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Quantifying the electric service panel capacities of California's residential buildings

Eric Daniel Fournier *, Robert Cudd, Samantha Smithies, Stephanie Pincetl

The California Center for Sustainable Communities (CCSC) at the Institute of the Environment and Sustainability (IoES), University of California Los Angeles (UCLA), USA

A B S T R A C T

This study seeks to quantify the size distribution of existing installed electrical service panels within California's residential buildings, a potentially significant barrier to future decarbonization efforts. A large sample of historical building permit data was collected for municipalities throughout the state, from which permitted panel upgrades were extracted and analyzed. These data were used to develop a method for estimating panel capacities that incorporates information about historical code requirements for panel sizing in new construction with a statewide database of parcel-level building attributes. Overall, we find that 3% of single-family (SF) and 10% of multi-family (MF) properties in California have panels in the smallest size range, which will most likely require upgrades. However, 32% of SF and 59% of MF properties have panels of intermediate size, which will likely require the addition of load management systems to support comprehensive electrification. Future panel upgrade needs are expected to be more acute within disadvantaged communities, where the proportion of SF homes with the smallest-sized panels is 4x that in more affluent neighborhoods. We discuss the implications of these and other results within the context of existing and planned future state policies related to residential electrification.

1. Introduction

The electrification of end-use appliances has been identified as the preferred technology transformation pathway for decarbonization of the residential energy sector (Wei et al. 2013; Steinberg et al. 2017; Ebrahimi et al. 2018; Mai et al. 2018). As states and municipalities begin to grapple with the momentous task of operationalizing this electrification transition at scale, they are having to reckon with numerous, often unforeseen, challenges associated with the real-world implementation of new technologies and systems (Deason and Merrian Borgeson, 2019; Denholm et al., 2021; Gold, 2021). One of these challenges, which is the focus of this analysis, relates to customer-owned service panel hardware that function as the physical point of interconnection to utility electrical service. This hardware must possess sufficient physical space and rated capacity to support the interconnection of requisite electrical end-use appliances and equipment, or else the panel most likely needs to be replaced and upgraded. The need to augment the capacity of a property's associated utility service agreement could also be an issue, one with its own costs and logistical concerns. However, these are considered beyond the scope of this particular study.

1.1. Service panel fundamentals

Electrical service panels are the last piece of complex equipment located behind-the-meter at a given utility service interconnection point. This means that they are owned by the customer and must be maintained and/or upgraded at their expense. Service panels house a main breaker, which provides bidirectional overcurrent protection for both upstream utility infrastructure and downstream customer loads. Sitting below this main breaker, in the customer's direction, are various branch circuits, and potentially even sub-panels, which organize end-use loads and outlet receptacles into discrete units that can be physically isolated to repair and replace equipment as needed.

Within a service panel, branch circuits are physically connected to the service main via one or more bus-bars which allow for some flexibility in terms of operating voltage. Residential loads typically operate on a single phase of alternating current at either 120 or 240-V. Breakers for the panel's branch circuits are typically sized in increments of 15 or 20 Amps but can be as large as 60 or 100 Amps for larger 240-V loads. Older generations of service panel technologies use fuses instead of breakers, which have to be physically replaced if "blown" by an overcurrent event. Modern breakers take advantage of the capabilities of solid-state electronics to provide a reversible disconnect mechanism that simply requires flipping a hardware switch to reset.

* Corresponding author. 5362 Life Sciences Building University of California Los Angeles, Los Angeles, CA, 90025, USA.
E-mail address: efournier@ioes.ucla.edu (E.D. Fournier).

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The size and configuration of the service panel determines the number and size of end-use loads that can concurrently draw utility power. The utility's ability to provide a given volume of power is a separate matter and is independently determined by the capacity of the utility distribution infrastructure serving the customer and the details of the customer's utility service interconnection agreement. It is possible that a customer could install service panel hardware with capacity that exceeds the capacity of their utility service interconnection agreement, although this is highly unlikely in most cases.

Primarily for reasons of cost efficiency, most buildings have historically been built with electrical service panels that were sized to minimally accommodate the combined power demands of their existing installed appliances and equipment. It is only recently that code requirements have begun to mandate the installation of panel hardware with excess capacity relative to the needs of existing loads, as a means of "future proofing" relative to anticipated end-use electrification (Franconi et al. 2021).

1.2. The role of service panels in building electrification

Building electrification measures take two general forms: (1) fuel substitution and (2) new end-uses (Paloma Sisneros-Lobato et al., 2022). Fuel substitution measures involve the replacement of existing gas and other fossil-fueled appliances and equipment with electrically powered alternatives. A good example of this would be replacing an existing gas stove/range with an electric induction version. New end-use additions involve the installation of fundamentally new types of equipment and appliances that provide energy services which were not previously available at the premises. Here, electric vehicle (EV) fast chargers provide perhaps the best, and potentially most significant, example. This is because previously, with internal combustion engine (ICE) vehicles, virtually all fueling took place outside of the home.

Both fuel substitution and new end-uses can increase the power demands at a customer premise to an extent that their combined load exceeds the rated capacity of their installed service panel hardware. There are three general strategies which have been proposed to avoid the need for panel upgrades while pursuing electrification. The first involves the installation of switching equipment, introduced between the loads and the service panel, such that two or more large appliances are allowed to run in an "either/or" configuration, and not simultaneously, which would overload the panel's rated capacity. The second involves the use of low power appliances, which avoid the need for extra panel breaker capacity. And the third involves the adoption of smart panel or smart breaker hardware/software solutions which dynamically adjust the power demands from individual loads to ensure that their combined current draw does not exceed some desired limit.

Nearly all of these solutions involve significant tradeoffs in terms of cost, implementation complexity, and potential impacts to the performance or capabilities of a building's energy system. Consequently, it is expected that there will need to be significant numbers of service panel upgrades to support comprehensive electrification retrofits of existing buildings throughout the state, even if there is widespread adoption of these alternative solutions. This is especially true for smaller, older buildings, such as those common in lower-income, disadvantaged communities, as they are the most likely to have been built with smaller capacity panels and the least likely to have undergone a major capacity upgrade since construction.

2. Background and literature review

The size of electrical service panels in existing buildings and likely needs for future upgrades to support comprehensive building electrification have been the focus of several previous studies conducted by national laboratories, utilities, trade organizations and private research firms. Perhaps the most relevant among these are recently published reports by researchers at the Residential Building Systems Group at Lawrence Berkeley National Laboratory (LBL) and private research firms Pecan Street and NV5 (Walker et al., 2021; Pecan Street 2021; NV5 2022). However, there has been very little published work on these topics within peer-reviewed academic journals.

2.1. Building electrical code requirements for panel sizing

From the perspective of the National Electrical Code (NEC)–specifically, sections 220.83 and 220.87–the required size of the service panel at a residential property must be determined by standard calculation methods which account for the combined Volt-Amperage draw of all anticipated end-use loads as well as the overall size of the property's living areas (NFPA 70 2022). There are several important points of understanding relative to the NEC's current and historical panel sizing guidelines. The first is that the guidelines are not strictly prescriptive with respect to a particular building's size and construction vintage. Rather, only a portion of the panel sizing calculations scale as a function of built square footage and do so in a manner that depends upon the specific version of the NEC referenced. In contrast, NEC panel sizing calculations are strictly prescriptive relative to the number, rated power consumption, and usage characteristics (i.e. continuous versus intermittent operation) of installed end-use loads. Importantly, NEC panel sizing guidelines do not take into account the actual peak power demands experienced on-site from real-world usage patterns. Thus, it is possible that many NEC compliant panels could be sized such that they have significant excess capacity relative to a property's actual power needs.

