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Effects of Climate Change in Electric Power Infrastructures

Daniel Burillo

Abstract

Climate change mitigation and adaptation has been a major driving force to modernize electric power infrastructure and include more renewable energy systems. This chapter explains several ways in which electric power infrastructure has contributed to climate change, how climate change affects electric power infrastructure, mitigation options, and adaptation options. Electricity infrastructure categories include power generation technologies, transmission lines, substations, and building loads. Climate change categories include atmospheric greenhouse gas concentration levels, rising sea levels, changes in precipitation patterns and river flows, as well as more extreme air temperatures. Specific quantitative case studies are provided to estimate vulnerabilities from heat waves in the US desert southwest, including long-term forecasting of infrastructure performance, as well as, various supply-side and demand-side strategic options to maintain reliable operations.

Keywords: climate change, risk management, demand forecast, load volatility, vulnerability, failure prediction, outage prediction, long-term planning

1. Introduction

Climate change occurs because of both natural and human causes. A geographic area that has a particular prevailing weather condition is said to have a particular climate [1, 2]. Over the course of time, earth has gone through several global climate changes, including the asteroid that killed the dinosaurs [3], the ice ages, and the warm period that we are in now [4]. Specific regions of the earth have also gone through local climate changes due to large storms, earthquakes, and volcanic eruptions that mostly only affect the target locations [5, 6]. Since human civilizations started intelligently designing ecosystems by channeling water, doing agriculture, building cities, and so on—we have been intentionally, and sometimes unintentionally, changing climates as well.

Civilization arguably did not start contributing to climate change at a global scale until after the industrial revolution with the proliferation of coal-powered steam engines and the burning of fossil fuels into the air [7]. The portable energy transformation device was revolutionary; the abundance with which humans lived and moved increased dramatically. Then, in 1896, Swedish chemist Svante Arrhenius estimated that the long-term effects of coal burning would enhance the natural greenhouse effect, and that a doubling of carbon dioxide in the atmosphere would warm the earth a few degrees Celsius. Modern-day climate models have maintained Arrhenius's conclusion, and only added more specifics to the predictions, with

details such as less average freezing at the earth's poles, higher sea level, more forceful storms, and various different weather patterns in particular geographies [8, 9]. Oil spills, trash barges, mass pavement, deforestation, various air-borne pollutants, and so on have also affected earth's ecosystems and climates [10].

Climate change is now affecting infrastructure systems by changing the weather conditions in which they must operate. The United States Department of Homeland Security has defined 16 critical infrastructure sectors that are considered vital to the “security, national economic security, and national public health or safety” of the country [11]. These critical infrastructure sectors are: chemicals, commercial facilities, communications, critical manufacturing, dams, defense, emergency services, energy, financial services, food and agriculture, government facilities, healthcare and public health, information technology, nuclear, transportation, and water and wastewater systems [11]. Across these infrastructure sectors, climate change will impact physical assets, operations, and use [12, 13]. As public awareness of the risks of climate change has risen, vulnerability assessments and adaption planning studies have been rapidly emerging in recent years too [13–16].

Climate is typically considered in infrastructure system designs by using several years' recent weather conditions to specify tolerances. This can be problematic for two reasons. First, because weather is not exactly the same every year, and more robust hardware is typically costlier, investors are often faced with tough risk management problems for low-probability high-impact events. Second, climates are changing. Thanks to advancements in global climate modeling, researchers are now able to forecast changes in future climate conditions and plan for extreme weather conditions with higher confidence. Climate change assessments generally rely on scenarios standardized by the Intergovernmental Panel on Climate Change (IPCC) [17]; however other considerations are made as well for factors such as the anthropogenic change in urban environments [18, 19]. The IPCC standard scenarios are referred to as Representative Concentration Pathways (RCPs), and are numbered corresponding to the amount of radiation forcing increase from the sun associated with the greenhouse gas effect relative to pre-industrial times, for example, RCP 4.5 and RCP 8.5 (4.5 and 8.5 W/m²) [20, 21].

The newest technological advancements in climate change modeling and long-term weather forecasting include high-resolution spatial projections based on “downscaling” techniques. These downscaling techniques aim to improve the geographic and temporal resolution of specific weather projections, including air temperature, wind speed, solar radiation, precipitation, snowpack, and hydrology for specific geographic regions [22–27]. However, challenges still exist in incorporating climate change data into practice [28–30]. These challenges range from a lack of understanding of what parameters to use in complex models, to the methods used in the models, to what to do about the results. Significant literature is emerging to disentangle the contribution of different mechanisms to the response patterns, yielding more transparent models and results [31]. Further solutions to these challenges are expected to be met through ongoing collaboration between climate scientists and engineers, which we have included examples for in this chapter for electricity infrastructure and heat waves.

2. Electricity infrastructure vulnerabilities to climate change

Electric power infrastructure broadly consists of three systems: generation, delivery, and demand. In terms of the physical processes, electrical power is created by generators to meet demand via delivery hardware. In terms of functionality however, it is the demand for electric power that drives the development of the

other two systems. Reliable electric power is central to urban development, and is a critical service in modern cities as almost all other major infrastructure and services rely on it: commerce, communication, manufacturing, defense, emergency, finance, agriculture, healthcare, information technology, transportation, and water [32]. Climate change can affect energy trade over time in ways that are significant to economics and natural resource consumption. For example, more extreme summer and winter temperatures necessarily result in more demand for cooling and heating, respectively. Climate change can also affect electric service reliability. A shortage of electric power generation, or sequence of faults in the delivery network, can result in an interruption in service at any second. This is why generation and delivery systems are built with multiple redundancies, such that individual component outages can occur safely. Unless there are multiple simultaneous outages, the infrastructure system can still deliver power to buildings and other loads without an interruption in service. **Table 1** provides a summary of major climate variables and their associated impacts on the power sector, adapted from [33].

Generation is vulnerable to flooding, reduced streamflow, warmer water, and warmer air temperatures, which can all cause a shortage of power supply in the system [34]. There are many ways to physically generate electric power, but to evaluate the effects of climate change we have chosen to broadly categorize them as those that use water, and those that do not as follows. Conventional hydroelectric and water-cooled turbine generators (e.g., nuclear, coal-fired, and some natural gas) use water, and so are vulnerable to changes in three ways. First, flooding can damage physical hardware of above and below ground equipment if that hardware is not sufficiently shielded [35]. For example, sea level is projected to rise by 1–1.4 m by the end of the century, and if that is the case, then 25 coastal plants in California will be at risk of flooding during 1-in-100 year high-tide events [36]. Second, if the water levels in natural sources are too low (e.g., low river flow during droughts), then production capacity can be dependent upon priority level in access rights or reduced to zero if the water level physically goes below the intake pipe [37]. Third, some once-through generators are vulnerable to increases in water temperature in coastal plants, as a certain amount of temperature rise is necessary to cool the generators. Environmental regulations prevent expelling of water that is too hot to be safe for the ecosystem [38]. In August of 2015, the Pilgrim Nuclear Power Station in Massachusetts cut its power because the temperature of sea water used as influent was too high [39]. Power generators that do not use water include dry combustion natural gas and solar photovoltaics. These types of “dry” power generators are generally inland and could be at risk of flooding if they are located in a basin-like landscape that would collect water from a storm. Dry power generators also operate less efficiently under higher ambient air temperatures, which mean they also have lower production capacity to meet peak demand [40]. Dry generators are also vulnerable to changes in humidity that can affect their air circulation systems, as well as flooding and storm-gusty winds in general [33].

