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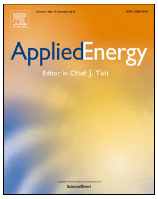

Forecasting peak electricity demand for Los Angeles considering higher air temperatures due to climate change

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HIGHLIGHTS

- Peak electricity demand projected to increase by 0.2–6.5 GW (2–51%) by 2060.
- Rising air temperatures projected to increase peak demand by 4–8% by 2060.
- Maximum temperatures in inland regions are projected to reach 54 °C (129 °F).
- Shared wall housing can reduce peak demand by up to 50% per building.
- Air conditioner SEER ratings effective for annual demand, but not peak demand.

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ABSTRACT

Los Angeles County (LAC) is a large urbanized region with 9.7 million residents (as of 2010) and aging infrastructure. Population forecasts indicate that LAC will become home to an additional 1.2–3.1 million residents through 2060. Additionally, climate forecasts based upon representative concentration pathway (RCP) scenarios 4.5 and 8.5 indicate that average air temperatures will increase by 1–4 °C (2–7 °F) in the region. Both of these factors are expected to result in higher summertime peak electricity demand due to growth in the number of buildings, the percentage of installed air conditioners (ACs), and the additional cooling load on those air conditioners. In order to understand potential power reliability issues, and support infrastructure planning efforts, a long-term peak demand forecast was developed using hourly residential and commercial (R&C) building energy models. Peak hour electricity demand was estimated to increase from 9.5 to 12.8 GW for R&C sectors, to 13.0–17.3 GW (2–36%) and 14.7–19.2 GW (16–51%) by 2060 for the population forecasts from the California Department of Finance and the Southern California Association of Governments respectively. While marginal increases in ambient air temperature due to climate change accounted for only 4–8% of future increases in peak demand, differences in annual maximum temperatures within the 20-year periods affected results by 40–66% indicating a high sensitivity to heat waves. Population growth of at least 1 million people is anticipated to occur mostly in the northern cities of Palmdale, Lancaster, and Santa Clarita, bringing an additional 0.4–1 GW of peak demand in those regions. Building and AC efficiency are anticipated to improve as national and state efficiency standards increase, and as older, less efficient units are replaced; this could offset some of the projected increases in peak demand. Additionally, development of shared wall, multi-family dwelling units could enable population growth of up to 3 million people without increasing peak demand.

1. Introduction

Demand for electricity increases significantly as air temperatures rise in urban environments with high levels of air conditioning (AC) penetration [1–8]. Despite a general understanding of this phenomenon, little knowledge exists as to how increases in air temperatures due to climate change can affect peak demand within cities [9]. Previous studies have observed that rising air temperatures can result in both direct effects of increased electricity use due to increased AC use, as well as compound effects from increased implementation of

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AC over long periods of time [10,11]. Moreover, extreme heat waves can result in outages within regions due to high demand, capacity shortages, and cascading failures [12–16]. Several such incidents have occurred in Los Angeles County (LAC) which has high levels of AC penetration [14,17,18,19]. Because outages can happen at the transmission-, circuit- or neighborhood-level [20], it is valuable to be able to predict peak demand with the same level of detail. While electric service providers may have historically planned for annual peak demands during the winter, or 90th percentile summer peak demands (e.g. California Energy Commission, Western Electricity Coordinating Council, North American Reliability Corporation [2,16,21,22]), in a warmer future, peak demand may occur in the summer instead, or be so much higher during extreme heat events that safety margins are exceeded as in the record breaking cases in [19,23,24]. Hence, developing a better understanding of the relationship between climate change and peak demand is critically important for maintaining reliable electric power service and reliable critical infrastructure in general [25].

Prior studies have considered effects of rising air temperatures on annual energy consumption and peak demand, including growth within LAC specifically [26,27]. No study to date has considered the combined effects of population growth, changing building technology, energy appliance technology, and climate, each at a high-spatial resolution throughout a region on peak demand. Top-down statistical models, and bottom-up building energy models have become the methods of choice to analyze various aspects of the problem. Burillo et al. 2017 [1], includes a review of "top-down" approaches, and advanced those further by developing a structural equation model, based on non-linear stochastic performance of AC units, which demonstrates how peak electricity demand can be forecast more accurately for heat waves at a regional-scale using fewer predictor variables than other models. The US DOE's EnergyPlus physics-based building energy simulation software has become a popular tool for researchers to develop detailed "bottom-up" models of individual buildings specifically calibrated for various building standards, climates, and occupant usage patterns around the world, including [28–31]. Huang and Hwang 2015 [32] used such models to consider effects of rising temperatures on annual energy demand for representative future years (aka time slices) in Taiwan, and Dirks et al. 2015 [9] did the same for both annual and peak electricity demand for cities throughout the eastern US. Similarly, Reyna and Chester 2017 [33] developed calibrated residential building archetypes for LAC, which were subsequently used in this study, by considering annual electricity consumption spatially throughout the region. Those studies relied on weather station data and/or representative year time slicing; no study considered maximum temperature forecasts in a spatially explicit manner throughout a region. Doing so would enable consideration of the most stressful potential conditions at any location.

LAC is a valuable location to explore these issues because it is a complex and fast-growing region with increasing population, aging infrastructure, rising AC penetration levels, and rising air temperatures across five different climate zones [26,34,35,36]. As field assets continue to age, and growth continues, there will be need for both new and retrofitted infrastructure investments [20]. LAC's coastal, inland, and desert climates capture a range of conditions where AC use would be required [17,37]. First, the region could experience 1–4 °C or 2–7 °F warmer temperatures, on average, by mid-century. Additionally, while historical 90th percentile hottest temperatures have been 33 °C (91 °F) in LAC [21], maximum air temperatures could reach up to 54 °C (129 °F) by 2060 in certain parts of the County [38,39]. Approximately 45% of residential buildings in LAC currently have air conditioning [33,40], and with its current stock of 2.3 million buildings, peak demand increases at a rate of 300–400 MW, or 2–5%, per 1 °C (1.8 °F) over the range of 25–40 °C (77–104 °F) [1,3]. New development favors installation of central AC units, so those rates will increase in the future, especially in neighborhoods which currently have low AC penetration [10,40]. Population is expected to increase, from 9.7 million in 2010, by 1.2–3.1 million people (12–32%) by 2060 [35]. Therefore, residential and commercial buildings energy use would likely increase proportionally without efforts to improve energy efficiency [41,42]. Not coincidentally, new buildings in LAC will be constructed to meet Title 24 building energy standards—with significant improvements beyond the existing stock in attics, walls, water heating, and lighting efficiency [43]. But, percent reductions in peak demand from those standards are not nearly as large as they are in annual energy consumption [43]. There is also a requirement for solar PV to be installed on all new homes. While implementation of rooftop solar PV (and or batteries) will, if implemented behind the meter, reduce metered energy consumption and likely further exacerbate the "duck curve" phenomenon [44], such electricity generation resources have no direct effect on building energy demand. Also, while high-density multi-family housing is generally more energy efficient than single-family housing, a net increase in population can still result in a net increase in annual energy consumption and peak demand. Consequently, our case-study specific research goal is to understand what ranges of peak demands are reasonable to expect in LAC through 2060, considering potential changes in population, building stock, AC penetration, appliance efficiency, and higher air temperatures due to climate change.