2.2. Panel sizes in existing buildings

In terms of previous work, the studies with greatest relevance to the goals and scope of this analysis are those which relate observations of the existing size of electrical service panels to the physical attributes of buildings, such as their construction vintage years and square footages. These provide essential information both in terms of understanding the distribution of existing service panel sizes within the building stock as well as for developing assumptions about what sized panels should be deemed sufficient to support the comprehensive electrification of existing buildings. Table 1 provides an overview of these most relevant previous works as well as information about their effective sample sizes and the data collection approaches used. The methods applied range from quantitative field studies to more qualitative surveys and case study-based meta-analyses.

Among the sources cited in Table 1, the most useful points of reference for this analysis are field data collected from TECH Clean California program and survey data collected by the Electric Power Research Institute (EPRI). The TECH program is a California-specific, statewide, mid-stream, incentive program that provides financial incentives to contractors installing fuel substitution measures such as heat-pump HVAC systems and hot water heaters (TECH Clean California, 2024). The program's participation data are publicly available in machine readable format and contain relevant property-level attributes such as: disadvantaged community (DAC) status, construction vintage year, built square footage, and pre- and post-participation service panel size ratings. Fig. 1 plots the distribution of available information for initial panel size ratings among single-family (SF), at left, and multi-family (MF), at right, TECH program participants. These data are presented both in total and disaggregated by household DAC status for each.

As the effective sample sizes (n) of the disaggregated TECH program data illustrate, participation in TECH is strongly biased towards non-DAC households, with only 7.7% of the total number of SF homes with valid listed pre-participation panel size ratings located within DACs. This balance between DAC and non-DAC participation improves significantly within the MF context; however, the significantly smaller number of MF household participants overall can, itself, be considered a reflection of this same bias. Of greatest concern within these plots are

Table 1
Previously published studies identifying electrical service panel capacities in existing residential buildings.

Reference	Study Title	Effective Sample Size	Building Sector	Data Collection Approach
TECH Clean California, 2024	TECH Clean California Program Participation Data	n = 19,579 (SF) & 2017 (MF)	Single-Family & Multi-Family	Field Study
Quinn and Mark Martinez (2023)	Electrical Panel Technology Review: The Challenges and Solutions for Electrification How Many May Need to be Upgraded?	n = 1858 (SF) & 1092 (MF)	Single-Family & Multi-Family	Survey
Davis, Rhys (2022)	Total Electrification of Existing Multi-Family Buildings: A Case Study	n = 6232	Multi-Family	Utility Meter Data Analysis
Armstrong et al., 2021	A Pocket Guide to the Electrification of Single-Family Homes	N/A	Single-Family	Case Study Review
Pecan Street (2021)	Addressing an Electrification Roadblock - Residential Electric Panel Capacity Analysis and Policy Recommendations on Electric Panel Sizing	n = 263	Single-Family	Field Study
StopWaste (2021)	Accelerating Electrification of California's Multifamily Buildings – Policy Considerations and Technical Guidelines	N/A	Multi-Family	Case Study Review

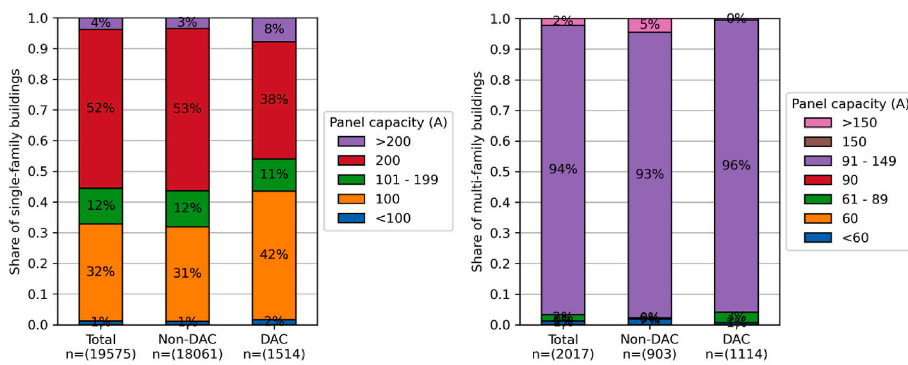

Fig. 1. Distributions of pre-participation electric service panel sizes for single-family (left) and multi-family (right) TECH Clean California Program participants, in total and disaggregated by DAC status.

the proportions of households identified as having the smallest sized electrical service panels. By convention, we identify these as being <100 Amps for SF properties and <60 Amps (per dwelling unit) for MF properties. Among TECH program participants only 1.18% of SF households and 1.2% of MF households were observed to have pre-existing panels in these smallest size categories.

Compared to the TECH program data, recently presented survey results from EPRI tell a very different story (Quinn and Mark Martinez, 2023). According to the EPRI study's findings, 21% of the survey respondents from western states (CA, OR, WA) and living in SF homes (n = 364) reported having service panels with <100 Amps of capacity. Moreover, 42% of the respondents in this same group indicated that they either could not locate the service panel for their home or could not identify its rated capacity when found. These huge discrepancies suggest that further research is needed. Moreover, there are structural flaws with the data collection approaches used in both cases. For example, while the panel size estimates from the TECH program data can generally be considered reliable, as they were reported by trained electrical contractors, the sample is undoubtedly biased towards households possessing the necessary financial resources and motivation required to pursue electrification measures in the first place. Alternatively, for the EPRI study, though the survey sample is less likely to be similarly structurally biased, the reported panel size estimates are not as reliable. This is because they were provided by home occupants who lack sufficient technical training to either locate their home's service panel or reliably identify its rated capacity. Generally, however, data from both the TECH program and EPRI study, as well as from the others cited in Table 1, support the conclusion that service panel capacities are positively correlated with the building size (ft^2) and negatively correlated with the construction vintage year of existing properties.

2.3. Panel sizes required to support future electrification

The anticipated need for increased electrical service panel capacity stems from an understanding of the power requirements of new end-use equipment required for full electrification. Table 2 provides an ordered list of the top five end-use service categories in which future electrification is most likely to drive the need for residential electrical service

Table 2
Ranked list of end-use energy service categories, and corresponding electric appliances, whose future adoption will likely drive the need for future residential service panel upgrades.

Rank	End-Use Energy Service Category	Electric Appliance Technology Category	Typical Equipment Size Range	Required Circuit Breaker Size Range *
1	Electric Vehicle Charging	Level-2 Electric Vehicle Fast Chargers	3.3–20 kW Peak Power Rating	15–100 Amps at 240-V
2	Cooking	Induction Cooktops and Ranges	7.2–12 kW Peak Power Rating	30–50 Amps at 240-V
3	Heating, Ventilation, and Air Conditioning	Centrally Ducted/Mini-Split Heat Pump HVAC Systems	1–7 Tons (12,000–84,000 BTU)	15–125 Amps at 120/240-V
4	Water Heating	Heat-Pump/Resistance Based Water Heaters	10–100 Gallon Tank Capacity	10–30 Amps at 120/240-V
5	Clothes Drying	Heat-Pump/Resistance Based Clothes Dryers	1.5–9.0 ft^3 Drum Capacity	15–30 Amps at 120/240-V

* Quoted amperage ratings include NEC required margins of safety which must be applied to the sizing of breakers used for continuous loads with backup equipment.

panel upgrades. Within the table, min/max range estimates are provided for the sizes of the circuit breakers needed to support the installation of different available appliances and equipment from major manufacturers. As the values in Table 2 illustrate there can be considerable variation in the power demands of individual product offerings within each end-use category. These ranges are an important consideration when attempting to establish what size service panels should be deemed sufficient to support comprehensive electrification. The service panel capacities that are necessary will ultimately depend upon the combined power requirements of the set of specific appliances and equipment selected by the individual homeowners and contractors.