Delivery systems can be affected by climate change due to higher temperatures causing higher demand, reduced capacity, and congestion; wildfires that can render power lines inoperable due to ionized air; and large storms that can cause physical damage via flooding and high winds that make trees fall on lines [41]. Delivery systems physically consist of various types of power lines that transport energy, transformers which convert the power to different voltage levels, quality devices for efficiency and reliability, and protection devices that interrupt power flows during hazardous conditions. Climate change can cause failures via physical hardware damage or create operational conditions that exceed hardware tolerances. Higher temperatures can cause individual components to become inoperable because protection devices will cut them off if power flow is too high for the weather

Climate hazard	Key impacts	Impacted segment	Adaptation strategies
Increased air temperatures	<ul style="list-style-type: none"> • Lower generation efficiency • Decreased coal-to-gas conversion efficiency • Decreased combined cycle gas turbine efficiency • Decreased solar PV efficiency 	Generation	<ul style="list-style-type: none"> • Implement air chillers or more efficient chillers • Site new generation in cooler locations
	<ul style="list-style-type: none"> • Reduced carrying capacity of lines and transformers • Increased losses in lines and transformers 	Delivery-Transmission & Distribution	<ul style="list-style-type: none"> • Underground hardware • Use more heat-resistant materials • Implement more effective cooling for transformers
	<ul style="list-style-type: none"> • Increased peak demand and total energy demand for cooling 	Demand-End Use	<ul style="list-style-type: none"> • AC energy efficiency • Building thermal efficiency • Peak load shifting
Increase in precipitation	<ul style="list-style-type: none"> • Reduced combustion efficiency due to increased moisture content of coal 	Generation	<ul style="list-style-type: none"> • Protect coal stockpiles • Switch to fuel that is more moisture resistant (e.g., natural gas)
	<ul style="list-style-type: none"> • Damaged power lines from snow and ice • Flooding of underground infrastructure • Damaged towers due to erosion 	Delivery-Transmission & Distribution	<ul style="list-style-type: none"> • Improved flood protection for equipment at ground level • Use covered and/or insulated conductors • Include lightning protection (e.g., earth wires, spark gaps) in the distribution network
	<ul style="list-style-type: none"> • Decreased availability of freshwater for thermal cooling 	Generation	<ul style="list-style-type: none"> • Switch to recirculating or dry cooling • Switch to more “water-efficient” fuels (e.g., natural gas, wind, solar) • Increase volume of water treatment system • Restore/reforest land
Sea level rise/increased storm surge during hurricanes and tropical storms/increased nuisance flooding during high tides	<ul style="list-style-type: none"> • Flooding/damage to coastal/low-lying infrastructure 	Generation/delivery-Transmission and Distribution Demand-End use	<ul style="list-style-type: none"> • Implement flood control (dams, dikes, reservoirs, polders, etc.) • Improve coastal defenses (seawalls, bulkheads, etc.) • Build in and/or relocate to less exposed locations • Raise structure levels • Improved drainage systems • Protect fuel storage

Climate hazard	Key impacts	Impacted segment	Adaptation strategies
More frequent/severe extreme events (floods, typhoons, drought, high winds, etc.)	<ul style="list-style-type: none"> • Damaged infrastructure • Disrupted supply chains and offshore activity • Damage to facilities related to soil erosion 	Generation Delivery-Transmission and Distribution	<ul style="list-style-type: none"> • Same as above • Concrete-sided buildings instead of metal • Implement more rigorous structural standards • Implement porous materials for better wind flow • Increased decentralized energy generation • Cite infrastructure away from heavily wooded areas/rigorously prune trees

Table 1.
 Summary of key climate drivers and possible impacts to power systems.

conditions [42]. Additionally, higher temperatures can result in reduced capacity for above ground power lines to safely carry electricity. If too many components are offline or the capacity of the system is significantly reduced, then power may not be available when it is needed causing cascading failures and blackouts as happened in the US in 2003 and 2011 [43, 44]. Alternatively, if protection devices are not properly calibrated, then components can overheat. This has happened to hundreds of distribution-level transformers during recent record breaking heat waves in the US southwest [45]. Moreover, lines can sag to the point that they permanently deform. Not coincidentally, during these record-breaking heat waves, the air is very dry, and the risk of wildfires is high. If wildfires burn under power lines, then those components can fail as well due to air ionization. Like generators, substations are vulnerable to rising sea levels and storm floods near the coast and in basin-like land areas [36]. Flooding can erode or short the hardware in substations and underground power lines [33]. Lastly, severe storms can blow trees, and other things, into power lines and cause outages.

Electric power demand is primarily susceptible to higher air temperatures, which can increase both total energy consumption and the peak demand in regions with significant electric air conditioning [40, 46, 47]. Demand is typically planned for at city- and state-level geographies based on seasonal weather usage patterns, daily weather usage patterns, and local use patterns. In warm to hot climates, the peak electricity demand is usually in the late afternoon during the summer when businesses are still operating and people are coming home and turning on air conditioners [48]. Historically, preparing for higher peak demand means building additional generation and delivery capacity, but policies aimed at natural resource conservation have targeted building and appliance energy efficiency standards which also offset increases in peak demand [40]. In terms of climate change, higher average temperatures and higher maximum temperatures mean more demand for AC usage, which could mean more energy usage over time, higher power demand for ACs to operate at hotter temperatures, and more installations of ACs total in moderately warm climates. The combined effects could be a significant increase in per capita demand [40]. This may be more than local delivery infrastructure are capable of supporting without systemic or network-wide investments [49].