Projecting peak demand spatially into the future allows us to consider the efficacy of various strategies that regulators and utilities can use to maintain reliable infrastructure amidst rising air temperatures. Moreover, by considering the most stressful conditions in any geography, in any period, we can support infrastructure planning processes with a single image that accounts for all the potential heat wave scenarios that could affect different areas in the county at different times. In the discussion section we consider how regulators and utilities may better plan for resource adequacy requirements, neighborhood specific infrastructure capacity requirements, appliance energy standards, and building zoning. This type of detailed peak demand forecast can be used in siting and sizing new infrastructure investments to ensure reliable services. Whether new capital investments be in traditional bulk systems components or distributed renewables, effective grid modernization will maintain secure reliable infrastructure, and further mitigate harmful environmental emissions, improve public health through better air quality, and reduce hazardous emergency response incidents that have resulted in numerous automobile collisions and deaths [45].

2. Methods

To project peak electricity demand throughout Los Angeles County, we adopted and refined the bottom-up building energy modeling approach developed by Reyna and Chester [33], incorporating aspects of the daily maximum air temperature (T_{max}) approach developed by Burillo et al. in [1]. We used EnergyPlus hourly residential [33] and commercial [46] (R&C) building models calibrated for LAC specifically. We projected peak demand for the two sectors at census block group (CBG) resolution based on prior classification and allocation of building types from the County Assessor Database and Residential Appliance Saturation Survey in [42]. We did not consider demand from the industrial sector, e.g. transit, streetlights, heavy manufacturing etc., which account for 10–30% of total annual electricity consumption per [47,48], as the factors that influence that sector's demand do not necessarily scale with population or climate. The residential building models were originally calibrated for annual electricity consumption, and the original commercial building models were not specifically calibrated for electricity consumption [46]. Hence, the analysis was much more rigorous for residential buildings, and the commercial building results should be considered conservative per the performance characterization detailed in [49] Appendix B. Peak demand values were estimated as the average of modeled hourly consumption from noon-6 pm, per residential peak time of use pricing periods in the area [50,51]. Projections were developed with low and high demand scenarios for each of the following six factors, of which four are positive effects: rising air temperatures, population growth, building stock turnover and AC penetration; and two which are negative: housing densification and AC efficiency. Sensitivity analysis was conducted to test how significant each factor contributed to changes in peak demand and what opportunities may be most promising in terms of bolstering the region's ability to adapt to future record-breaking heat waves. Results were validated using historical data as explained in the Verification and Uncertainty section.

2.1. Rising air temperatures

Rising air temperatures were quantified in terms of daily maximum air temperature, T_{max}. This approach was taken based on stakeholder critiques of similar studies, summarized by the California Public Utilities Commission [8], which sought to clarify the sensitivity of systems to temperature rise and distinguish those impacts from the potential for such temperature rises at future dates. Data for base period values of T_{max} were obtained for 1981–2000 at 2 km^2 grid cell resolution [38,39], and future values were obtained from the same source based on the Intergovernmental Panel on Climate Change's (IPCC) standardized Representative Concentration Pathway (RCP) scenarios RCP 4.5 and RCP 8.5 for low and high future temperatures respectively. The time periods 2021–2040 and 2041–2060 were chosen as were stated most useful for planning purposes by staff at the California Energy Commission. The IPCC RCP scenarios are defined by differences in projected future concentrations of greenhouse gases in the earth atmosphere, and are named in accordance with their respective levels of radiative forcing (i.e. 4.5 and 8.5 W/m^2) in the year 2100 relative to pre-industrial values. As a reference, radiative forcing is up to about 1000 W/m^2 in the hottest parts of LAC.

Two sets of temperature projection images for T_{max} were created to inform two distinct issues. First, ***composite*** images of the highest projected T_{max} in each 2 km^2 grid cell for each period and RCP were created to project the highest peak demand in any CBG at any time. This was done to understand the highest heat-related stress on any component at any time and consists of T_{max} values from many different days. Second, ***hottest day*** images were created of the highest T_{max} throughout all of LAC on any one day. These images inform the resource adequacy requirements for the region during a possible record-breaking heat wave. Because LAC covers approximately 12,000 km^2 (5000 mi^2), and has five climate zones, the definition as to what the hottest day means for the county is debatable. We tested three definitions: number of days with the highest average T_{max}, highest single-cell T_{max}, and most grid cells over 35 °C (95 °F). Results indicated that the first definition consistently produced the highest peak demand projections in terms of GW. Therefore, we define the hottest day as the day with the highest average T_{max}. The spatially explicit temperatures used are shown in Fig. 1.

2.2. Population growth

Population growth is a direct driver of peak demand because the number of buildings consuming electricity is directly proportional to the population. Growth was modeled for two scenarios as land use zoning in the county could have a significant effect on density and sprawl [52]. The low growth scenario was based on the California Department of Finance (DoF) and U.S. Geological Survey's projections, which started at 9.7 million in 2010, and then increased to 10.3 million in 2040, and 10.9 million in 2060 primarily on the fringe and in the hotter northern region of LAC [53]. The high growth scenario was based on the Southern California Association of Governments (SCAG) projections, which included significant infill of already developed areas, resulting in total population values of 11.4 million in 2040 and 12.8 million in 2060, [35,54,55]. Both population projections were spatially explicit, although based on different methodologies, and required different allocation approaches to generate CBG level results, as detailed in [49] Appendix C. Following the work of Reyna and Chester 2015 [42], population growth (Fig. 2) was modeled as a function of proportionally increasing residential and commercial building stock in CBGs. In short, initial building stock was defined as a total of 2.3 million buildings in 2010, spatially located as in [33,42] based on the County Assessor Database. Four main types of residential building archetypes were used: single-family detached (SFD), single-family attached (SFA), multi-family small (MFS), and multi-family large (MFL) with up to 12 dwelling units (DU) per building structure. Fifteen commercial building archetypes. Residential building stock was increased at the rate of 3 persons per DU per statistics from the US Census [56] and SCAG projections [54]. Commercial building stock was increased proportionally in each CBG with population, with the same proportion of building types as existed in the sample in 2010.

2.3. Building stock turnover

Building stock turnover included replacement of older vintage buildings with new buildings for the residential sector only. Newer vintage buildings were designed in [33] to meet the most recent iteration of Title 24 building energy standards [43], minus rooftop solar, with more thermally efficient shell constructions and energy efficient appliances. Those residential buildings were developed for the five California Energy Commission Climate Zones in LAC and for seven vintages from pre-1940 to 2008. Turnover rates were modeled by replacing older buildings with the newest of the same type per the housing density scenarios. Low, medium, and high turnover rates of 0.03%, 0.3%, and 3% of DUs per year, per CBG were used, based on the range identified for LAC in [42]. It was assumed that all new buildings would have central AC and replace older buildings without central AC first. Thus, a higher turnover rate results in a larger peak demand in the model, as AC accounts for 60–70% of electricity consumption while in use in LAC [1]. While newer buildings are more energy efficient per square foot, they were also coded to have larger floorplans [33], so the net correlation between building vintage alone and energy consumption is not consistent in the models.

