\sigma_E + \frac{\beta-\lambda(1-\gamma(1-\beta))}{\gamma\lambda(1-\beta)}\sigma_N \tag{31}$$

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 depend 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

$$\begin{aligned}-\frac{dz_E}{dk} &= -\left(\frac{z_E/q_E}{k/q_E}\right)\left(\frac{dz_E}{z_E}\Big/\frac{dk}{k}\right) \approx \frac{\alpha-1}{\alpha}\frac{\hat{z}_E}{\hat{k}^*} \\ &= (1-\alpha)(1-\lambda)\{\sigma_E-(1-\gamma(1-\beta))\sigma_N-\gamma(1-\beta)\sigma_U\}\mathcal{D}_0^{-1}\end{aligned} \tag{32}$$

[5] Assuming no price response, the upstream capital input coefficient determines the percentage change in power supply. The downstream intermediate and final electricity input coefficients determine the change in the rest-of-economy output and the direct (via the residential electricity demand channel) and indirect (via the downstream goods demand channel) effects on household utility.

[6] 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, $\alpha\lambda\sigma_E$.

[7] Note that the weights on σ_E and σ_N are strictly positive.

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

$$\sigma_E > (1-\gamma(1-\beta))\sigma_N + \gamma(1-\beta)\sigma_U \tag{33}$$

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

$$-\frac{dz_N}{dx} \approx \frac{\beta-1}{\beta}\frac{\hat{z}_N}{\hat{x}} = \frac{\beta-1}{\beta}\left\{\frac{\lambda\sigma_E-\lambda(1-\gamma(1-\beta))\sigma_N-\gamma\lambda(1-\beta)\sigma_U}{\lambda\sigma_E+(1-\lambda(1-\gamma(1-\beta)))\sigma_N-\gamma\lambda(1-\beta)\sigma_U}\right\} \tag{34}$$

$$-\frac{dq_N}{dc} \approx \frac{\phi-1}{\phi}\frac{\hat{q}_N}{\hat{c}} = \frac{\phi-1}{\phi}\left\{\frac{\lambda\sigma_E+(\beta-\lambda(1-\gamma(1-\beta)))\sigma_N-\gamma\lambda(1-\beta)\sigma_U}{\lambda\sigma_E+(\beta-\lambda(1-\gamma(1-\beta)))\sigma_N+(1-\lambda\gamma)(1-\beta)\sigma_U}\right\} \tag{35}$$

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

Fig. 2 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 >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 of smaller magnitude 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 residential electricity consumption 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 in Section 4.1 by one to two orders 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 the three criteria discussed on p. 14. The first is the investment that minimizes the loss of infrastructure capacity, which by Eq. (17) simply follows the fixed rule

$$\hat{b}^{K0} = \hat{b}\Big|_{\hat{k}^{Net}=0} = -\xi^{-1}\hat{k}^* \tag{36}$$

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[8]:

$$\hat{b}^{E0} = \hat{b}\Big|_{\hat{q}_E=0} = -\alpha\eta\{\lambda\sigma_E+(1-\lambda)(\gamma(1-\beta)\sigma_U+(1-\gamma(1-\beta))\sigma_N)\}\mathcal{D}_1^{-1}\hat{k}^* \tag{37}$$

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

$$\begin{aligned}\hat{b}^{U0} &= \hat{b}\Big|_{\hat{u}=0} \\ &= \alpha\eta\{\lambda\sigma_E+(\beta-\lambda(1-\gamma(1-\beta)))\sigma_N+(1-\beta)(\phi-\lambda\gamma)\sigma_U\}\mathcal{D}_2^{-1}\hat{k}^*\end{aligned} \tag{38}$$

The denominators $\mathcal{D}_1$ and $\mathcal{D}_2$ are second-order polynomials of the three substitution elasticities with coefficients that are complicated functions of the parameters that cannot be unambiguously signed.

To understand the implications of these expressions we numerically parameterize them based on Table 3. 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 Fig. 3, 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 larger, 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 from 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 ($\sigma_E \to 0$), 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 η and ξ with modest levels of investment is correspondingly broadened.

We close this section 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

[8] 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 $\hat{b} = \hat{b}^{K0}$.