2.4. Special considerations in the multi-family sector

MF properties are much more diverse in terms of their size, their types of installed end-use electrical equipment, and the ways in which the energy use of those equipment are distributed between individual tenants and the property owners. MF properties can range in size from as few as two units to more than 1000. And, in most cases, MF buildings' electrical systems differentiate between loads which are metered to the utility accounts of individual tenants, versus those which are metered to the property owner's/manager's accounts. The latter are commonly referred to as "house loads'' and will usually, but not always, consist of equipment that serve common areas, such as entryway or carport lighting. In some instances, centralized equipment can be metered as "house loads" but actually provide energy services to individual tenant units, such as in the case of centrally ducted air conditioning systems or communal laundry facilities. All of these complexities can lead to significant variations in the sizing and configuration of the service panels and load centers in MF structures, making them much more difficult to generalize about–whether it be in terms of their electrification readiness or potential upgrade costs–as compared to the SF context.

2.5. Strategies for avoiding service panel upgrades

There are three general strategies for avoiding service panel upgrades within the context of electrification retrofits: (1) choose lower power appliances and equipment, (2) install circuit splitting hardware, or (3) install dynamic load management hardware/software systems (BDC 2020; NV5 2022; Zank et al., 2022; Walker et al., 2021). These strategies can be implemented individually, or in concert, to provision more end-use energy services with less total power consumption and thus, avoid the need to upgrade smaller capacity service panels.

Today, there are a growing number of low-power appliance options which can use conventional 120-V outlets to provide the types of services that previously necessitated dedicated 240-V circuits. These can be excellent options where the quantity and quality of energy services that these appliances provide are sufficient for the homeowners needs. Beyond low power appliance and equipment options, circuit splitting hardware can also be installed at existing 240-V plug receptacles which allow for the connection of two high-power loads to the same physical breaker. These hardware only allow one load to operate at any given time. Finally, in terms of dynamic load management solutions, there exist a number of different integrated hardware and software products which can intelligently throttle individual loads such that their combined power draw does not exceed a desired threshold (Madduri et al. 2022; Armstrong et al., 2021). These systems can either operate at the panel or individual breaker levels and make use of solid-state electronics to avoid an overcurrent draw on the service main. These "smart panels" and "smart breakers", as they are popularly becoming known, will typically include a graphical user interface (usually available on a phone or tablet) which allows the building occupant to dynamically view and control the power demands from the end-use equipment within the building.

3. Methodology

3.1. Overview

Our methodology for estimating the size of existing electric service panels in residential buildings operates from the bottom-up and is fundamentally based upon parcel-level building attributes. It has been intentionally designed to complement previous program participation data and survey-based studies, to provide policy makers with a means of triangulation using estimates derived from fundamentally different approaches. As a general overview, the first step in the process is to establish an initial set of estimates for the as-built capacity of the electrical service panels at each property. These estimates are based on assumptions about the most common sizes of service panels installed in properties of different square footage ranges, built in different historical periods. These assumptions are grounded in observations reported in the studies listed in Table 1 and are detailed in Tables A3 and A4 in the included appendix.

Following from this initial step, the likelihood that a previous panel upgrade may have occurred at each property since the time of its initial construction is assessed using a set of empirical probability density functions derived from a database of statewide panel upgrade building permits assembled as part of the research. These likelihoods are conditional upon the property's age and the CalEnviroScreen 4.0 (CES) composite percentile score of the census tract in which it is located.[1] For a small minority of properties, the existing panel size is assigned on the basis of direct observations from the permit upgrade record. However, for the majority of properties, for which no permit data is available, a Boolean upgrade flag is assigned by sampling from the appropriate probability density function. In cases where a previous upgrade has been assessed as having likely occurred, a corresponding estimate of the existing service panel size is then derived by incrementing up from the as-built panel size according to a range of commonly used panel sizes. The detailed procedure by which these upgrade likelihoods are calculated, and destination panel sizes selected is described both within the following sections as well as by material in the included appendix.

3.2. Parcel data processing

A proprietary database of statewide parcel level building attributes for California was obtained from CoreLogic via a license agreement with the California Energy Commission (CEC). The primary data sources used to assemble this database are county-level tax assessor records and data sourced from other third-party brokers. Heterogeneity in the available attribute coverage of this dataset stems from the latitude afforded to individual county tax assessors to decide which parcel attributes are recorded, whether they are digitized, and how. Processing the CoreLogic parcel database for use in this type of analysis therefore involved the implementation of various quality control and standardization procedures.

In total, across all parcel use type designations and available geographies, the CoreLogic parcel database included identifiable attributes for 7,610,021 SF and 560,953 MF properties for the state of California. Of these, 7,240,031 (95.14%) SF properties and 506,315 (90.00%) could be incorporated into this analysis as they possessed non-null values for the following key attributes which are essential to our analytical methodology: use type, construction vintage year, total living area square footage, and total units (for MF properties). The geographic

[1] CalEnviroScreen 4.0 is a product of the California Environmental Protection Agency's Office of Environmental Health Hazard Assessment (OEHHA) that provides a comprehensive set of metrics for local energy burden and other measures of community disadvantage. Since its inception it has come into common use throughout the state as a means of assigning DAC status for purposes such as incentive program eligibility and funding allocations.

distribution of these missing attributes is not random, but rather is correlated with the boundaries of certain counties. Fig. 2 illustrates, at the county level, the percentage of SF (left) and MF (right) parcels for which panel size estimates were able to be generated; the parcels for which panel size estimates could not be generated were limited by the availability of parcel-level attributes. Table A1 in the appendix provides the detailed county level parcel counts and coverage ratios from which the maps in Fig. 2 are derived.

3.3. Building permit data processing

In most of the state's municipalities, construction projects involving major electrical work, such as a service panel upgrade, must receive advanced permitting approval. Historical records of these types of building permit data are increasingly being made publicly available by municipal permitting authorities through open, online data platforms. These publicly available building permit datasets have the potential to be used to develop insights about the rate and extent of electrical service panel upgrades throughout the state, and to do so with a specific focus on the participation of disadvantaged communities. This contrasts with many other sources of panel upgrade data, which may be derived from program participation or public opinion research studies, that can often be biased in terms of under-representing households in underserved communities.

The collection of building permit data involved an extensive manual process of searching for publicly available online data sources. We structured this process by first sorting a list of potential building permitting authorities–consisting of counties and census designated places–by their total populations and DAC populations, in descending order. In total, we identified 56 different municipalities which hosted historical permit records in a machine-readable format including key attributes which were identified as essential for the analysis. This included, at minimum, some indication of the permit issue date, work description, and some geographic identifier such as an Assessor Parcel Number (APN), latitude-longitude coordinates, or a street address. Only 47 of the 56 municipalities were found to contain permit records that could readily be identified as being either for panel upgrades or other related electrical work. Figure A1 in the appendix plots the relative proportion of permit records which were able to be obtained aggregated to the county level, inclusive of unincorporated areas as well as for census designated places. Likewise, Table A2 in the appendix provides counts for the total numbers of permits sourced from each municipality.