3. How heat waves can result in service interruptions

The fault tree in **Figure 1** shows the terminal event of a service interruption on the right, and the power- and material/hardware-based-failures that can lead to a service interruption logically proceeding from the left [50]. Hardware failures feed-back into the event triggers as their loss of functionality results in a loss of power-flow that could cause an interruption. System operators generally maintain an $n - 1$ redundancy standard in design at the high-voltage transmission level meaning that the single largest generator, transmission line branch, or substation can fail

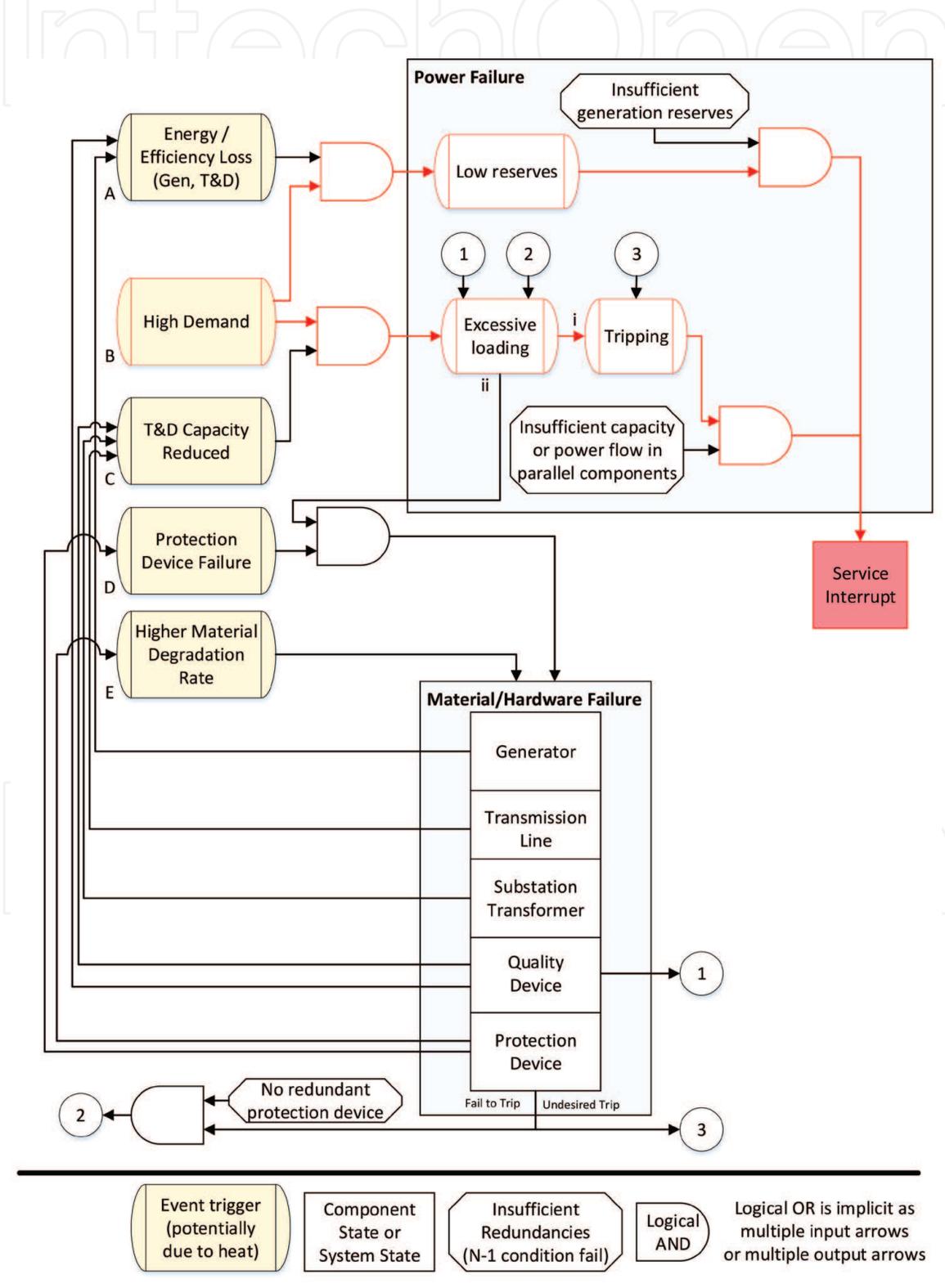


Figure 1.
 Fault tree from heat wave to service interruption.

at any time without any interruption in service [51]. These $n - 1$ redundancies are represented by octagon boxes and logical AND gates in the figure. Service interruptions due to major component failures only occur when more than one individual component fails at the same time. Such events can lead to cascading failures including blackouts as in the 2011 Arizona-California blackout [52]. The pathway for high demand is colored red because it is a critical condition for a service interruption in a system protected with multiple redundancies.

The two ways that a service interruption can occur as a function of purely rising air temperatures are that there is either not enough total generation to meet total demand, or particular power lines and substations do not have sufficient capacity to deliver power to loads. The following list explains how increases in ambient air temperatures can trigger failures leading to service interruptions consistent with the lettering in **Figure 1**.

- a. High air temperatures can result in loss of generation capacity and loss of efficiency in the transmission and distribution (T&D) network [36, 53]. If the system is also in high demand, (B), then load can exceed generation. If there are insufficient generation reserves, then there will be a service interruption.
- b. High air temperatures can result in higher demand, especially during the already hot summer months due to increased burden on building air conditioning systems [53].
- c. High air temperatures result in less capacity in T&D lines and transformers [36, 53]. If a circuit is in high demand, then power flow can result in components' temperatures exceeding safe operating temperatures [52].
 - i. If protection devices function correctly, then they will trip (open) the circuit under excessive loading and power flow will be instantaneously redistributed to parallel T&D components [52]. If there is insufficient capacity in parallel branches to deliver power to the load, then there will be a service interruption [52].
 - ii. If a protection device fails to trip and a circuit is over loaded, then excess heat accelerates the chemical degradation rate of sensitive materials and can result in mechanical failure (E) [54, 55]. Protection devices can fail because they are not accurately designed or calibrated for local climate conditions or other reasons [56]. Depending on the type and location of overload failure, a generator, transmission line, substation, quality device, or other protection device can fail. If a generator fails, then the system state goes to (A) as the system now has less generation. If a line or transformer fails, then the system goes to (C) as the T&D network operates at lower efficiency and or has less power flow capacity. If a power quality device fails, then it goes to (A) or (C) again or directly to excessive loading depending on the circumstances. If another redundant protection device fails, then the cycle of potential failures repeats for additional components on connected circuits.
- d. High air temperatures can result in a protection device failing to trip [56]. The device could be calibrated to a certain power rating that should be lower for the actual air temperature. If that occurs during high loading, then a component can become overloaded and fail as in (ii).
- e. High air temperatures can result in an accelerated physical material degradation rate, which can result in accelerated failures for any electrical devices [57]. The

same failure scenarios can occur as described above, with the addition of an undesired trip of a protection device. If a protection device fails with an undesired trip, and there is no redundant power flow, then a service interruption occurs.

4. Case study 1: quick estimate of peak demand for record-breaking heat waves

How can we know how much electricity demand there will be if weather conditions are more severe than they have ever been in the past? With no past records, how can we know what the future will be? How do we know if there will be sufficient generation resources to meet the demand? These are not straightforward questions to answer as demand and generation are, at the city scale, rather complicated with millions of moving parts. In this case study, adapted from Burillo et al. [40], we show how analysts can produce a reasonable city-scale predictive model using basic computational tools, and simple publicly available data for buildings, electricity demand, and air temperature.