2.4. Housing densification

Housing densification was primarily considered as a mechanism for accommodating future population growth. Single family detached buildings require more land area per capita and are generally less energy efficient per area than multifamily attached buildings [42]. The 2010 initial allocation for LAC was SFD = 47%, SFA = 8%, MFS = 24%, and MFL = 21% per [33], and consistent with SCAG in [54]. According to SCAG, "66 percent of the 1.5 million new homes expected to be built in the SCAG region will be multifamily units, reflecting demographic shifts and anticipated market demand" [54]. Therefore, we used the recent historical allocation for the high demand scenario, the SCAG allocation for medium demand, and a ratio of 90% MF to 10% SF for new buildings for the low demand scenario.

2.5. Air conditioning penetration

Air conditioning penetration was considered explicitly because a significant portion of homes in LAC do not currently have central AC. The initial AC penetration values in each climate analysis zone (CZ) were obtained from [33], allocated by building type and CBG at 45% for LAC at large, where CZ6 = 39% (coast), CZ8 = 42% (central-basin), CZ9 = 39% (urban), CZ14 = 78% (Mojave desert), CZ16 = 61% (forests) [57]. AC penetration levels were increased in the model in two ways. First, as new buildings were added to meet population growth, and second, through building turnover by replacing older buildings without AC.

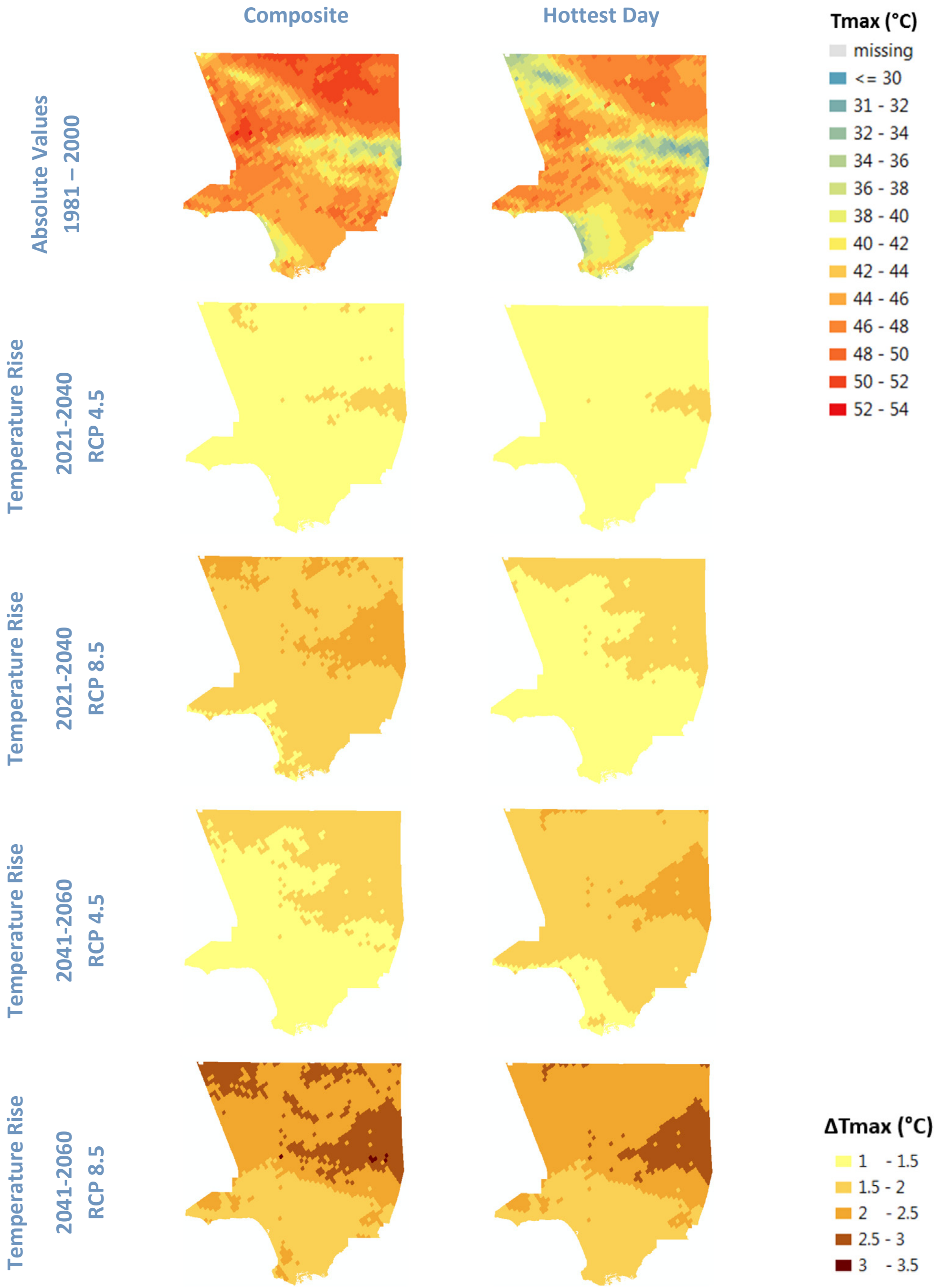

Fig. 1. Historical and future maximum temperature projection images. Top images are the base period. Bottom images are changes from the base in future periods. The actual values of temperature increases range from 0.9 to 3.2 °C.

2.6. *Air conditioning efficiency*

Air conditioning efficiency was adjusted for all residential buildings in the model. Current standards require SEER 13 for new residential sized ACs in California [43]. The California Energy Commission projects that these standards will rise to at least SEER 16 by 2040 [58]. Therefore, we set all residential buildings to use SEER 16 in the low-efficiency (high demand) scenario, and the highest available option in the software, SEER 21, in the high efficiency (low demand) scenario. The original building energy models developed in [33] were coded with 20 different types of ACs to represent the current building stock implementations based on the California Residential Appliance Saturation Survey (RASS) [59]. For technical reasons, we further clustered residential AC in to three categories as listed in Table 1 per the characterization in [49] Appendix B.