Each unique source of raw permit data had its own processing considerations related to differences in provenance and structure. This required that each raw dataset be individually parsed to achieve the end goal of a single collated and standardized table of permit data. A critical component of the methodology involves assigning each collected permit to its relevant tax-assessor parcel record to establish a connection to building attributes such as use-type, construction vintage year, total floor area, etc. that are essential for inferring existing panel sizes. As introduced previously, different permit data providers made location data available in different formats. Where Lat/Lon coordinates were provided, these were reprojected into a standard reference coordinate system (EPSG:3310) and spatially joined to the CoreLogic parcel boundaries. Where APNs were provided, these were used directly as the join key to the CoreLogic database. Finally, where address fields were provided, these were first parsed into a composite PostgreSQL standard address type and then fed to an online geocoding API. Geocoding request responses were then parsed based upon their match quality score (0–100) and validation checks were performed to ensure that the resulting Lat/Lon coordinates were within the state and municipality associated with the record. Records that did not pass these validation checks were discarded.

3.4. Identifying permits for panel upgrades and related measures

Different municipalities were found to use different schemes for the classification of their permit records. In a minority of cases, these classifications were quite specific, enumerating categories of project type (i.e., "Panel Upgrade," "EV Charger Installation," "Solar PV Installation," etc.). However, in the majority of other municipalities, they were frustratingly generic (i.e., "Electrical" or "Construction"). To augment cases where dedicated fields indicating the presence of a panel upgrade or other related work were missing, permits were classified on the basis of the included "Work Description" field. This is a free-form text field completed by the permit applicant and provides the most detail about the scope of the proposed work.

This classification procedure involved tokenizing the work description field's contents and searching against a list of different keywords and phrases to develop match scores. These scores were then assigned appropriate Boolean flags based on defined thresholds for the following different work categories: ["Main Panel Upgrades," "Sub-Panel Upgrades," "PV System Installations," "Battery Energy Storage System Installations," "EV Charger Installations," and "Heat-Pump HVAC System Installations"]. These categories reflect permits that were either explicitly for service panel upgrades or otherwise involved related work,

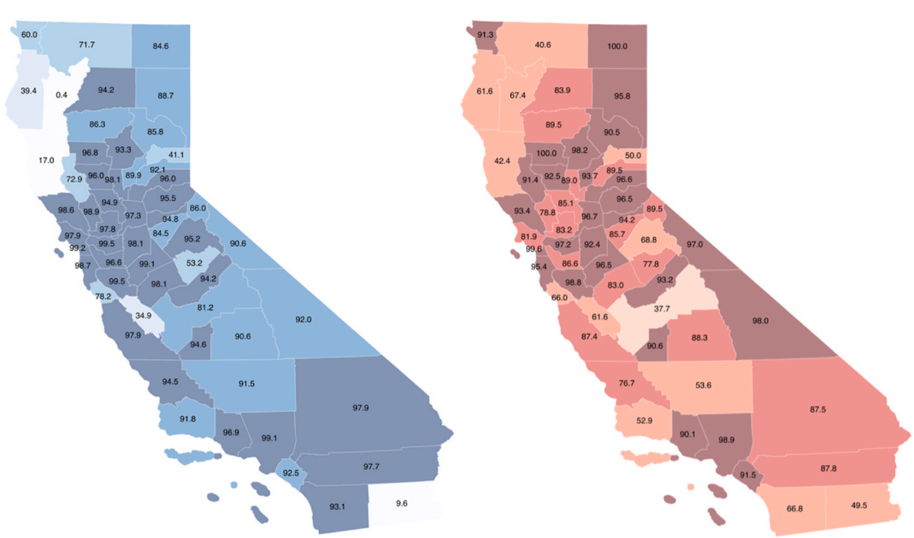

Fig. 2. Map of California counties illustrating the percentage of single-family (left) and multi-family (right) parcels for which panel size estimates were able to be derived in the analysis.

such as for the installation of major new electrical loads, that could otherwise be useful as context for subsequent efforts to estimate existing panel sizes, particularly in cases where the as-built panel size estimate were too small to be considered feasible to support these new electrical loads. Only direct panel upgrade observations, i.e. those which correspond to permit records where the work description indicated that a panel upgrade had occurred and the upgraded panel size was specifically enumerated, were used to parameterize the probability density functions used for the subsequent panel size inference procedure.

3.5. Inferring existing panel sizes

As discussed in the overview, the first step in our panel size inference methodology is the assignment of an initial best-estimate of the as-built service panel capacity rating for all properties where the requisite parcel attributes were available. For SF properties, this process involved the development and use of a lookup table that indicated the most likely size of the panel used at the time of construction based upon a property's size (ft^2) and construction vintage year. For MF properties, where there is much less differentiation between the sizes of individual units, only the construction vintage was used. These lookup tables were assembled using information about historical panel sizing requirements specified in historical iterations of the National Electrical Code (NEC) as well as empirical data about the as-built condition of sampled SF homes in various parts of the United States (Pecan Street 2021; Armstrong et al., 2021; Davis, Rhys, 2022; TECH Clean California, 2024). The detailed threshold values for building square footages and vintage years are provided in Tables A3 and A4 in the appendix.

For properties not associated with direct panel upgrade observations in the permit data, a parametric simulation approach was developed to (1) assess the likelihood of an upgrade occurring since the time of initial construction and (2) infer the most likely existing panel size if a previous upgrade was assessed to have likely occurred. The methodology for assessing the likelihood of previous upgrades is based upon the frequency distribution of properties with directly observed panel upgrade permits relative to the property's age at the time of permit issuance. Alternatively, the methodology for determining the most likely destination panel size when an upgrade was determined to have likely occurred was based on incrementing up an upgrade ladder of commonly used panel hardware sizes. Both methods are detailed in Fig. 3, with an alternative version, oriented towards the MF sector, provided in Figure A2 in the appendix.

Within the workflow diagram depicted on the left in Fig. 3, the weights of the connections between elements reflect the relative proportion of SF properties involved. Stepping through the workflow: once the set of initial as-built panel size estimates have been assigned to all eligible properties, if an individual property is found to be associated with one or more records in the permit database, then the existing size of its service panel is set as the destination size described in the work permit (green). If this is not known, because it was not specified in the permit's work description, then the existing panel size is inferred from an upgrade routine that is applied using the as-built panel size as the starting point (aqua). If the permit or permits associated with the property were not specifically for a panel upgrade, but rather other related work, then a modified version of this as-built panel upgrade procedure is applied which sets a minimum threshold value for the existing panel size that depends upon the combination of permits observed (turquoise). If no permits were found to be associated with the property, then a binary prediction is made as to whether or not the property is likely to have received a panel upgrade in the past (yellow). If no such previous upgrade is predicted, then the existing panel size is set to the same as the as-built condition (red). Alternatively, if a previous upgrade is predicted, then the same as-built upgrade routine that was used previously is applied (aqua).