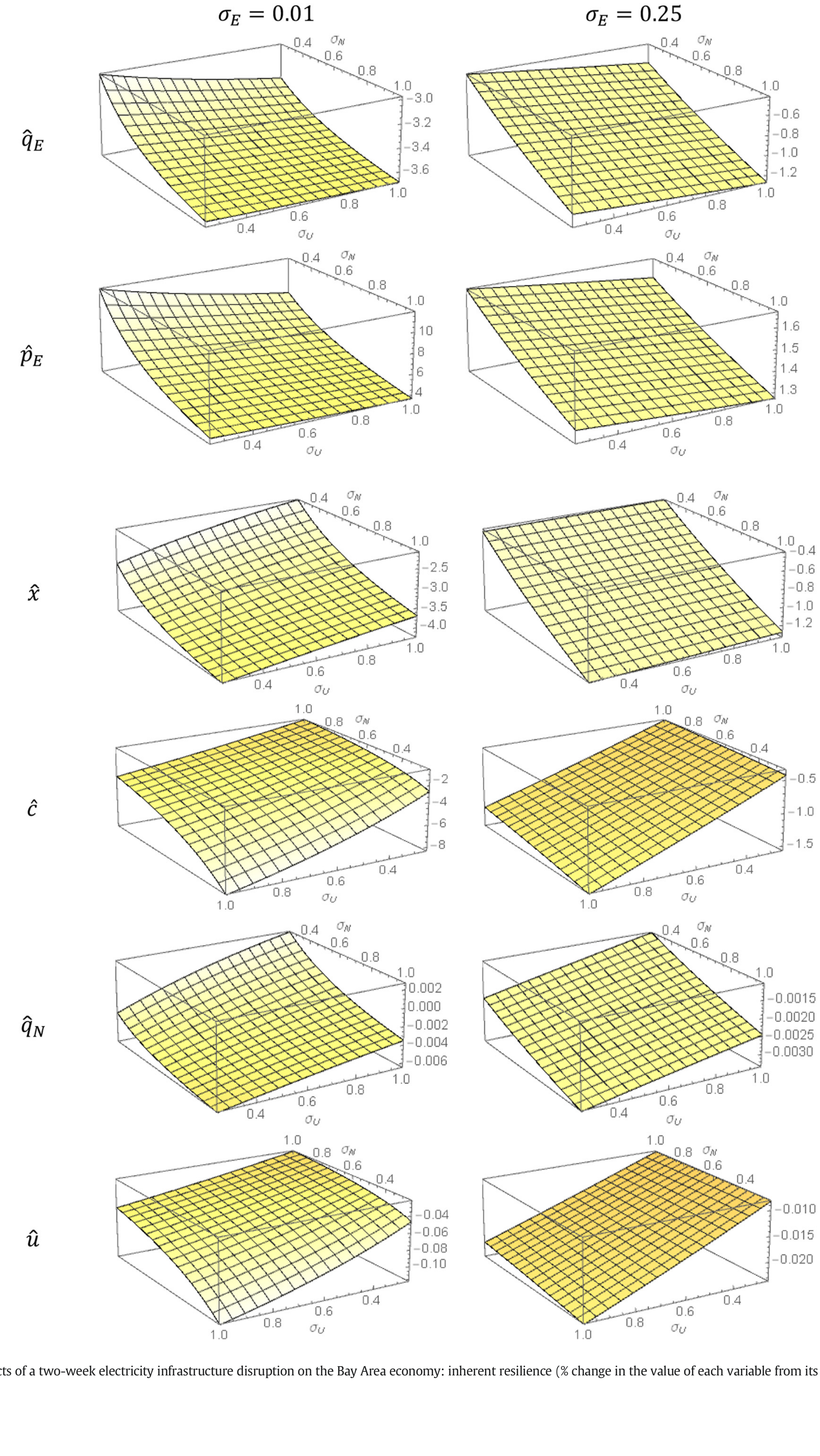

Fig. 2. Impacts of a two-week electricity infrastructure disruption on the Bay Area economy: inherent resilience (% change in the value of each variable from its baseline level).