3. Results

Peak demand was projected to increase in LAC for residential and commercial sectors from 9.5—12.8 GW in 2010 to 12.3–16.7 GW (~30%) by 2040 and 13.1–19.2 GW (~45%) by 2060. As shown in Fig. 3, in the low population growth DoF scenario, additional demand was projected primarily in the Lancaster, Palmdale, and San Fernando Valley regions (CZ 14 and CZ 16). In the high population growth SCAG scenario, additional demand was projected primarily in the area from West Valley to Pomona (CZ 9). The lower value demand projections

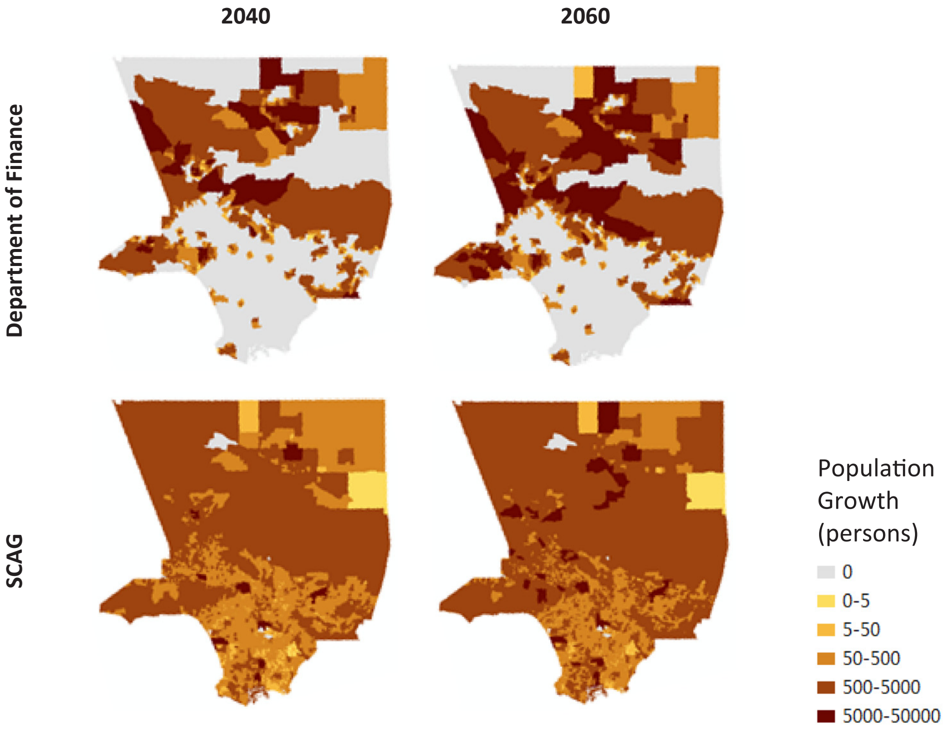

Fig. 2. Projected Increases in Population from 2010 to 2040 and 2060 from DoF/USGS and SCAG by Census Block Group.

Table 1
AC technology classification.

AC type	Definition	Clustering of [33]	Base allocation (%)
No AC	No AC	No AC	44
Low efficiency	SEER 8	All SEER 10 or less + 1/2 of all RACs	26
Medium efficiency	SEER 16	All SEER > 10 + 1/2 of all RACs	30
High efficiency	SEER 21	n/a	0

were attributable to high implementation of multi-family dwelling units with high efficiency AC and appliances. Such a scenario would likely require aggressive regulation based on historical precedent [52,60,61]. In all 2060 scenarios, the major increases in peak demand were in areas with both high population growth and high air temperatures: Santa Clarita (0.33 GW in 2010 to 0.62–1.26 GW by 2060) and Palmdale plus Lancaster (0.63 GW in 2010 to 0.65–1.3 GW by 2060). The remainder of demand increases were spread around existing developed areas, consistent with the population projections. The highest demand increase scenario, with 19.2 GW peak, was based on approximately 1 million new lower-efficiency SFDs in CZ 9 from West Valley to Pomona, which may not be feasible due to space limitations, and 100% AC penetration. Those values should be considered an upper estimate. Several CBGs appear green in the northern region due to AC efficiency gains larger than the effects of population growth. In both low demand scenarios, the in-basin area has significant green on the map in Fig. 3. In the DoF case, peak demand decreased from 4 GW in 2010 to 3.33 GW by 2060 in the in-basin area. In the SCAG case, peak demand stayed the same overall in-basin with small pockets of increases in the Manhattan Beach, Torrance and Long Beach areas. In the SCAG high efficiency scenario, the central CZ 9 region from West Valley to Pomona's peak demand was projected to increase from 7.5 GW in the base period to 9 GW by 2060. In all Fig. 3 maps, CBGs with > 50% area classified as protected lands are masked per the 2017 California Protected Areas Database [62].

Total peak demand values for the scenarios are listed in Table 2, with residential and commercial sector breakdowns listed in [49] Appendix B. The composite image projection values were cumulatively about 10% higher than in the hottest day projections. The distribution of peak demand in the base period was estimated at 37–44% residential and 56–63% commercial, and it increased more in the residential sector over time in the model. This was due to the increasing AC penetration rate over time in the residential sector, and because several commercial buildings' peak demands did not increase with higher T_{max} in the models. Results for the commercial sector should be considered conservative, and future work should include further research and development of the commercial building models, as again, the NREL manual explicitly states that this type of energy demand forecasting is beyond the scope of use of the tools at this iteration in their development [46].

The difference in LAC's peak demand across the range of historical hottest days was more significant than the potential increase due to climate change. In future scenarios, rising air temperatures accounted for 4.8–8.3% of the increases in peak demand on the hottest days. In the base period, the annual hottest day average T_{max} ranged from 34—43 °C (93–110 °F), for peak demand of 9.5–12.8 GW, or a 34% difference in R&C sector peak demand. The effects of RCPs 4.5 and 8.5 were increases in average T_{max} from 42.7 °C (108.9 °F) to 44.2 °C (111.6 °F) and 44.6 °C (112.3 °F) by 2060 respectively. The resulting peak demand forecasts were 13.03 GW and 13.14 GW in the 2060 low growth (DoF) scenario, and 18.89 GW and 19.18 GW in the 2060 high growth (SCAG) scenario respectively. The range of future sensitivity to air temperature is due to the range of possible technology implementations modeled that could occur. The major difference was increase in AC penetration rates associated with building stock turnover, which had a 27–30% effect