We will consider Phoenix, Arizona and Los Angeles, California as regions because they have summertime peak demands with significant air conditioner (AC) penetration, and are expected to have higher air temperatures in the future with climate change [58–60]. A simple approach to predicting peak demand for future temperatures would be to plot daily peak electricity demand against daily maximum air temperatures, T_{max} , and draw a straight line, but doing so would be an oversimplification as it results in an overestimate of demand. Overestimating peak demand would be very costly from a planning perspective because it would inflate delivery capacity and resource adequacy requirements. Instead, we are going to use regression techniques to fit the structural equation model (SEM) developed in [40] using the number of residential and commercial utility customers, daily peak demand data for those customers, the air conditioning penetration percent from the county assessor's office, and daily T_{max} .

A full explanation of the theory and equations are in [40], but the concept in brief has two main parts as follows. First, at a micro-scale, as outdoor thermal forces (sunlight and air temperature) increase, the work that individual ACs do increases and so does their electrical load. In our prior study, we found that the most common AC units (split indoor-outdoor dry air-cooled) have an increase in active load of 1.33% kW per $1^{\circ}\text{C} \pm 0.35\%$. Second, at a macro scale, AC duty cycles increase proportional to the ratio of incoming and outgoing building thermal energy at the thermostat set point. At higher T_{max} , the number of ACs simultaneously active in a region during the peak period increases as well up to a theoretical limit of 100%. This behavior can be effectively modeled in the form of an s-curve.

The results for the peak demand SEM are shown in **Figure 2** compared to a straight-line approach. Peak demand in Phoenix is more sensitive to average historical seasonal changes in air temperatures than Los Angeles, but results show that *marginal* changes in peak demand are more significant in Los Angeles than in Phoenix at summertime highs. Peak demand for Phoenix increased more in its historical range because its 90th percentile, T_{90} , was relatively higher, and Phoenix has higher AC penetration. From historical T_{90} to the highest projected T_{max} however, peak demand increased more in Los Angeles than Phoenix, another 3.9 GW vs. 1.2 GW or 34 vs. 16%. In this case, the larger increase in peak demand in Los Angeles was due to the larger relative difference between historical T_{90} and future T_{max} . As shown in **Figure 2b**, Phoenix's ACs expect to already be running at nearly 100% duty cycle at its T_{90} , whereas Los Angeles's ACs expect to only run at about 60% duty cycle at its T_{90} . Thus, the potential for a record-breaking heat wave to affect peak demand is higher in Los Angeles than Phoenix.

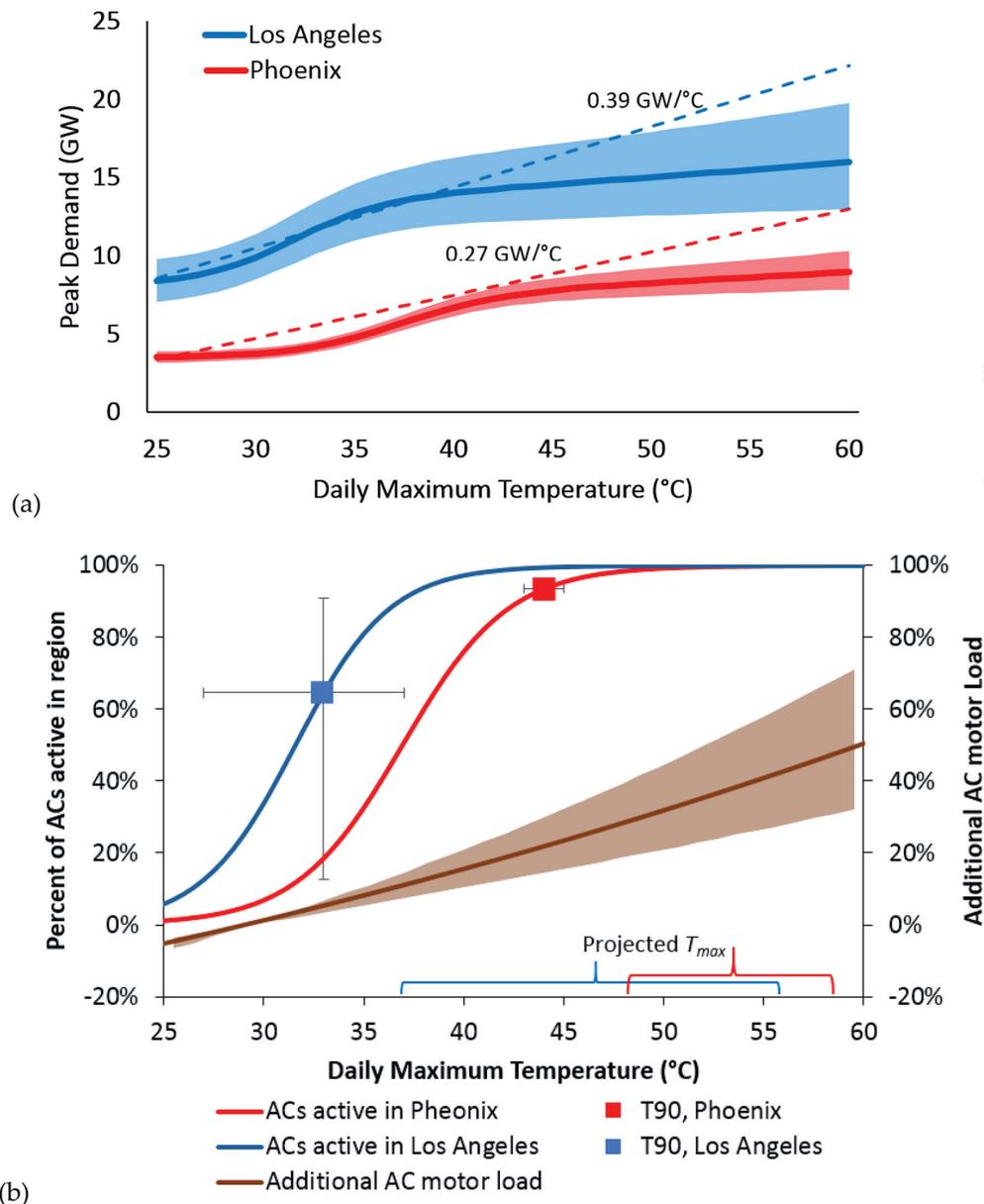


Figure 2. (a) Peak demand. (b) Peak demand SEM factors. (a) Shows SEM approach results in solids. Straight-line approach shown in dotted lines. (b) Shows the two s-curved lines are expected values. T90 ranges represent the range of 90th percentile values for the locations sampled.

5. Case study 2: using downscaled climate data to inform long-term demand forecasts and capital infrastructure planning

While city-scale blackouts often make for bigger headlines in the news, neighborhood-scale outages are much more common. In the last case study, we saw how forecasting peak electricity demand was critical for planning generation resource capacity, and how those efforts could be enhanced with better quantitative understanding of climate change. In this case study, based on [61], we incorporate climate change projections at the next level in electricity infrastructure planning and consider the highly complex problem of siting and sizing delivery component capacities.