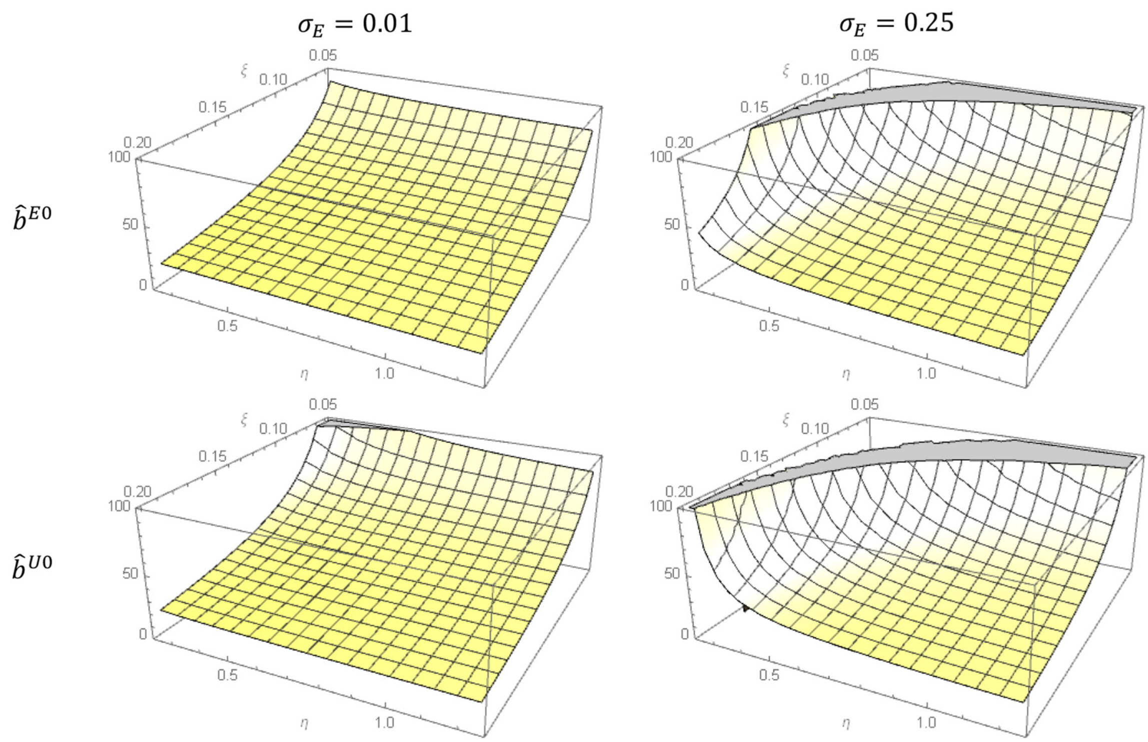

Fig. 3. Energy supply disruption minimizing and optimal backup technology penetration (% change in backup capacity from its baseline level).

$\mathcal{G}$ are complicated algebraic functions of the parameters. 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 4 reports the median and range of values of the variables calculated under 32 different combinations of the substitution elasticities, while keeping the technology parameters fixed at representative values ($\eta = \{0.5, 0.75\}$, ξ and δ as in Table 1). Across scenarios there are only slight 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 changes in 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

Table 4
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]	[0.076,2.6]	[−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]	–

up to an order of magnitude. For a given baseline backup capacity, 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.

5. Comparison ICGE model results

The ICGE model's key numerical results are summarized in Fig. 4, below. Impacts are not distributed evenly, either spatially or sectorally. In affected counties, sectors that are the largest users of electricity (though not the most electricity-intensive) experience the biggest reductions in output. Importantly, sectors in unaffected counties also experience losses, due to changes in commodity prices, and adjustments in imports and exports, but the latter are much smaller. Because household ownership of capital generally, and electricity transmission/distribution capital in particular, increases with income, the incidence of electricity service disruptions is mostly progressive, with losses concentrated in middle- and upper middle-income households. However, the geographic pattern of changes in consumption is not straightforward, with losses concentrated in San Francisco, Marin, Napa and Solano reflecting both income and substitution effects.