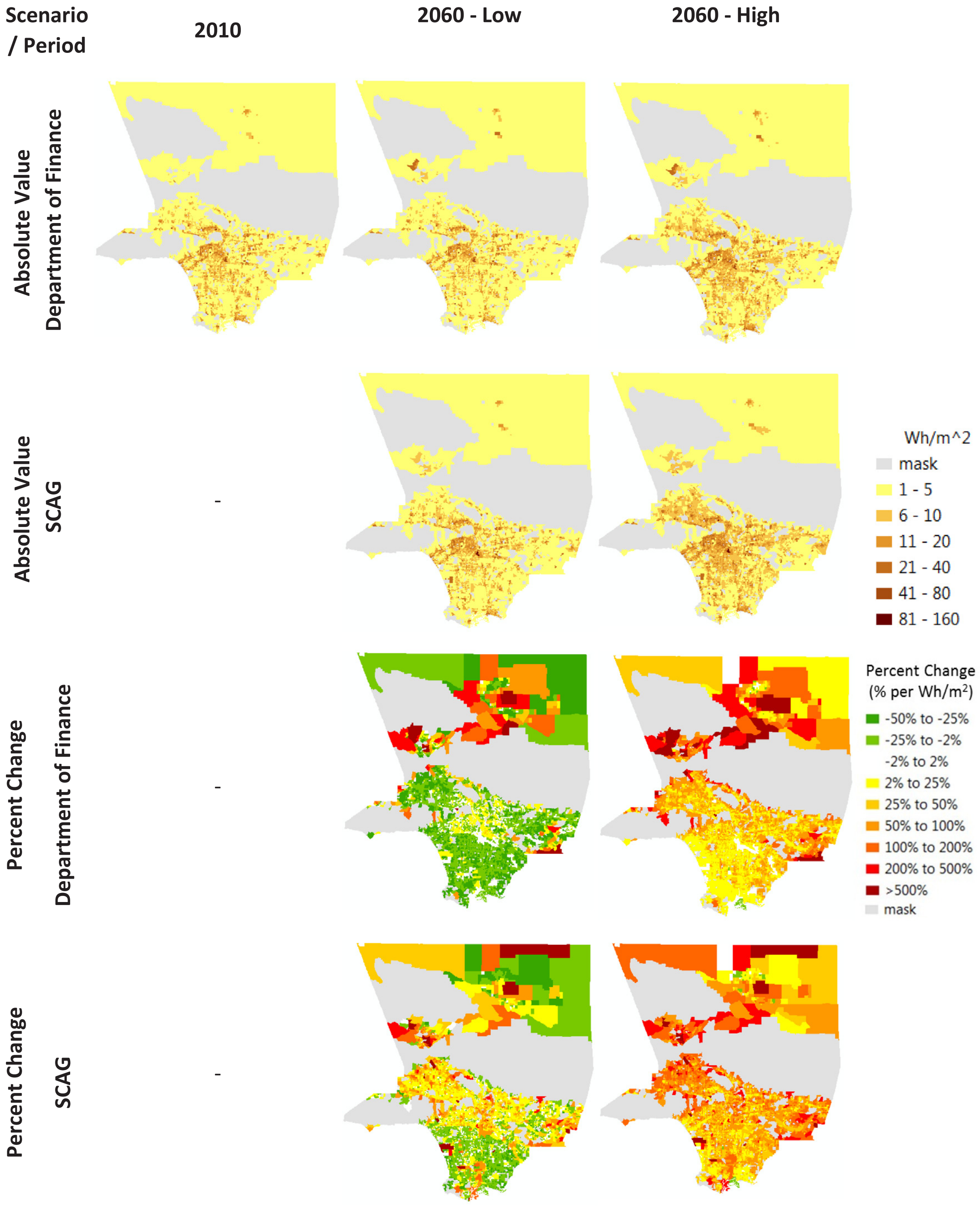

Fig. 3. Peak Demand Projections for Composite Temperature Images.

Table 2
Peak Demand Projections for LAC Residential and Commercial Sectors.

	LAC Total Peak Demand (GW)			
Time Period	DoF - Low	DoF - High	SCAG - Low	SCAG – High
Hottest Day				
2010	9.5	12.8	–	–
2040	12.3	15.8	13.1	16.7
2060	13.0	17.3	14.7	19.2
Composite				
2010	–	13.5	–	–
2040	12.9	17.3	13.8	18.4
2060	13.6	18.8	15.4	20.9

across the scenarios. New DUs with shared walls had 25–50% lower peak demand than single-family detached units at temperatures over 35 °C (95 °F). The range of new DU types implemented with increasing population had a cumulative 1–4% effect on peak demand across the range of allocations. Raising the AC rating from SEER 16 to SEER 21 increased peak demand by up to 2%; hardware optimization for SEER ratings appeared to be counter effective for peak demand according to EnergyPlus at temperatures above 45 °C (113 °F) [49] Appendix B. The effects of increases in AC penetration are generalizable to approximately 0.65% peak demand per percent AC penetration.

3.1. Verification and Uncertainty

In order to verify the reasonableness of our work, we compared the results of both the individual building models and the total county projections to observed data in the base period. For future scenarios, a straight-line increase in peak demand with population growth would be 12% and 32% by 2060 for the DoF and SCAG projections respectively. Therefore, given the range of building efficiency (shell/envelop/appliance) scenarios considered, and allocation of population to mostly warmer climate regions which already have higher AC penetration and demand, we consider both the projected increase of 2–36% in the DoF case, and 16–51% in the in SCAG case to be reasonable.

Countywide peak demand was estimated as 9.5–12.8 GW for residential and commercial sectors only in the base period, which we verified as reasonable based on data from three different sources which we used to estimate peak demand for LAC in three different ways. As a predecessor, residential and commercial sectors account for 70–90% of total annual electricity consumption per EIA records and UCLA's Energy Atlas [47,48]. Therefore, if the same proportion is true for peak demand, then extrapolating our estimates of 9.5–12.8 GW for residential and commercial yields 11–18 GW for LAC's total peak demand. This range mostly overlaps the following three estimations, which range from 12.8 to 17.3 GW, therefore we consider our base values reasonable. First, according to EIA hourly records, peak hourly demand for LADWP was 6,870 MWh in 2016, and was 2.0 times the average in that year [63]. Scaling LADWP's peak demand by the number of residential customers (1.3 million) and population (3 persons per household) [64] to the 2010 population of LAC (9.7 million) yields a peak demand of 17.3 GW. Second, according the UCLA Energy Atlas, LAC's annual electricity consumption was approximately 20 billion kWh for residential buildings, 16 billion kWh for commercial buildings, and 20 billion kWh for industrial and other in 2010, or 56 TWh total [47]. The average of the annual median electricity consumption for LAC in 2010 over a one year hourly period was 2.3, 1.8, and 2.3 GWh respectively, or 6.4 GWh total [47]. If peak demand were two times the annual average measure, then it would be 12.8 GW. Third, according to the California Energy Commission, peak demand for the entire state of California was 57–64 GW each year from 2005 to 2016 [34]. The population of LAC is approximately 1/4 the state's population (37.3 million in 2010) [56], so a straight population allocation results in a peak demand estimate of 14–17 GW.

CBG specific results were limited in their precision by source data for population and buildings, and technical data processing as explained in [49] Appendix C. Land in certain CBGs may not actually be feasible to build on due to forests, lakes, or other constraints. These details do not affect the overall insights of this study but should be considered in any neighborhood-specific land development studies before any specific urban development plans are implemented.