On the right of Fig. 3 is a graphical illustration of the SF panel size upgrade ladder that is used for the assignment of existing panel sizes when a previous upgrade is predicted to have occurred. This ladder is composed of the most common panel amperage sizes historically in use. Each panel amperage on the ladder is grouped into one of five corresponding size categories: ["Small," "Medium," "Large," "XL," "XXL"]. This categorization scheme is used to ensure that assessed upgrades do not result in a trivial increase in panel capacities from the as-built condition, as at the lower range of the upgrade ladder the differences between commonly used panel amperages can be small and would likely

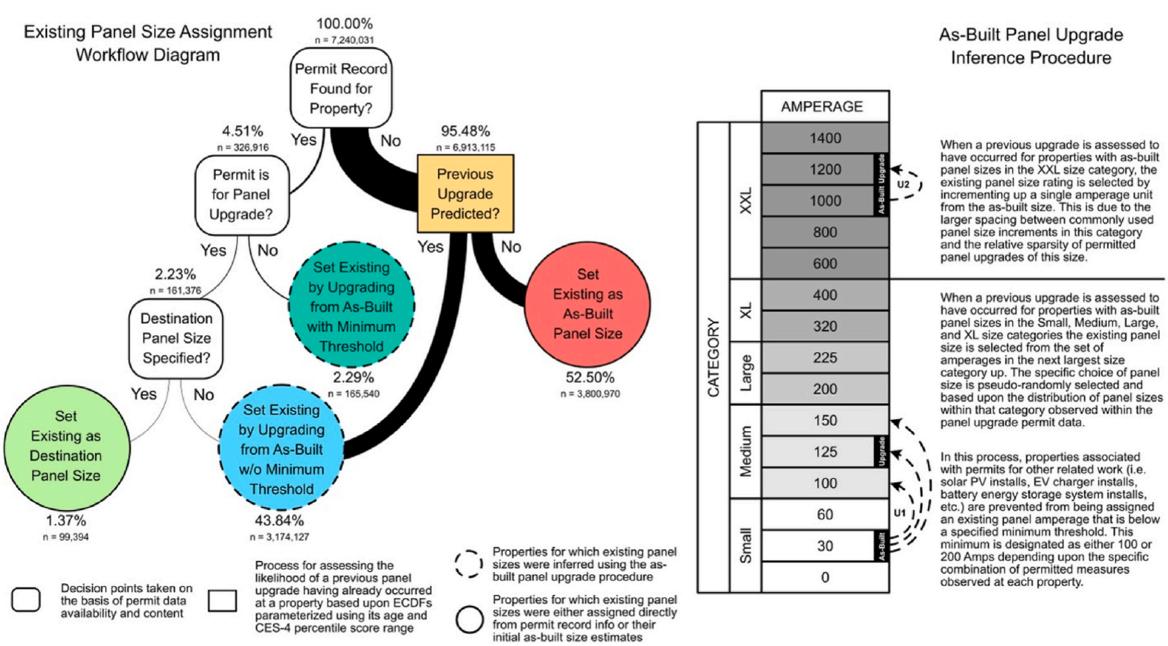

Fig. 3. At left is a workflow diagram illustrating the various pathways by which existing panel sizes were assigned for single-family properties. The weights of the connections correspond to the proportions of properties involved. To the right is a graphical illustration of the as-built panel upgrade inference procedure. This procedure was used to estimate the existing sizes of panels for the groups of properties represented by the turquoise and aqua colored circles in the workflow diagram.

not be considered a significant enough increase in capacity to warrant the labor and expense associated with a panel upgrade project. According to the implementation of the procedure, for properties with as-built panel sizes in all but the largest (XXL) category, a panel upgrade will always result in an existing panel size that is in the next size category up from that of the as-built condition. The specific choice of the existing panel size for each property is pseudo-randomly assigned, with the relative likelihoods associated with selecting each amperage rating determined based upon their observed distributions within the panel upgrade permit record.

Whether or not a previous panel upgrade has occurred at a given property is predicted by inputting the property's age into an empirical cumulative density function (ECDF) that was fit using data about the ages of properties at the time of observed panel upgrades within the permit data record. This process does not rely upon a single ECDF, but rather 20 different ones that were each fit to a subset of the permitted properties sampled at 5 percentage point increments based upon the CES percentile scores of the tracts in which they are located. This specific number of ECDFs (20) was selected to balance the need to have robust sample sizes within each subset group with the desire to maximally differentiate between upgrade patterns in DAC versus non-DAC regions.

4. Data availability

Final output estimates for the total number of SF and MF properties within different panel upgrade size classes will be made available at the following levels of geographic aggregation: by census tract, county, building climate zone, as well as by California Air Resource Board air basin and air district–for those areas where results are available. These data layers will be hosted as public feature layers using ArcGIS Online and otherwise made available upon request. Several of the underlying data sources used to conduct this analysis were obtained under non-disclosure agreement and cannot be similarly publicly shared. Per the discussion of the methodology, we will also not be sharing parcel-level results, though available, as they were generated from stochastic sampling procedures.

5. Results

5.1. Service panel lifespans

Fig. 4 plots the ECDFs that were developed for use in the parametric simulation routine. These provide some interesting insights into differences in the service lifespans of panel hardware between DACs and non-DACs. Looking at the plot at the left of Fig. 4, we can observe that among SF homes located in census tracts with the lowest composite CES percentile scores (purple) that received permitted panel upgrades 50% of the upgraded properties were less than 40 years in age. By comparison, among upgraded SF homes located within tracts having the highest CES scores, corresponding to the most disadvantaged communities (red), the same 50% percent threshold is only achieved among homes that are approximately 70 years old. This means that the median expected service life of an electrical service panel is roughly 30 years longer within the most underserved communities as compared to their more affluent counterparts. Moving on to the plot at the right in Fig. 4, which shows similar information derived from properties permitted upgrades within the MF sector, we can see that there is significantly less differentiation in the upgrade age distribution between properties by CES score range. Furthermore, the values on the horizontal axes indicate that, overall, the service panels in MF properties tend to be in service for far longer than those in the SF sector. As an illustration of this, the observed median service panel lifespans for MF properties range between 60 and 85 years, likely reflecting the difference in personal incentives for MF property owners to make such improvements as compared to their SF counterparts.

5.2. Housing stock characteristics

Overall, 79.83% of the analyzed SF properties were found to be within non-DACs, with the remaining 20.17% being located within DACs. Across all these SF properties, the median floor area was computed as 1660 ft^2 with a median construction vintage of 1973. Within the MF sector, 57.73% of properties were found to be within non-DACs, with a disproportionate share, 42.27%, being located within DACs. Across all these MF properties, the median construction vintage was 1953. Likewise, the median total floor area per property was 2250 ft^2 with an average of 5649 ft^2. The median number of units per property was three, indicating that more than half of the MF properties in the state consist of duplexes and triplexes. However, the standard deviation of the total number of units per property was 22.7, indicating a wide range of MF property sizes overall. The median floor area per unit was 758 ft^2 with a mean of 861 ft^2. Tables 3 and 4 show summary statistics for the salient differences in key building attributes between DAC and non-DAC communities for the SF and MF sectors, respectively.

Table 3
Structural differences in the characteristics of single-family homes in CA by DAC status.