Owing to the additional substitution options incorporated into the CGE model, its simulations yield impacts that are comparable in magnitude to the analytical model's numerical results. Gross output across all downstream (non-electricity) sectors declines by 0.19% ($2.07 Bn) in the five directly impacted counties, 0.17% ($2.1 Bn) in the nine-county Bay Area region, but only 0.07% ($2.6 Bn) for the state as a whole due to its larger economic base. Table 5 illustrate that these figures are paralleled by aggregate GDP losses—0.14% ($0.94 Bn) in the five directly impacted counties, 0.13% ($0.95 Bn) in the nine-county Bay Area region, and 0.06% ($1.25 Bn) for the state of California. In the peripheral Bay Area Counties the effects of the shock are dampened by substitution of imports of electricity and other commodities that would ordinarily be supplied by affected counties.

To put our analytical model results in context, we treat the quantity $\hat{u}$ as percentage equivalent variation, and multiply it by the combined annual personal income of the affected counties in the ICGE model's benchmark accounts ($537 Bn). 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.

6. 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 inherent resilience due to substitution alone, power output declines between −3.7% and −0.42%, the electricity price increases by 3% to 12%, intermediate and residential electricity use fall by −4.2% to −0.39% and welfare declines by 0.02%. Mitigation via expanding backup infrastructure capacity can reduce these effects by as much as two orders of magnitude, and, in the limit, completely nullify the loss in welfare. In percentage terms the ultimate welfare impacts are small, ranging from −0.13% assuming no substitution whatsoever to −0.0081%.

The magnitude of these economic impacts is substantially smaller than those derived using partial equilibrium WTP estimates. By comparison, applying an average $2/h long-duration residential outage cost (e.g., Sullivan et al., 2015: Tables 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! This disparity highlights the need for research to reconcile costs derived from general equilibrium frameworks of the kind developed here with bottom-up analyses. We conjecture that one reason for this divergence is potential bias in residential customers' responses to stated preference surveys that reflects misperceptions of household substitution possibilities as the prices of both electricity and other goods change.[9] In such circumstances, WTP is given by Eq. (3), and is at the upper end of the range of estimates discussed above. It is less clear whether similar kinds of perceptual biases might influence estimates of commercial and industrial customers' WTP—given that these respondents are acutely aware of their own production costs. However, our results suggest that, because of economies' input-output structure and opportunities for input substitution on the part of both producers and consumers, simply adding up WTP estimates from residential and commercial/industrial customers is likely to overstate the true economy-wide costs of electricity disruptions.[10]

Further considering 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

[9] We have difficulty finding evidence for the hypothesized superiority of econometric models over simulation-based approaches, or vice versa. There are two relevant empirical literatures. The first considers the effects of electricity supply interruptions on firm—and to a lesser extent household—outcomes, overwhelmingly in developing countries that experience low electricity service quality and frequent blackouts (Alby et al., 2012; Allcott et al., 2016; Anderson and Dalgaard, 2013; Burlando, 2014; Fisher-Vanden et al., 2015; Harish et al., 2014; Steinbuks and Foster, 2010). The second is stated preference surveys that elicit industrial, residential and commercial customers' willingness to pay to avoid electricity service disruptions of different durations (e.g., Sullivan et al., 2018; Shawhan, 2019), focused on developed countries where blackouts are infrequent. The rarified, hypothetical character of the disruptions posed by stated preference surveys complicates comparisons with the myriad specific features of a real-world major disruption (e.g., Baik et al., 2018), and to our knowledge no study has undertaken a clean head-to-head comparison between a simulation-based and econometrically-based approaches of loss estimation. Moreover, stated preference estimates in this area typically are done in partial equilibrium settings (and with no substitution possibilities), while our analysis is in a general equilibrium setting, so, of course, our estimates are likely to be lower. In a general equilibrium setting, resilience is a relatively low-cost way to cope with outages and hence reduce their economic consequences, in contrast to mitigation, so this explains why our results would be lower than general equilibrium analyses based on stated preference inputs. Our study represents a first step toward bridging this gap; although the details of the initiating event may be hypothetical, the very real character of the affected economy provides an opportunity to understand the pathways of transmission of the shock.