It is not enough to simply have generation resources in the same city as loads. There must also be lines, substations, and transformers to get the power from the generators to the users, and each of those have their own capacities which are a function of how hot the devices can safely operate at. Where and how should we build immovable field assets with 30–70-year useable life spans? How do we know what the urban landscape,

the buildings, the appliance technology, the population, and so on will look like that far into the future? Doing this well is a highly coordinated effort with many steps and iterations across multiple planning departments, as we shall get a taste for below.

If we are going to attempt to model a map of the future infrastructure requirements with any accuracy, then first we need a model that produces an accurate map of current conditions. The full details of our approach are described in Ref. [61], and the concept at brief is as follows. We used high-resolution (2 km^2) data for daily maximum ambient air temperatures (T_{max}), residential and commercial building models calibrated for the region, a geographic map of the buildings' locations, and a geographic map of lines and substations. With these tools and data we are able to validate a map of the base period (2010) electric power demand and infrastructure loading in Los Angeles County, California as shown in **Figure 3**.

With a reasonably accurate and verified model of base period electricity demand, and initial loading on delivery hardware, we can use historical climate data to estimate overloading risks in the base period. We do this by re-running our models with the composite image of the highest temperature values that historically occurred in any location at any historical period in time. We also use that temperature image to estimate the reduced capacity on infrastructure hardware. Combining the two together, we can compute the thermally de-rated load factors on hardware as shown in **Figure 4** for substations with corresponding definitions in **Table 2**.

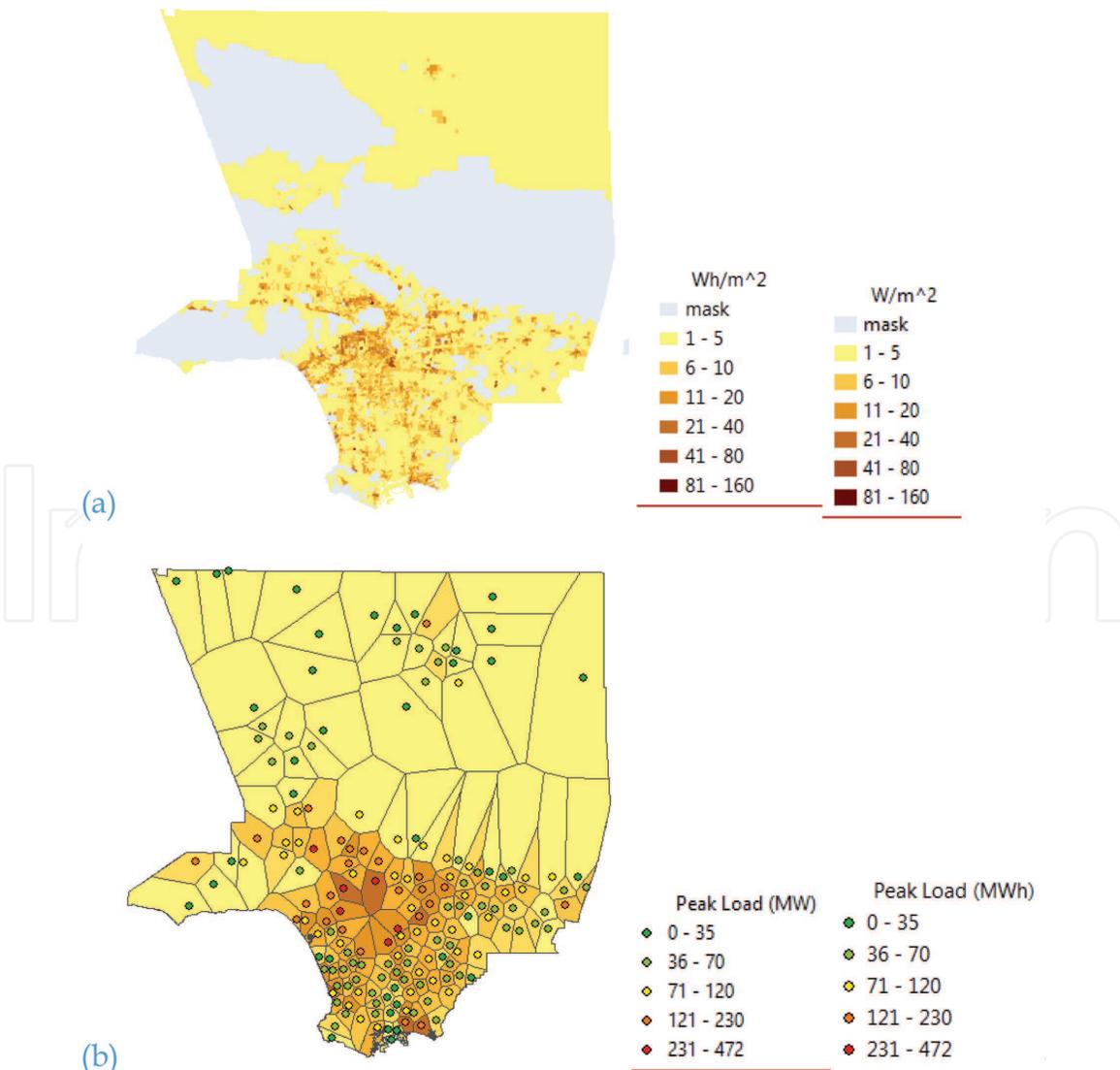


Figure 3. Map of Los Angeles County, California. (a) Peak demand and (b) substation loading in base period.