Individual building peak demand was modeled as the average of noon-6 pm hourly results, which we verified as within a reasonable range based on historical values. According the UCLA Energy Atlas [47], the 2010 median annual electricity consumption for buildings was: 6726 kWh (0.5 Wh/ft^2) or 0.77 kWh per hour for single family units, 9612 kWh (0.43 Wh/ft^2) or 1.1 kWh per hour for multi-family units, and 38,599 kWh (0.96 Wh/ft^2) or 4.4 kWh per hour for commercial buildings [47]. The low-end of peak demand per DU across LAC in the base period was modeled at 1.5, 1.0, 0.7, and 0.7 kW for the SFD, SFA, MFS, and MFL types. These values were approximately twice the median values, and therefore we considered them reasonable estimates as the SCE residential static load profile peak values were approximately twice the median in the summer months [65]. Commercial buildings were modeled as 108 kWh on average per building using the lowest value from the three vintages published. Those values overlapped the range of median values when considered over the range of building floor spaces listed in [49] Appendix B. Again, as quoted there, the use of the commercial building models exceeded their intended use in this report as they were not specifically calibrated for electricity consumption. Again, the high T_{max} commercial peak demand values are likely underestimates because, as shown in that same Appendix, they did not significantly increase with air temperature in the model.

Temperature effects on peak demand were approximately 300 MWh per 1 °C, or 3–4% per 1 °C for the base period infrastructure, which is consistent with historical observations found in [1,3,10]. Increases in peak demand did not appear to decline until $T_{max} = 53\,^{\circ}C$, approximately 10 °C higher than estimated in [1], which we attribute to the method of averaging noon-6 pm building consumption as opposed to using individual buildings' maximum hourly consumption which typically occurs later in the day in LAC summers. Understanding this difference between different customer sector's hourly, peak, total demand is an important topic for future research given the expected proliferation of distributed energy resources.

AC efficiency clustering, i.e. grouping AC types into as few as possible for technical/computational purposes, may have resulted in high estimates of peak demand at maximum temperatures due to the method of allocating room air conditioners into half SEER 8 and half SEER 16. Consequently, the percent demand reductions from upgrading ACs in high efficiency scenarios should be considered an upper estimate. Moreover, using only SEER ratings does not account for additional AC specifications that are known to affect performance, including compressor motor type [66]. Furthermore, SEER ratings are based on performance over a weighted range of outdoor temperatures from 18 to 40 °C (65–104 °F) [67], whereas the range of outdoor temperatures in this study are up to 54 °C (129 °F). Thus, model results which indicated that some SEER 21 rated ACs performed less efficiently than SEER 16 at temperatures above 40 °C are not implausible because incentives exist to optimize hardware to a specification that affects average annual energy consumption as opposed to the highest peak amount.

AC penetration initial values were obtained from [33] based on the RASS [59], equal to 0.39, 0.42, 0.39, 0.78, and 0.61 for CZ 6, 8, 9, 14, and 16 respectively. These values were different than the values estimated in the Energy Commission's Residential Energy Demand Model, which were also based the RASS at 0.908, 0.514, 0.595, 0.730, and 0.742 for CZ 6, 8, 9, 14, and 16 respectively. Values from [33] were used because it is more reasonable that the coolest climate zone, CZ6 would have the lowest AC penetration value, not the highest. AC penetration increased in the model with building turnover and new buildings only, which may be conservative, as people may purchase AC units for the first time in existing buildings without as well.

Other factors. We did not consider electrification of other technologies such as natural gas ovens, stoves, water heaters, nor petroleum-based vehicles. Efficiency improvements in home appliances were projected in [33] to reduce annual electricity consumption by 13–15% for water heaters, refrigerators, and television/computers each. If that consumption were spread evenly throughout the day, then it would have a 1–2% effect on peak demand. Electric vehicles could have positive or negative effects on peak demand depending upon their charging schedules and whether battery discharging is realized and how it is accounted for.

4. Discussion

Our results show wide ranges of increases in peak demand are possible for LAC. This could pose significant problems or opportunities depending upon the constraints on existing infrastructure capacity. At the transmission level, LAC is a net importer of electric power, and was estimated to have demand for 1–6 GW of imported power as of 2017 to supplement its own local generation in the event of extreme heat waves [1]. At the same time, LAC had approximately 13 GW of total import capability from Arizona, Nevada, the Pacific Northwest, and San Diego Gas and Electric [68]. Therefore, since LAC's peak demand was projected to increase by up to 6.5 GW in the highest scenario, new long-distance transmission imports should not be necessary by 2060. If growth occurs disproportionally along the outskirts of the network, and land is readily available, then either central generation or distributed energy resources (DER) may be practical to meet demand. However, if demand increases are concentrated downstream within the delivery network, then options could be limited in practice. Even if transmission capacity is available in the future, central generation systems may not be viable sources of energy production as some lower voltage lines and substations may not have the capacity to support the additional power flow. Future work should consider our spatial demand forecasts as they relate to infrastructure components' capacities and identify any hardware in regions that may be at risk of overloading. Growth in such areas could be prime locations to pilot "smart city" grid modernization projects with DER such as solar PV and storage and meet California's renewable generation goals including SB 350 [69]. Further research could identify locations where DER implementations could supplement infrastructure capacity at lower cost than upgrading power lines ($1–3 million per mile) and substations ($10–130 million each) [70].

The tools and techniques developed in this study can be used to assist in addressing California's growing "duck curve." Due to rapid growth of solar PV implementations, load is being offset from the perspective of the grid during the day and peak load is being shifted later towards sunset [44]. The surplus generation is so significant in California during the day, that Arizona has been paid to take the excess energy on numerous occasions [71]. To inform this issue, the residential and commercial building energy models used in this study could be further calibrated throughout each hour of the day to characterize the difference between the demand profile and the shifting load profile that is occurring with the implementation of distributed solar PV. Combined with local infrastructure capacity data, the difference in the performance curves would provide critical insight into the amount of peak load that would need to be shifted to maintain safe operating loads on components. Moreover, such tools would support developing specifications for batteries to meet demand during near-peak hours after sunset. This is becoming higher priority, especially since the levelized cost of battery energy is still two orders of magnitude higher per kilowatt-hour than other resources [72,73].

Improvements in building and appliance energy efficiency can also play a significant role in preventing peak demand from rising excessively beyond infrastructure capacity. The major opportunity identified in the results was that dwelling units with shared wall spaces had as much as 50% less peak demand per capita than single-family detached units. Because 60–70% of peak demand within residential buildings was attributable to AC, the increase in peak demand associated with increased AC penetration is approximately cancelled if old single-family detached dwelling units are replaced with new high efficiency multifamily units.

Improvements in air conditioner efficiency were identified as not necessarily beneficial in reducing peak demand depending upon the standards. While improvements in SEER ratings are significant for total annual electricity consumption, their effects on peak demand saturate and become counter effective above SEER 16. A different metric is necessary to optimize for performance under extreme heat conditions. A new "peak performance rating" for ACs could be useful to adapt to extreme heat conditions as there would then be incentive for ACs to be engineered for more efficient performance at temperatures above 45 °C (113 °F). Peak demand will be more sensitive to air temperature in the future, as AC penetration increases, and therefore future work should consider tradeoffs between AC standards that result in designs optimized to minimize peak demand instead of annual energy use.