[10] Note that in our simple closed economy, $\hat{q}_N$ identifies both the effect on the output of downstream commercial and industrial electricity users as well as the consequences for households' consumption of that output. This structure suggests that in a more general open-economy setting, a portion of the forgone output that would implicitly be embodied in nonresidential customers' WTP will also end up as a component of the reduction in households' consumption, and hence residential WTP. The larger the overlap between forgone production and forgone residential nonelectric consumption, the larger the potential for double-counting.

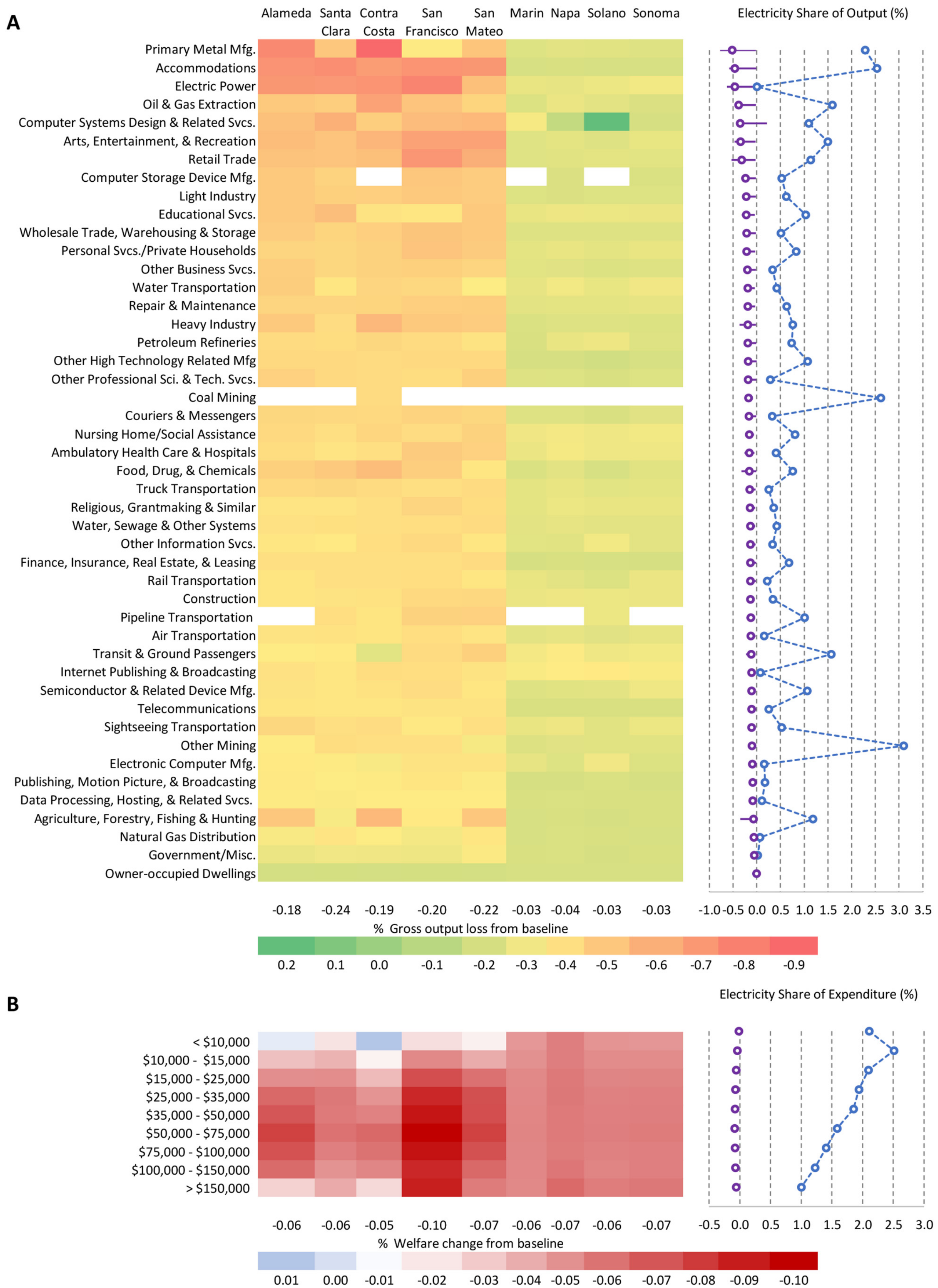

Fig. 4. CGE model impacts of electric power disruption in five Bay Area counties on (A) sectoral gross output and (B) aggregate consumption of households by income class.