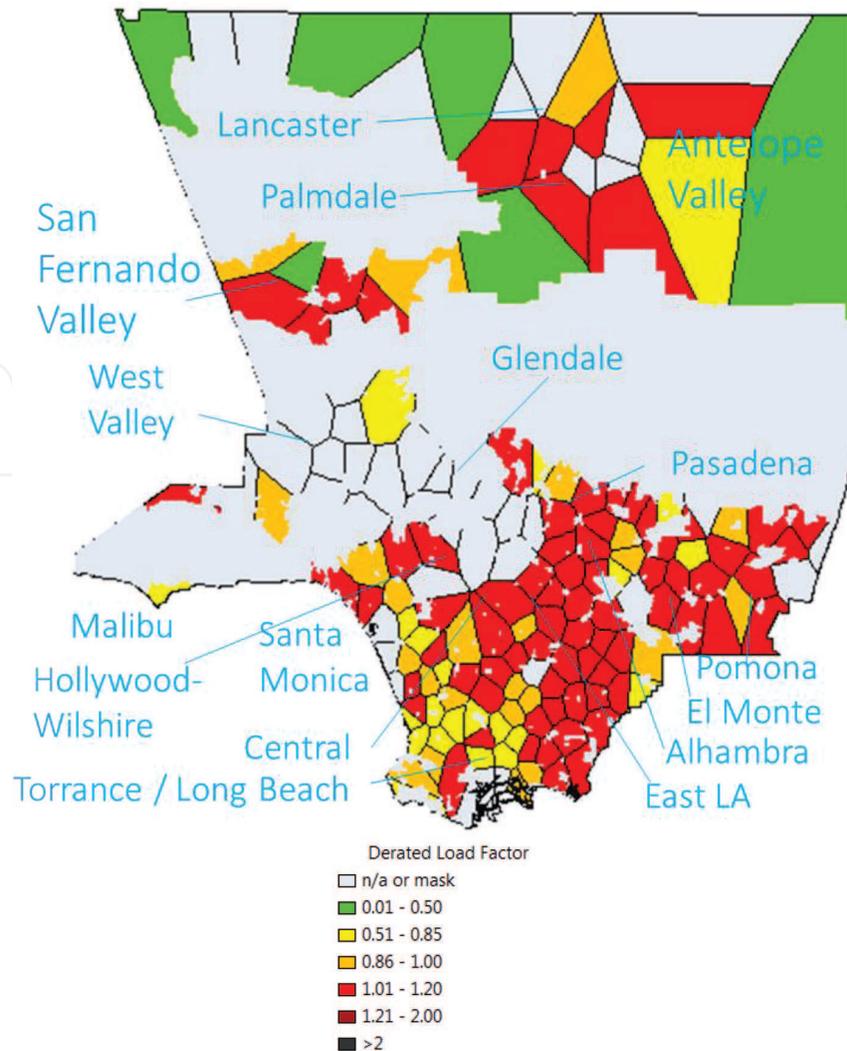


Figure 4.
 Map of Los Angeles County, California substation risks in base period.

Load factor	Risk level	Reference	Description
n/a	Unknown	n/a	Substation(s) exists in this space according to national database [1], but not shown in SCE DERiM [2], so load factor data were unavailable
0.01–0.5	Very safe	Assumption	Negligible thermal wear, probably n – 2 reliable if in parallel/redundant configuration
0.51–0.85	Safe	15% rule	Very low thermal wear, probably n – 1 reliable if in parallel/redundant configuration
0.86–1.00	Caution	15% rule	Some thermal wear, probably not n – 1 reliable
1.01–1.20	Warning	[3, 4]	Moderate thermal wear, component overloaded, automatic switching may occur within 24 h to 30 days if loading continues at this level depending upon switch gear settings
1.21–2.00	Emergency	[3, 4]	Significant thermal wear, component very overloaded, automatic switching may occur within 30 min depending upon switch gear settings
>2	Outage	[4]	Extreme thermal wear, switchgear will automatically trip to prevent combustion and permanent hardware damage

Table 2.
 Substation derated load factor risk metrics.

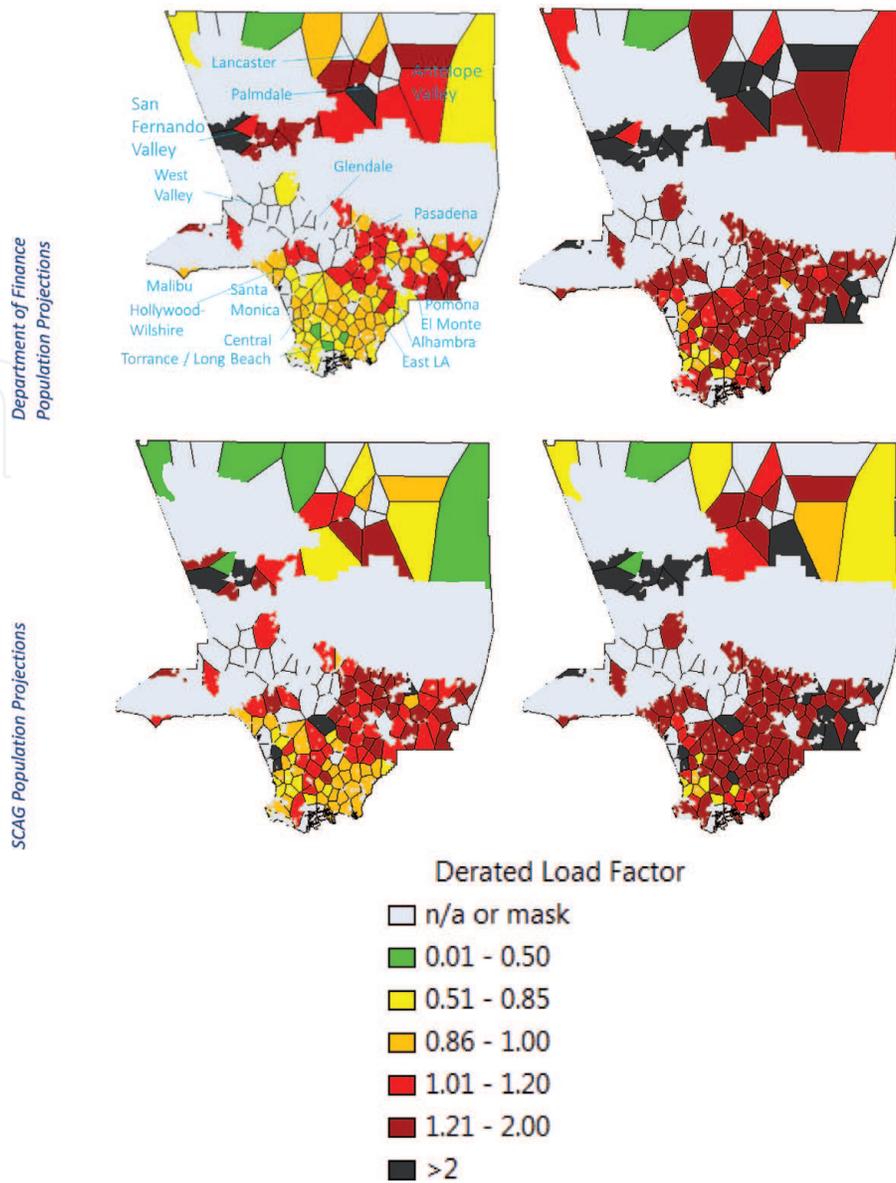


Figure 5.
Map of Substation Risks by 2060.

We can now forecast into the future for a variety of factors. In this case, we considered rising air temperatures, population growth, building stock turnover, housing densification, air conditioning penetration, and air conditioning efficiency. All of these factors were technically specified in either the building energy models or at the census block group in making spatial allocations to the maps. The results are shown for two population growth scenarios, and two energy efficiency scenarios for substation loading in **Figure 5**. This is what the peak hour could look like during a heat wave in 2060 with the same infrastructure as in the base period. Specific cities and neighborhoods are identified as being at risk of overloading and outages as shown in **Figure 5**.