5. Conclusion

Peak demand in LAC was projected to increase by 0.2–6.5 GW (2–51%) by 2060, including 4–8% increase due to rising air temperatures from climate change. Additional transmission import capacity should not be necessary to meet demand, but future work should consider where available capacity is in delivery infrastructure to prioritize investments in DER to meet California's renewable energy goals. Both DoF and SCAG population growth projections result in net increases in peak demand in the northern and central parts of LAC, but reductions are possible in the south with aggressive energy efficiency measures.

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References

[1] Burillo D, Chester MV, Ruddell B, Johnson N. Electricity demand planning forecasts should consider climate non-stationarity to maintain reserve margins during heat waves. Appl Energy 2017;206. https://doi.org/10.1016/j.apenergy.2017.08.141.

[2] Garcia-cerrutti M, Junker B, Bender S, Jones M. Revised short - term (2011–2012) Peak Demand Forecast Commission. Energy 2012.

[3] Sathaye Ja, Dale LL, Larsen PH, Fitts Ga, Koy K, Lewis SM, et al. Estimating impacts of warming temperatures on California's electricity system. Glob Environ Chang 2013;23:499–511. https://doi.org/10.1016/j.gloenvcha.2012.12.005.

[4] Bartos M, Chester M, Johnson N, Gorman B, Eisenberg D, Linkov I, et al. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. Environ Res Lett 2016.

[5] Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—a review. Energy Build 2015;98:119–24. https://doi.org/10.1016/j.enbuild.2014.09.052.

[6] Sailor DJ, Muñoz JR. Sensitivity of electricity and natural gas consumption to climate in the U.S.A. – methodology and results for eight states. Energy 1997;22:987–98. https://doi.org/10.1016/S0360-5442(97)00034-0.

[7] Sailor DJ. Relating residential and commercial sector electricity loads to climate – evaluating state level sensitivities and vulnerabilities. Energy 2001;26:645–57. https://doi.org/10.1016/S0360-5442(01)00023-8.

[8] Ralff-Douglas K. Climate adaptation in the electric sector: vulnerability assessments & resiliency plans; 2016.

[9] Dirks JA, Gorrissen WJ, Hathaway JH, Skorski DC, Scott MJ, Pulsipher TC, et al. Impacts of climate change on energy consumption and peak demand in buildings: a detailed regional approach. Energy 2015;79:20–32. https://doi.org/10.1016/j.energy.2014.08.081.

[10] Sailor DJ, Pavlova AA. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 2003;28:941–51. https://doi.org/10.1016/S0360-5442(03)00033-1.

[11] Isaac M, van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 2009;37:507–21. https://doi.org/10.1016/j.enpol.2008.09.051.

[12] Hines P, Balasubramaniam K, Sanchez EC. Cascading failures in power grids. IEEE Potentials 2009;28:24–30. https://doi.org/10.1109/MPOT.2009.933498.

[13] FERC. The August 14 Blackout compared with previous Major North American Outages; 2003.

[14] Ferc Nerc. Arizona-Southern California Outages on September 8 2011. vol. 133; 2012. 10.1093/toxsci/kft047.

[15] Eaton. Blackout Tracker United States Annual Report 2013; 2013.

[16] NERC. 2015 Long-term reliability assessment; 2015.

[17] Barry Fisher. STAT OF THE WEEK: Los Angeles shatters its record for peak electric demand, twice – Opower : Opower; 2014. < https://blog.opower.com/2014/09/peak-electric-demand-record-los-angeles/ > .

[18] van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. Clim Change 2011;109:5–31. https://doi.org/10.1007/s10584-011-0148-z.

[19] MacDonald-Evoy Jerod. Power outages impact thousands around Arizona. Arizona Repub; 2016. < http://www.azcentral.com/story/news/local/mesa-breaking/2016/06/05/1900-mesa-homes-lose-power-record-breaking-heat/85464650/ > .

[20] Willis HL, Welch GV, Schrieber RR. Aging power delivery infrastructures. Marcel Dekker, Ins.; 2001.

[21] Miller NL, Jin J, Hayhoe K, Auffhammer M. Climate change, extreme heat, and electricity demand in California: CEC-500-2007-023; 2007.

[22] WECC. 2014 Power Supply Assessment; 2014.

[23] LADWP. LADWP Customers Set All-Time Record for Energy Demand of 6,196 Megawatts 2014. < http://www.ladwpnews.com/go/doc/1475/2243054/ > [accessed December 21, 2016].

[24] The Associated Press. Southern California Heat Triggers Power Outages. US News 2018. < https://www.usnews.com/news/best-states/california/articles/2018-07-09/southern-california-heat-triggers-power-outages > [accessed July 9, 2018].

[25] Rinaldi SM, Peerenboom JP, Kelly TK. Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Syst Mag 2001;21:11–25. https://doi.org/10.1109/37.969131.

[26] LADWP. Power Integrated Resource Plan; 2016.

[27] CAISO. Regional Resource Adequacy Issue Paper; 2015.

[28] Sun K, Hong T, Taylor-lange SC, Piette MA. A pattern-based automated approach to building energy model calibration. Appl Energy 2016;165:214–24. https://doi.org/10.1016/j.apenergy.2015.12.026.

[29] Royapoor M, Roskilly T. Building model calibration using energy and environmental data. Energy Build 2015;94:109–20. https://doi.org/10.1016/j.enbuild.2015.02.050.

[30] Kim YS, Heidarinejad M, Dahlhausen M, Srebric J. Building energy model calibration with schedules derived from electricity use data. Appl Energy 2017;190:997–1007. https://doi.org/10.1016/j.apenergy.2016.12.167.

[31] Chaudhary G, New J, Sanyal J, Im P, O'Neill Z, Garg V. Evaluation of "Autotune" calibration against manual calibration of building energy models. Appl Energy 2016;182:115–34. https://doi.org/10.1016/j.apenergy.2016.08.073.

[32] Huang KT, Hwang RL. Future trends of residential building cooling energy and passive adaptation measures to counteract climate change: the case of Taiwan. Appl Energy 2016;184:1230–40. https://doi.org/10.1016/j.apenergy.2015.11.008.

[33] Reyna JL, Chester MV, Wagner G, Wagner G, Kainuma M. Energy efficiency to reduce residential electricity and natural gas use under climate change. Nat Commun 2017;8:14916. https://doi.org/10.1038/ncomms14916.

[34] California Energy Commission. California Energy Demand Updated Forecast, 2017–2027; 2014.

[35] SCAG. 2016 – 2040 RTP/SCS Final Growth Forecast by Jurisdiction 2016 – 2040 RTP/SCS Final Growth Forecast by Jurisdiction; 2016.

[36] Number D, Title P, Demand E, Tn F, Title D, Energy C, et al. California Energy Demand Updated Forecast 2017:2017–27.

[37] Burillo D, Chester MV, Ruddell B. Power system planning and operation across multiple coincident non-stationary temperature futures. Int Conf Sustain Infrastruct 2017;2017:293–302.

[38] Hall A, Sun F, Walton D, Capps S, Qu X, Huang H-Y, et al. Mid-Century Warming in the Los Angeles. Region 2012;1..