Table 5
Impacts of electricity disruption on Bay Area counties' GDP.

	Change in GDP	
	Billion $	%
Alameda	−0.153	−0.13
Santa Clara	−0.309	−0.13
Contra Costa	−0.078	−0.12
San Francisco	−0.227	−0.16
San Mateo	−0.170	−0.17
Marin	−0.004	−0.02
Napa	−0.003	−0.03
Solano	−0.004	−0.02
Sonoma	−0.005	−0.02
Rest of California	−0.257	−0.02
Total	−1.251	−0.06

of our analytical model: 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.

Our analytical model is subject to numerous additional caveats. 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. Also omitted are commodity imports from outside the region, an additional margin of adjustment with the potential to further moderate the shock's effects on prices, reallocation of goods and factors, and consequent welfare losses. 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. Our stylized representation of consumer behavior is too highly aggregated to accommodate representation of multiple income and/or demographic groups that are likely to differ systematically in their inherent flexibility and ability to engage in substitution. Notwithstanding, when these shortcomings are addressed in a large-scale numerical ICGE model, it is encouraging to see changes in quantities. In the disaster literature, the concept of mitigation generally incorporates hardening of infrastructure that enables assets to continue to deliver services at levels close to their design capacity while withstanding the effects natural or anthropogenic hazards (e.g., building stronger structures and equipment, or burying power lines underground). We have defined mitigation as costly investment in back-up (spare or redundant) capacity that facilitates smaller reductions in output from a given shock. Infrastructure hardening is qualitatively different. When such investments are made ex ante, they moderate the initial capacity loss, which is manifested as a reduction in the magnitude of the shock. (Note that this is distinct from inherent resilience, which enables economic actors to respond more elastically to a shock of a certain magnitude.) In this analytical setup the challenge is to compare in a consistent fashion the general equilibrium benefit of aggregate cost savings against the partial equilibrium investment expenditure when the latter's economy-wide opportunity costs are not explicitly taken into account (see also, Farrow and Rose, 2018).

The broader related issue is that the relative abilities of mitigation and resilience measures to moderate the economy-wide losses calculated here depend on these measures' costs and benefits. On the cost side, mitigation measures as we have modeled them always require expenditure, while many types of inherent resilience need not, being a byproduct of production flexibility associated with routine investment decisions not specially related to power outages. For example, an important element of supply-side inherent resilience is the availability of multiple facilities with sufficient slack capacity in the benchmark equilibrium to facilitate low-cost shifting of production to locations unaffected by an outage. Importantly, while there are no costs directly associated with input substitution as represented within the model, indirect costs still arise as a consequence of the general equilibrium feedbacks on relative prices of producers and consumers reallocating inputs that are imperfectly fungible. On the benefit side, mitigation expenditure simultaneously reduces losses to direct and indirect customers, whereas pre-existing inherent resilience measures must be undertaken by each customer individually. A key unknown is the potential for mitigation scale economies, namely, whether lumpy upstream backup capacity investments might actually be less than the individually smaller direct and indirect costs incurred by numerous downstream customers, and whether the benefits of such heterogeneous, uncoordinated expenditures exceed those of shorter duration of less geographically widespread power disruptions. Unfortunately, capturing these processes requires substantial extensions to our simple modeling framework, and so we defer them to future inquiry.