6. Climate change risk mitigation and adaptation options in the electric power sector

There are many ways to maintain stability in electric power systems in light of climate change. Several mitigation and adaptation options are listed in **Figure 6** for our case studies of insufficient supply-side resources during rising air temperatures, with effects on stability and other factors important for consideration as well. We categorically consider several options in the form of technology implementations, market

Options / Effects		Resource adequacy				Other factors				
		Climate-independent peak load	Climate-dependent peak load	Bulk gen. & transmission capacity	Load variance	Total energy consumption	Power quality	Power congestion	Water use	Greenhouse Gas emissions
Technology implementation										
Resources	Distributed solar PV without VAR control	↓	↓	-	↓	-	↓	↓	-	-
	Distributed solar PV with smart-inverter & energy storage	↓	↓	-	↓	-	↑	↓	-	-
	Combined cycle natural gas plant	-	-	↑	-	-	↑	↑	↑	↑
	Nuclear power plant	-	-	↑	-	-	↑	↑	↑	-
Loads	General appliances: higher energy efficiency standards	↓	↓	-	↓	↓	-	↓	-	↓
	ACs: variable speed motors for refrigerant systems	-	-	-	-	-	↑	-	-	-
	ACs: dual-systems with ice thermal storage	-	↓	-	↓	-	-	↓	↑	-
	ACs: water-based evaporative systems	-	↓	-	↓	↓	↑	↓	↑	↓
Market incentives										
Util.	Utility profits dependent on energy sales	↑	↑	-	↑	↑	-	↑	-	↑
	Utility profits dependent on load consistency	↓	↓	-	↓	↓	-	↓	-	↓
Ratepayer	Time-of-use rates with summertime super-peak	↓	↓	-	↓	-	-	↓	-	-
	Demand response incentives	↓	↓	-	↓	-	-	↓	-	↑
	Economically viable prosumer options	↓	↓	-	↓	-	-	↓	-	↓
	Energy efficiency rebates	↓	↓	-	↓	↓	-	↓	-	↓
Urban form										
	High-density transit oriented development	↓	↓	-	↓	↓	-	-	↓	↓
	High building albedo and shading	↓	↓	-	↓	↓	-	↓	-	↓
	High building thermal insulation	↓	↓	-	↓	↓	-	↓	-	↓

Options / Effects		Stability factors				Other factors				
		Peak load, normal	Peak load, heatwave	Load variance	Delivery congestion	Power quality	Total energy consumption	Water use	Air emission	Land use
Technology implementation										
Resources	Distributed - solar PV without VAR control or storage	↓	↓	↓	↓	↑	-	-	-	-
	Distributed - solar PV with smart-inverter & storage	↓	↓	↓	↓	↑	-	-	-	-
	Central - CCNG, nuclear, or other	-	-	-	↑	↑	-	↑	↑	↑
	Imports, long distance transmission	-	-	-	↑	↑	-	-	-	↑
Loads	Appliances: higher energy efficiency standards	↓	↓	↓	↓	-	↓	-	↓	-
	ACs: peak performance metric	-	-	-	-	↑	-	-	-	-
	ACs: dual-systems with ice thermal storage	-	↓	↓	↓	-	-	↑	-	-
	ACs: water-based evaporative systems	-	↓	↓	↓	↑	↓	↑	↓	-
Market incentives										
Util.	Utility profits dependent on energy sales	↑	↑	↑	↑	-	↑	-	↑	-
	Utility profits dependent on load consistency	↓	↓	↓	↓	-	↓	-	↓	-
Ratepayer	Time-of-use rates with summertime super-peak	↓	↓	↓	↓	-	-	-	-	-
	Demand response incentives	↓	↓	↓	↓	-	-	-	↑	-
	Economically viable prosumer options	↓	↓	↓	↓	-	-	-	↓	-
	Energy efficiency rebates	↓	↓	↓	↓	-	↓	-	↓	-
Building stock										
	Growth on fringe (single-family or multi-family)	↑	↑	↑	↑	-	↑	↑	-	↑
	Growth in-basin (densification with multi-family units)	↑	↑	↑	↑	-	↑	↑	-	-
	Improved building albedo and shading	↓	↓	↓	↓	-	↓	-	↓	-
	Improved building thermal insulation	↓	↓	↓	↓	-	↓	-	↓	-

Figure 6. Climate change risk mitigation and adaptation options and effects.

incentives, and building stock. We consider load variance as an effect explicitly because less variance means more consistent load, more capacity for contingencies, and lower operations and maintenance costs [49]. We also identified effects of those options on several other complex interdependent factors that are priorities for stakeholders too. This discussion should not be considered exhaustive nor advocate any particular option, but simply present several options as we have identified so far in a structured manner.

6.1 Electrical systems: resources

The major tradeoffs between generation technologies—distributed solar PV (with storage and power quality controls) and centralized systems—in meeting demand are: land space requirements, delivery congestion relief, water usage, air

emissions, and marginal capital costs. Solar PV can be installed on building roofs, whereas centralized systems require their own dedicated land footprint and delivery infrastructure [62–65]. When implemented at the distribution level, solar PV can power load directly without going through delivery components that are necessary for central systems. The net effect is a relative decrease in load from the perspective of the grid relative to demand. Yet these distributed systems beg the question of storage given peak demand occurs once the PV systems decline in production of power. At the same time, this will be an important metric to monitor for reliability purposes going forward—if storage is included—as those two values have historically been one and the same. The most prominent fast-ramping central generation technology is combined cycle natural gas plants, which both consume water and emit various gasses into the atmosphere. Combustion-only natural gas plants could be implemented, which would not use water, but would be more sensitive to rising air temperatures, as well as less fuel-efficient, and therefore more costly and emissions intensive per kWh. While levelized costs of solar PV are now at or below parity with bulk generation plants on a per kWh basis, the combined costs of solar PV with storage to provide 24/7 dispatchable energy and regulation services are still higher than traditional central generation plants [66]. Thus, the best options for new resource procurement across competing objectives, will be those that consider the current and future state of the delivery infrastructure.

Implementing DER with new buildings may be the most cost-effective way to meet demand associated with growth in areas where delivery infrastructure are already over capacity during extreme heat waves. In such areas, some substations may be able to be adapted with improved heat sinks, forced air, or water cooling systems to increase capacity. But some may not, and overhead power line capacity will still be limited to convective cooling. The cost of increasing delivery infrastructure capacity necessary to meet demand through central generation, or long-distance imported power could be quite significant at \$10–130 million USD per substation and \$1–3 million USD per mile of line length leading all the way out of the urban center [67, 68].

Future work for vulnerable neighborhoods should consider implementation of adaptation options by considering 24-h load profiles on distribution-level circuits, the total Watt-hours of necessary storage capacity to complement solar PV capacity, and opportunity for network aggregation in supplying ancillary grid services. Circuits with higher portion of commercial and industrial loads may be preferable for the installation of DERs, as their load profiles may more closely match the PV generation profile (peaking at mid-day) allowing for more storage efficiency. Effective implementation of energy storage would reduce load variance by charging during off-peak hours and discharging during peak hours, resulting in a more consistent load, which is more readily manageable by system operators, and therefore has lower operations and maintenance costs [49]. This could occur through some kind of automated and networked market incentives that are available for wholesale markets as of February 2018 [69].