[39] Bartos M, Chester M. Assessing future extreme heat events at intra-urban scales: a comparative study of Phoenix and Los Angeles; 2014.

[40] Fraser AM, Chester MV, Eisenman D, Hondula DM, Pincetl SS, English P, et al. Household accessibility to heat refuges: residential air conditioning, public cooled space, and walkability. Environ Plan B Urban Anal City Sci 2017;44:1036–55. https://doi.org/10.1177/0265813516657342.

[41] Sleeter BM, Wilson TS, Sharygin E, Sherba J. Future scenarios of land change based on empirical data and demographic trends. Earth's Futur 2017:1–16. https://doi.org/10.1002/eft2.262.

[42] Reyna JL, Chester MV. The growth of urban building stock: unintended lock-in and embedded environmental effects. J Ind Ecol 2015;19:524–37. https://doi.org/10.1111/jiec.12211.

[43] CEC. Building Energy Efficiency Standards for Residential and Nonresidential Buildings; 2016.

[44] California ISO. Duck Curve Fast Facts; 2016. < www.caiso.com > [accessed July 20, 2018].

[45] Winn V. PG&E's 2017 Risk Assessment and Mitigation Phase Report (U 39M); 2017.

[46] Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, et al. U.S. Department of Energy commercial reference building models of the national building stock. Publ; 2011. p. 1–118. doi:NREL Report No. TP-5500-46861.

[47] Pincetl S, LA Energy Atlas Development Team. LA Energy Atlas. Calif Cent Sustain Communities UCLA; 2017.

[48] EIA. Electric power sales, revenue, and energy efficiency Form EIA-861 detailed data files; 2014. < https://www.eia.gov/electricity/data/eia861/ > .

[49] Burillo D, Chester M, Pincetl S, Fournier E, Walton D, Sun F, et al. (University of California Los Angeles). Climate Change in Los Angeles County: Grid Vulnerability to Extreme Heat. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: CCCA4-CEC-2018-013; 2018.

[50] LADWP. Electric Rate Schedules; 2016. < https://ladwp.com/ladwp/faces/ladwp/aboutus/a-financesandreports/a-fr-electricrates/a-fr-er-electricrateschedules;jsessionid=v7vPYKqTKr3hMPFJps1Y8hGyTXvcLLmKQyhK3L2MMbJNgRQJ5Khy!545368516?_adf.ctrl-state=cs0kc1rp1_4&_afrLoop=268583008846984&_afrWindowMode > [accessed March 15, 2017].

[51] SCE. Residential Rates | Rates & Pricing Choices | SCE Tariff Books | Regulatory Information | Home – SCE; 2017. < https://www.sce.com/wps/portal/home/regulatory/tariff-books/rates-pricing-choices/residential-rates/!ut/p/b1/tVJNU8IwEP01PYYsbemHtw44WBxUBEbaC5OGtI22SUmDqL_ewHDQEUQO5pRs3r7d93Zxihc4FeSVF0RzKUi1e6fechQPou7QteOhPxpA9DDwB_NHr-vedg0gMQA4cSI4l_-EU5xSoRtd4qSlbE > [accessed March 15, 2017].

[52] Whittemore AH. Zoning Los Angeles: a brief history of four regimes. Plan Perspect 2012;27:393–415. https://doi.org/10.1080/02665433.2012.681140.

[53] Sleeter BM. USGS Land-Use and Climate Change Team; 2017. < https://geography.wr.usgs.gov/LUCC/california_landchange_projections.php > [accessed June 8, 2017].

[54] SCAG. The 2016–2040 Regional Transportation Plan/Sustainable Communities Strategy; 2016.

[55] SCAG. RTPSCS Appendix - Demographics & Growth Forecast; 2016.

[56] US Census Bureau 2010 Census Interactive Population Map; 2017. < https://www.census.gov/2010census/popmap/ > [accessed June 14, 2017].

[57] CEC. Energy Maps of California; 2017. < http://www.energy.ca.gov/maps/renewable/building_climate_zones.html > [accessed November 3, 2017].

[58] Stoms D. Personal Communication; 2017.

[59] CEC. Residential Appliance Saturation Study; 2009. < http://www.energy.ca.gov/appliances/rass/ > [accessed October 1, 2016].

[60] Mideksa TK, Kallbekken S. The impact of climate change on the electricity market: a review. Energy Policy 2010;38:3579–85. https://doi.org/10.1016/j.enpol.2010.02.035.

[61] Vine E. Adaptation of California's electricity sector to climate change. Clim Change 2012;111:75–99. https://doi.org/10.1007/s10584-011-0242-2.

[62] GreenInfo Network. California Protected Areas Data Portal; 2018. < http://www.calands.org/ > [accessed May 31, 2018].

[63] EIA. U.S. Electric System Operating Data – Hourly; 2016. < http://www.eia.gov/beta/realtime_grid/#/data/graphs?end=20160916T00&start=20160909T00 > .

[64] EIA. Electric Power Annual 2014. EiaDoeGov; 2016, 0348:2.

[65] SCE. 2018 Static Load Profiles; n.d. < https://www.sce.com/wps/portal/home/regulatory/load-profiles/2018 static load profiles/!ut/p/b1/rZJNc4IwEIb_ij1wxCwEAXtjpEOx1dZap8DFgRA-HEwQotZ_3-DYgzO11pnmlOy–84-u0ERClDE4l2Zx6LkLK66d2Qux77raJ6h-541dsF5dS138WZqxpMmBaEUwIXjwLX6DxShiDBRiwKFLaFLwpmgT > [accessed October 6, 2018].

[66] Faramarzi R, Coburn B, Sarhadian R, Mitchell S, Pierce RA. Performance evaluation of rooftop air conditioning units at high ambient temperatures, ACEEE; 2004.

[67] SCE. EER & SEER As predictors of seasonal cooling performance; 2003.

[68] CPUC. Energy Division Proposal for Proceeding 14-10-010 Order Instituting Rulemaking to Oversee the Resource Adequacy Program, Consider Program Refinements, and Establish Annual Local and Flexible Procurement Obligations for the 2016 and 2017 Compliance Years; 2016.

[69] California Energy Commission. Renewables Portfolio Standard (RPS); 2018. < http://www.energy.ca.gov/portfolio/ > [accessed February 11, 2018].

[70] Mason T, Curry T, Wilson D. Capital costs for transmission and substation recommendations for WECC Transmission Expansion Planning; 2012.

[71] Toll EJ. California pays APS to take surplus solar power -. Phoenix Bus J; 2016. < https://www.bizjournals.com/phoenix/news/2016/10/05/california-pays-aps-to-take-surplus-solar-power.html > [accessed February 15, 2018].

[72] CA ISO. Electricity 2030 - Trends and Tasks for the Coming Years; 2017.

[73] Zakeri B, Syri S. Electrical energy storage systems: a comparative life cycle cost analysis. Renew Sustain Energy Rev 2015;42:569–96. https://doi.org/10.1016/j.rser.2014.10.011.