DAC	Median Construction Vintage Year	DAC Difference	Median Floor Area	DAC Difference
No	1976	+18 Years	1757	−23%
Yes	1958		1356	

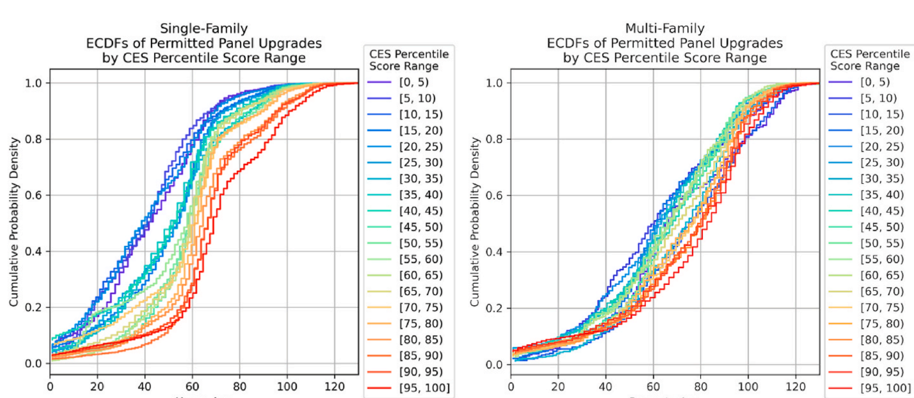

Fig. 4. Empirical cumulative density functions of permitted panel upgrades by binned CES percentile score for single-family (left) and multi-family properties (right). CES percentile scores are plotted from low to high using a purple to red graduated color ramp.

Table 4
Structural differences in the characteristics of multi-family homes analyzed for CA, separated by DAC status.

DAC	Median Construction Vintage Year	DAC Difference	Median Total Floor Area	DAC Difference	Median Floor Area Per Unit	DAC Difference
No	1956	+7 Years	2560	−29%	848	−27%
Yes	1949		1823		624	

5.3. *Trends in permits for panel upgrades and related measures*

The assembled permit dataset provides insights into historical drivers of panel upgrades, the rates in which they have been occurring, and levels of adoption between DAC and non-DAC households. There are a number of caveats which must be taken into account when interpreting these data, however. First and foremost, the time periods over which permits were recorded within each municipality's dataset varied. In some instances, the period of permit data availability extended back several decades. Steps were taken to ensure that the results presented here correspond to a common reference time period (1996–2022). Another issue is that the rates at which these permits have been issued need to be interpreted within the context of the population of properties represented by the sampled territories, as the data are not representative of adoption rates statewide over this time period.

Fig. 5 plots the relative frequency of the different categories of identified SF (top) and MF permits (bottom) both in terms of total counts (left column) and normalized relative to the total numbers of DAC and non-DAC properties throughout the state (right column). It is important to note within this figure, that multiple permits within this dataset could potentially apply to the same property, and that prior to the subsequent use of these data in the panel upgrade analysis, individual permit records had to be grouped by common parcel associations and their attributes coalesced. As such, the total number of permit records depicted in this plot does not perfectly reflect the total number of unique properties involved.

From the plots in Fig. 5 we can see that, on a normalized basis, rates of directly observed main service panel upgrades were actually slightly higher within DACs both for SF and MF property types. Non-DACs possess a greater prevalence of more newly constructed buildings, with panels built to newer code requirements. This results in less of a need for these types of retrofit upgrades. Relative to permits for other categories of related work, the normalized rates observed within DACs were generally significantly lower than within non-DACs for both the SF and MF sectors. This is consistent with the findings of previous analyses which have looked at the disparities in distributed energy resource and electric end-use technology adoption throughout the state.

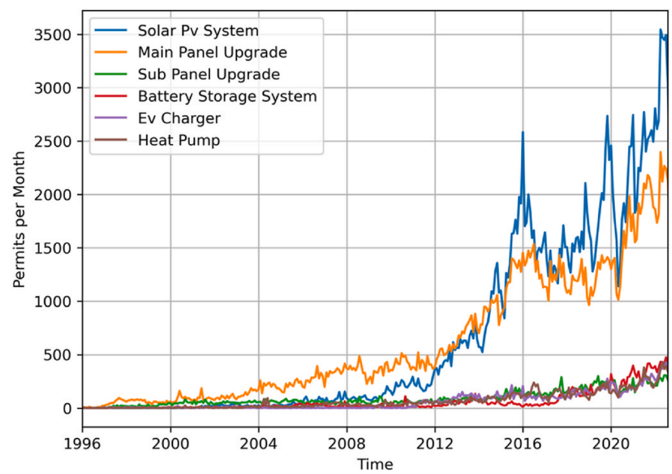

Fig. 6. Time series plot of the monthly rates of issued permits within the sampled municipalities disaggregated by derived permit type.

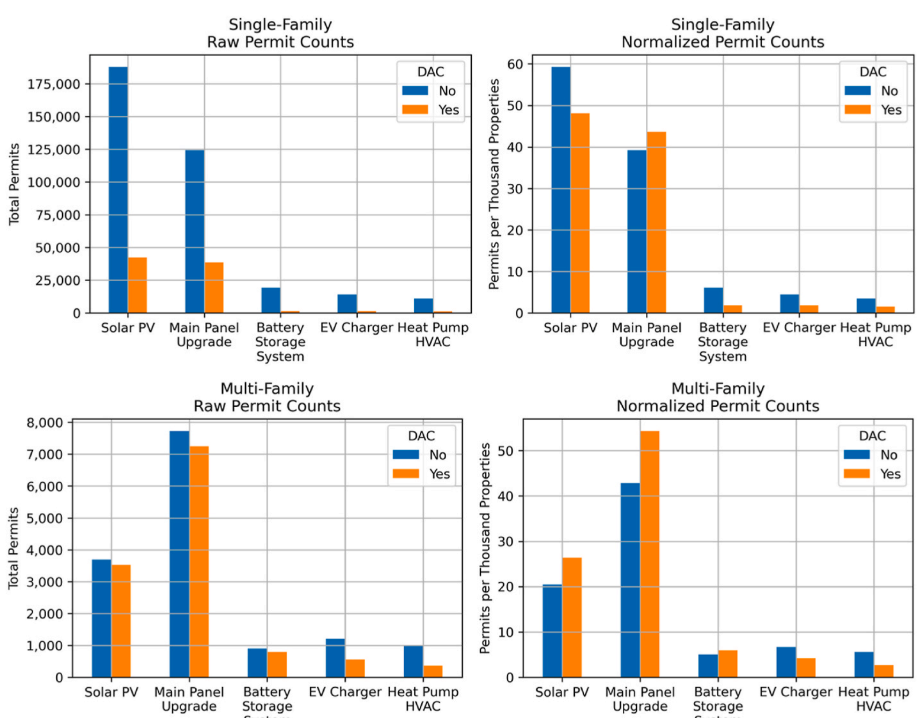

Fig. 5. Total (left) and normalized (right) count frequencies of identified permits by type and disaggregated by DAC status for SF (top) and MF properties (bottom).

Moving on, Fig. 6 below provides a time series plot of the rate of permits issued per month for six different derived permit types. These include both explicit panel upgrades and associated electrification measures. As this plot clearly illustrates, the adoption of rooftop solar PV appears to be a significant driver of service panel upgrades within the sampled territories. This is likely because a typical sized (3-5 kW-DC) rooftop PV system can require its own dedicated 100 Amp breaker within a home's service panel. For many installs, there can also be the need to install other supporting equipment which must be wired into the panel and may justify an upgrade. These will often include an automatic shutoff switch, a communications gateway, and even a critical loads subpanel in some cases.

5.4. Observed panel upgrade sizes

As discussed in the previous methodology section, permits identified as panel upgrades for which the destination panel sizes could be extracted from the work description were flagged as direct panel upgrade observations to be used in subsequent analyses. Fig. 7 plots the count frequency distribution of the size ratings for this set of observed panel upgrades, both in total and disaggregated by their DAC status. For the SF case, the bulk of the upgraded panels were of a 200 Amp size rating, with 100 and 125 Amp rated panels making up the next most frequently occurring sizes. There were a small number of upgraded panels in the <100 Amp size category. However, it is likely that these do not so much constitute upgrades as they do straightforward replacements of failed existing hardware and occurred in the earlier portions of the permit data's temporal coverage period.