Implementation of new bulk generation systems and delivery infrastructure may be more valuable in the northern areas of San Fernando and Antelope Valley. The areas are relatively less developed there and so land should be more readily available for construction. Future studies should consider the reliability and security benefits of redundant central and distributed energy systems, and determine what amount of each, including storage, is optimal for different outage risk tolerances.

6.2 Electrical systems: loads

More energy efficient appliances can reduce use-phase load, load variance, and thus provide benefits to power systems' stability. To mitigate risks from heat waves

however, focus should be directed towards air conditioner units. Differences in lighting and other appliance efficiencies only affected peak demand in the models by 2% in California, but that state already has aggressive energy efficiency policies, so other areas around the world could benefit more. AC units generally accounted for 60–70% of summertime peak demand within residential buildings, and higher air temperatures resulted in a 3–7% increase in demand per 1°C (1.8°F). Los Angeles County currently has only 45% AC penetration in its residential buildings, meaning that peak demand in just over half of the current building stock does not increase with air temperature. By 2060 almost all buildings could have AC.

Policies that would guide new or replacement ACs based on different performance constraints or different technologies would aid in reducing the risk of excessive peak demand during extreme heat events. It is possible to design AC units that are more efficient under the hottest conditions or that utilize thermal storage to achieve ‘flat’ efficiency curves that do not degrade at the hottest temperatures [70, 71]. For example, developing a new ‘peak performance rating’ for ACs at 50°C (122°F) could be useful to mitigate peak load during extreme heat waves. Doing so could provide incentive for ACs to be optimally engineered for more efficient performance at or near such extreme temperatures. Current standards, SEER and EER [72], are primarily for temperatures at or below 35°C (95°F). The current SEER standard, SEER 13, is already optimized to the point that improvements in SEER ratings in the model up to SEER 21 only affected peak demand by a few percent and were slightly counter-effective in some instances where temperatures exceeded 45°C (113°F) due to tradeoffs in engineering design optimization. Water-based evaporative cooling systems are another option that uses much less electric power, but requires water to operate, and are often not accepted by users as the sole-source of air conditioning due to insufficient comfort levels when the weather is both hot and humid [73, 74]. Further study may be useful to identify the practicality of hybrid designs.

6.3 Market incentives: supply side and utilities

Some studies suggest that the traditional utility business model, that couples energy sales to profits, is not compatible with certain energy efficiency goals or large amounts of DER [85]. The former issue is because utility revenues are primarily dependent on total energy sales, but the costs of providing reliable infrastructure are primarily dependent on capital expenditures, operations, and maintenance [75]. Profits increase with volumetric energy sales, and costs are relatively flat. Therefore, financial incentives must exist to be relatively inefficient in some processes. Hence, public regulatory commissions exist to oversee the prices set for rate-payers. The alternative business model is referred to as a “decoupled” market, where “excess” profits are carried forward and accounted for in adjusting the following years’ prices [76, 77]. When utility profits are decoupled from energy sales, load serving entities can implement effective conservation programs without violating fiduciary responsibility to shareholders [78]. This structure has been implemented in several states with positive effects on energy efficiency. For example, California’s per-capita annual energy consumption has remained relatively flat since decoupling was implemented in the 1980s, whereas many other states’ has steadily risen [79]. Market design determines rules by which participants must play [80]. If utilities’ profits were a function of key reliability precursors, such as smaller load variance, then utilities would have a direct incentive to reduce peak load (including shifting it to off-peak hours), resulting in less congestion, higher utilization of lower-cost base-load bulk generation resources, and more contingency capacity for non-stationary extreme heat events.

6.4 Market incentives: demand side and ratepayers

One philosophy for evaluating public policy is to consider whether the rules are equitable, efficient, transparent, administratively simple, and support achieving greater policy goals [81]. Current retail electricity rate schedules in Los Angeles and Phoenix generally meet these criteria via monthly energy billing with tiered and time of use rates [82–85]. Charging residential ratepayers monthly based on total energy use is simple, transparent, equitable, and promotes energy efficiency. Higher electricity prices during peak hours helps to reduce peak load by incentivizing ratepayers to take action to shift flexible or non-critical usage to off-peak hours when electricity can be generated at lower cost [86]. Incentivizing ratepayers to turn off loads in the form of demand response relieves congestion on the grid; however, the majority of that relief comes from industrial customers who often switch to onsite diesel power or natural gas combined heat and power units [87]. Rebates are available in some localities for ratepayers to obtain solar PV, storage, or demand management technologies [88]. One-time rebates for building energy efficiency enhancements have also been found to reduce demand and peak load [89]. Overall, these incentives generally reflect the philosophy that electricity is both a critical infrastructure necessity and a non-critical commodity. Electricity is critical for powering infrastructure systems such as water, transportation, food, fuel, communications, and finance [32]. It is also critical in residential buildings for lighting, cooking, cleaning, and climate control.

6.5 Building stock

Population growth will increase peak demand, but where and by how much will be significantly influenced by decisions relating to the management of urban systems. Housing demand in less developed areas can be met through either single family or multi-family dwelling units. To meet population growth through densification however, most housing demand would need to be met through new multi-family dwelling. In addition to conserving land space, the benefits of building new multi-family unit residential housing can be as much as a 50% lower peak demand per capita than single-family detached units. Those benefits are due to reduced volume and shared walls, which significantly reduce exposure to extreme heat. In addition, street albedo and widths should be considered for urban heat island impacts.

7. Conclusions

Climate change is a broad term used to describe ecosystem disruptions that result in long-term changes in weather patterns. Industrial processes have had various impacts on ecosystems over time, and for the most part business peace treaties have been effective in the form of government regulations to limit climate-altering emissions that are harmful to human health. While electric power generation is not the only contributor to climate change, it has historically been a major one with various emissions regulations developed for the solid, liquid, and air-borne wastes of different processes. Carbon-dioxide emissions, once thought relatively harmless, are now understood to be the primary contributor to higher solar energy retention by the earth's atmosphere, and thus lower average annual ice formation, higher sea-levels, warmer air temperatures, and various related effects around the globe. As public understanding of the risks of climate change have increased in recent years, several advancements in technology, analytics, and regulations have been piloted

to reduce carbon emissions as well. Through advancements in weather forecasting tools, analysts are better able to characterize extreme weather conditions, and support electric power systems planning to forecast peak demand, resource adequacy requirements, delivery infrastructure capacity, and avoid outages during heat waves. While public understanding of the risks of climate change has increased, little knowledge exists of the value of low-cost energy available to the public nor the public risk of unstable power systems. As power systems around the world undergo transformation to lower-emissions technology standards, analysts can use the techniques demonstrated in this chapter to clearly define other risky climate conditions and support development of tools, regulations, and implementations that manage risks of other power stability issues in conjunction with climate change.

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Conflict of interest

None.

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