Finally, an important limitation of our analysis is that does not consider adaptive resilience. For example, conservation—i.e., price and non-price induced input-saving technical change by producers and consumers—is an important tactic that, all else equal, may temporarily preserve the levels of output and consumption. Other post-outage adaptive resilience measures, such as production recapture (temporarily scheduling additional shifts post-outage, taking advantage of normal slack capacity to make up for forgone output), can be low as well, depending on the benchmark economy's equilibrium level of slack capacity. However, the cost advantage of adaptive resilience is that it need not be implemented until the outage has taken place. In risk-benefit modeling, advance expenditures on inherent resilience or infrastructure hardening are balanced against mitigation benefits that must be multiplied by the probability of occurrence of a hazard. However, in the case of adaptive resilience, costs and benefits both arise only in the event of a disruption. The inherent resilience of firms' input substitution or spatial reallocation of production also need not be multiplied by this probability. The benchmark regional economy embodies the possibilities to do so, but actual substitutions do not need to take place unless an outage occurs.

How then might our analysis inform the development and application of CGE models to analyze electricity disruptions' broader economic consequences? It is important to realize that a more sophisticated economic simulation model will still be subject to many of the uncertainties that have proved difficult to constrain in the present framework, but at least are capable of being dealt with parametrically. This highlights the need to steer well clear of the trap of spurious precision: while elaborating the present model to include multiple sectors and household groups can certainly yield additional insights, that in itself is no guarantee that the resulting impacts will be accurate. This point is especially relevant given that the substitution possibilities on which the ultimate general equilibrium consequences depend need to be captured by elasticity parameters that are unlikely to be empirically validated at the fine sectoral, spatial and temporal disaggregation necessary to capture the impact of power disruptions. Indeed, if the length of the blackout being investigated is sufficiently brief, CGE models may not be the appropriate analytical tool, as the assumption of equilibrium implicitly assumes that adjustments take place over the so-called economic “short period”, the approximately 6-month horizon on which producers and consumers detect price signals and alter their behavior in ways that enable markets to clear. At the same time, our model is one of disequilibrium analysis in relation to a power outage shock. Moreover, substitution elasticities can be constrained to very low levels representing limited equilibrium adjustment possibilities in the short period. A related point is that 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 preceding 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 coming to fruition, we feel 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.

CRediT authorship contribution statement

Ian Sue Wing: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition.**Adam Z. Rose:**Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2020.104756.

References

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

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

Alby, P., Dethier, J.-J., Straub, S., 2012. Firms operating under electricity constraints in developing countries. World Bank Econ. Rev. 27, 109–132.

Allcott, H., Collard-Wexler, A., O'Connell, S., 2016. How do electricity shortages affect industry? Evidence from India. Am. Econ. Rev. 106, 587–624.

Anderson, T., Dalgaard, C.-J., 2013. Power outages and economic growth in Africa. Energy Econ. 38, 19–23.

Baik, S., Davis, A., Morgan, G., 2018. Assessing the cost of large-scale power outages to residential customers. Risk Anal. 38, 283–296.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuk, M., Tierney, K., Wallace, W., Von Winterfeldt, D., 2003. A framework to quantitatively assess and enhance seismic resilience of communities. Earthquake Spectra 19, 733–752.

Burlando, A., 2014. Transitory shocks and birth weights: evidence from a blackout in Zanzibar. J. Dev. Econ. 108, 154–168.

Çağnan, Z., Davidson, R., Guikema, S., 2006. Post-earthquake restoration planning for Los Angeles electric power. Earthquake Spectra 22 (3), 589–608.

Chen, Z., Rose, A., Prager, F., Chatterjee, S., 2018. Economic consequences of aviation system disruptions: a reduced-form computable general equilibrium analysis. Transp. Res. A 95, 207–226.

Detweiler, S.T., Wein, A., 2017. The HayWired earthquake scenario. Earthquake Hazards: U.S. Geological Survey Scientific Investigations Report No. 2017-5013. https://doi.org/10.3133/sir20175013v1.

Eto, J.H., LaCommare, K.H., Larsen, P., Todd, A., Fisher, E., 2012. *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).

Farrow, S., Rose, A., 2018. Welfare analysis: bridging the partial and general equilibrium divide for policy analysis. J. Benefit-Cost Analysis 9 (1), 67–83.

Fisher-Vanden, K., Mansur, E., Wang, Q., 2015. Electricity shortages and firm productivity: evidence from China's industrial firms. J. Dev. Econ. 114, 172–188.

Fullerton, D., Metcalf, G., 2002. Tax incidence. Handbook of Public Economics 4, 1787–1872.