5.5. Existing panel size estimates

Fig. 8 provides bar charts summarizing the estimated proportions of SF (left) and MF (right) properties with different rated panel sizes, both in total, statewide, as well as disaggregated by DAC status. As the SF plot illustrates, 200 Amp sized panels predominate (39%). However, there is a significant proportion of homes with 100 Amp panels (32%) that will likely require the implementation of different load management strategies to fully electrify. In terms of the smallest panel size category (<100 Amps), that almost certainly will need to be upgraded in order to support full electrification, the estimated proportion statewide is encouragingly low (3%). However, when estimates are disaggregated by property's DAC status, we can see that the relative proportion of homes in this smallest panel size category is roughly four times higher within DACs (8%) as compared to non-DACs (2%). This is a significant equity consideration for the electrification transition, as more DAC households will likely require more financial support to overcome this barrier to participation.

Moving on to the plot illustrating the estimates for the MF context, we can see that 60 Amp dwelling unit sub-panel sizes predominate (59%). This panel size class is most analogous to the 100 Amp class within the SF context, and thus, will likely require the implementation of significant load management strategies to avoid the need for panel upgrades within the context of full electrification retrofits. Overall, the MF sector is observed to have a much smaller proportion of properties with estimated panel sizes that would likely allow them to immediately adopt full electrification retrofits without any additional load management strategies. Furthermore, we can see that there is much less differentiation between the estimated proportion of properties between DACs and non-DACs across all the panel size rating classes in the MF sector. This is due to the fact that there are disproportionately large numbers of MF properties within DAC census tracts.

Fig. 9 provides three additional perspectives of these same panel size estimate results, disaggregated by building vintage range (top), square footage range (middle), and the percentage of renter households within the containing census tract (bottom) for both the SF (left) and MF (right) contexts.

6. Discussion

The results of this study's analyses indicate that approximately 3% of SF properties and 10% MF properties throughout the state of California have existing service panels which will most likely have to be upgraded to support comprehensive electrification. Additionally, the relative proportion of SF homes predicted to have the smallest sized panels was found to be 4x larger in DACs than in non-DACs, representing a significant equity challenge. Despite these encouraging findings in terms of the low estimated proportions of properties with panels in this smallest size category, significant proportions of properties within each sector, 32% for SF and 59% for MF, were found to have panel sizes that will likely require implementation of different load management strategies in order to support comprehensive electrification.

Recent estimates derived from state incentive programs place the average cost of upgrading the service panel at a SF property between \$2500-\$5000 per dwelling unit (TECH Clean California, 2024). For the MF sector, these costs are less well documented, but generally understood to be much higher per property, with two recent studies estimating the cost of MF panel upgrades as \$12k-\$89k for smaller properties and between \$179k-\$281k for larger sized properties (StopWaste 2021; Betony, 2021). In the latter case, significant portions of these costs can often be attributed to infrastructure upgrades associated with the move to three-phase service and/or the need to install new step-down transformer hardware for the utility to be able to accommodate the increased site loads. Costs are anticipated to be a significant barrier to increasing the rates of these upgrades such that the distribution of panel sizes within DAC properties reaches parity with non-DACs in the near future. In addition to this cost barrier, DAC residents also disproportionately live within MF properties which, across the board, are far less likely to have received panel upgrades than SF homes due to the aforementioned

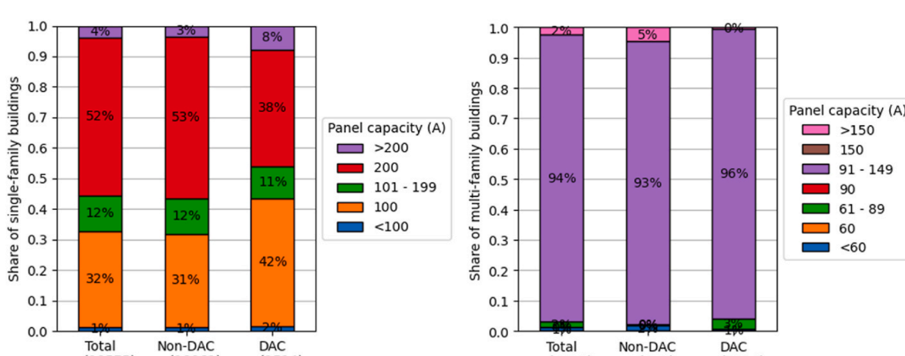

Fig. 7. Panel size ratings among directly observed panel upgrade permits for single-family (left) and multi-family (right) properties, both overall and disaggregated by DAC status.

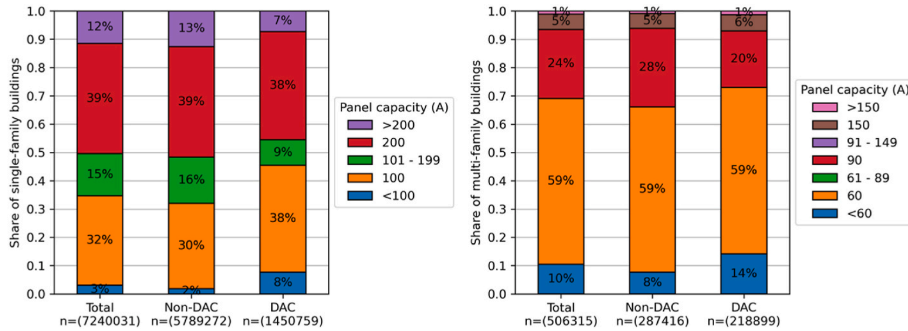

Fig. 8. Estimated panel size ratings for California single-family (left) and multi-family (right) properties, both in total and disaggregated by DAC status.