Greenberg, M., Mantell, N., Lahr, M., Felder, F., Zimmerman, R., 2007. Short and intermediate economic impacts of a terrorist-initiated loss of electric power: case study of New Jersey. Energy Policy 35, 722–733.

Harish, S., Morgan, G., Subrahmanian, E., 2014. When does unreliable grid supply become unacceptable policy? Costs of power supply and outages in rural India. Energy Policy 68, 158–169.

Kajitani, Y., Tatano, H., 2009. Estimation of lifeline resilience factors based on empirical surveys of Japanese industries. Earthquake Spectra 25 (4), 755–776.

Lanzi, E., Sue Wing, I., 2013. Capital malleability, emission leakage and the cost of partial climate policies: general equilibrium analysis of the European Union emission trading system. Environ. Resour. Econ. 55, 257–289.

National Research Council, 2017. Enhancing the Resilience of the Nation's Electricity System. National Academies Press, Washington, DC.

Rose, A., 2007. Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. Environmental Hazards 7, 383–398.

Rose, A., 2009. Economic resilience to disasters. Community and Regional Resilience Institute Report No. 8. Oak Ridge National Laboratory, Oak Ridge, TN.

Rose, A., 2017. Benefit-cost analysis of economic resilience actions. In: Cutter, S. (Ed.), Oxford Research Encyclopedia of Natural Hazard Science. Oxford, New York.

Rose, A., 2018. Incorporating cyber resilience into computable general equilibrium models. In: Okuyama, Y., Rose, A. (Eds.), Modeling Spatial and Economic Impacts of Disasters. Springer, Heidelberg.

Rose, A., Liao, S., 2005. Modeling regional economic resilience to disasters: a computable general equilibrium analysis of water service disruptions. J. Reg. Sci. 45 (1), 75–112.

Rose, A., Lim, D., 2002. Business interruption losses from natural hazards: conceptual and methodology issues in the case of the Northridge earthquake. Environmental Hazards: Human and Social Dimensions 4, 1–14.

Rose, A., Oladosu, G., Salvino, D., 2005. Economic impacts of electricity outages in Los Angeles: the importance of resilience and general equilibrium effects. In: Crew, M.A., Spiegel, M. (Eds.), Obtaining the Best From Regulation and Competition. Springer Science.

Rose, G.A., Oladosu, Liao, S., 2007. Business interruption impacts of a terrorist attack on the electric power system of Los Angeles: customer resilience to a total blackout. Risk Anal. 27 (3), 513–531.

Rose, A., Prager, F., Chen, Z., Chatterjee, S., 2017. Economic Consequence Analysis of Disasters: The E-CAT Software Tool. Springer, Singapore.

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

Shawhan, D., 2019. Using stated preferences to estimate the value of avoiding power outages: a commentary with input from six continents. In: Larsen, P., Sanstad, A., LaCommare, K., Eto, J. (Eds.), Frontiers in the Economics of Widespread, Long-duration Power Interruptions: Proceedings From an Expert Workshop. Lawrence Berkeley National Laboratory.

Steinbuks, J., Foster, V., 2010. When do firms generate? Evidence on in-house electricity supply in Africa. Energy Econ. 32, 505–514.

Sue Wing, I., 2008. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technology detail in a social accounting framework. Energy Econ. 30, 547–573.

Sue Wing, I, Balistreri, E, 2018. Computable general equilibrium models for economic policy evaluation and economic consequence analysis. Oxford University Press Handbook on Computational Economics and Finance. Oxford University Press.

Sue Wing, I., Rose, A., Wein, A., 2016. Economic consequence analysis of the ARkStorm scenario. Natural Hazards Review 17 (4), A4015002-1.

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

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

Sullivan, M., Collins, M., Schellenberg, J., Larsen, P., 2018. Estimating Power System Interruption Costs: A Guidebook for Electric Utilities. Lawrence Berkeley National Laboratory.

Xie, W., Rose, A., Li, S., He, J., Li, N., Ali, T., Wei, W., 2018. Dynamic economic resilience and economic recovery from disasters: a quantitative assessment. Risk Anal. 38 (6), 1306–1318.