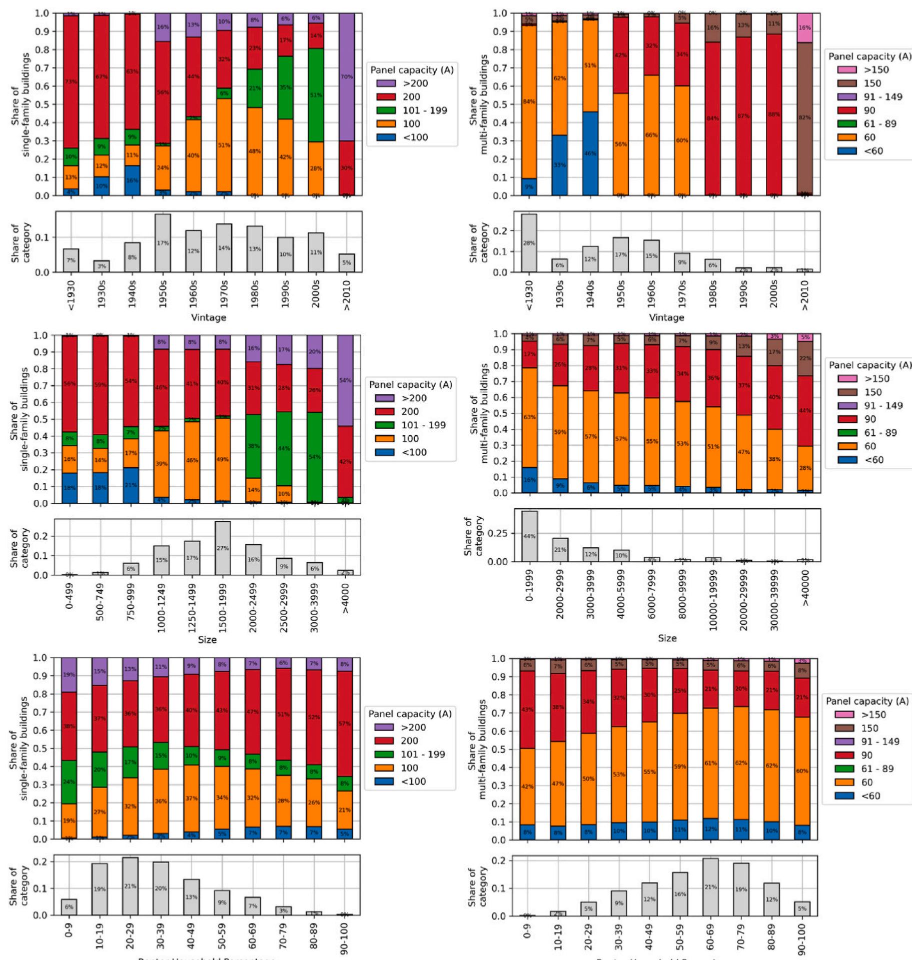

Fig. 9. Estimated panel size ratings for California single-family (left) and multi-family (right) properties, disaggregated by building construction vintage year range values (top), building size (ft^2) range values (middle), and the renter household percentage of the containing census tract (bottom).

split incentive problem. Though it was encouraging to observe in the assembled permit data that normalized rates of panel upgrades were even slightly higher within DACs than in non-DACs.

Precisely how many properties will actually require service panel upgrades going forward will depend significantly on the amount of progress which is made in reducing the power demands of new generations of electrical appliances and equipment. Importantly, however, it will also depend on the ways in which consumers respond and adapt to any potential changes in the performance capabilities of these new appliances as well as any trade-offs which might be associated with the use of circuit splitting hardware to connect multiple large end-use loads to a service panel that has insufficient capacity to run them simultaneously.

There is also growing interest in opportunities to avoid panel upgrades through the adoption of new low-power draw appliances which can operate off of standard 120-V outlets. It remains to be seen whether the efficiency improvements that can be achieved by this emerging category of low power equipment will be sufficient to render the same quantity (and quality) of energy services as had been provided by the higher power output devices which they are replacing. Much will likely depend upon individual user tastes and preferences. However, it seems that going forward more research will be necessary to better understand whether or not the installation of low power equipment meaningfully impacts patterns of use and levels of user satisfaction.

As demonstrated from the analysis of the permit dataset assembled as part of this research, the adoption of rooftop solar and, to a lesser extent, battery energy storage systems have been significant drivers of service panel upgrades. Future changes to net metering tariffs or other incentive structures which affect the cost or attractiveness of these types of distributed energy resources could significantly alter the rate of “natural” service panel upgrades from that which has been observed in recent years. Though seldom discussed, the fact that rooftop solar PV installations typically require panel upgrades amounts to an important ancillary benefit from efforts to increase the adoption of distributed solar PV, particularly within less affluent, underserved communities.

7. Conclusions and policy implications

As California seeks to electrify its residential sector, the hope is that the increased power efficiency of electrical appliances and paradigmatic shifts in the ways in which they operate–such as with heat pump technologies, for instance–can minimize the need for service panel upgrades. This outcome is far from guaranteed, however, as many property owners tend not to be aware that panel capacities could be a potential issue until faced with a marginal appliance upgrade decision, such as in the case of existing equipment failure. Moreover, many electrical contractors still do not have experience with, and thus are not likely to recommend, different load management strategies that could be used as alternatives to panel upgrades. These issues need to be addressed through improved contractor and consumer education, particularly at the point of sale for new electrical appliances and equipment.

Based upon the results of this analysis, it is clear that direct assistance programs will be required to ensure that low-income households are able to electrify without experiencing diminished quality energy services in the process. This is particularly true if new regulations are enacted in the future which result in the phase out of gas combustion in specific end-uses. Significant questions remain in terms of how generous the state is willing and able to be in terms of subsidizing panel upgrades or the installation of dynamic load management measures within DACs. Existing electrification incentive programs are primarily financed using utility ratepayer funds and mostly oriented towards SF homeowners. However, with the impending introduction of new Inflation Reduction Act (IRA) funded programs, taxpayer dollars will increasingly be used for this purpose as well, and with a renewed emphasis on renters and MF properties. Despite the increasing availability of such funding and improvements to program designs, incentives have historically been underutilized by qualifying DAC households (Scavo et al., 2016). This suggests that a lack of homeowner capital for service panel upgrades or demand management measures may continue to exclude low-income Californians from fully electrifying their homes.

Regardless of where it comes from, the process of providing financial support to DAC and low-income households facing panel capacity barriers to electrification must become more seamless and immediate. The process must minimize, or eliminate, time spent searching for programs, assessing eligibility, and waiting for retroactive rebate funding applications. This can be accomplished through the expansion of funding allocated to programs with statewide geographic eligibility, like TECH Clean California, which provides layerable incentives that are dispersed mid- or up-stream to contractors and equipment manufacturers, in ways that are transparent to consumers.

EV charging, which represents the addition of a fundamentally new category of end-use energy service within existing buildings, is likely to play a major role in determining the number of panel upgrades that are ultimately required. The power demands of EV chargers strongly correlate with the size and weight of EV models. This means that if new generations of EVs continue to skew towards the types of larger, heavier, SUV-type designs which have traditionally found favor in the American market, they will require correspondingly large batteries in order to deliver comparable driving ranges to similar ICE vehicles. The ability to charge such large vehicles overnight at one’s home, a reasonable consumer expectation, can require substantial electrical current; with some new high-power home EV chargers now consuming as much as 100 Amps of dedicated breaker space in a service panel (Acharige et al., 2023). Fortunately, these EV charging loads are quite flexible and there should be opportunities to modulate them using automated controls. However, accessing these capabilities requires the installation of new equipment, some of which may not yet be commercially available within certain multi-family contexts. Implementing these solutions also necessitate access to knowledgeable contractors willing to perform the work, something which can still be a challenge in certain areas.

The growing availability of these types of new load management solutions challenges the traditional operating assumption that service panels must be sized to accommodate the simultaneous peak draw of all installed end-use equipment within a structure. With circuit switching devices for example, the customer is left to decide which end-uses should be allowed to operate at any given time. With smart panels and breakers, such decisions are largely left to software controls which are programmed to operate within a set power threshold. It is interesting to observe that in the not-so-distant past, people were accustomed to adjusting their appliance use relative to their circuit capacities, understanding that if too many appliances were on at once, the circuit could be tripped. Today, it seems that this situation is unacceptable, providing insight into contemporary expectations of the levels of power that are accessible at residences.

Moving forward, building occupants may once again be faced with new limitations on when and how they are able use their appliances. This is in addition to any performance changes that they might experience from the choice of lower power equipment. These limitations were not something which individuals would likely have had previously considered when their different devices were fueled by different energy sources and thus, not similarly power constrained. It is natural to conclude that such limitations could potentially be perceived as a reduction in capability of these new equipment, given today’s expectations for high power output energy appliances. The promulgation of such negative opinions of electrical appliances and equipment could affect the decision of future property owners to adopt fuel substitution measures going forward. Despite this, we believe strongly that such desires for more and more capable end-use energy equipment should always be evaluated within a rational framework that is grounded in the principles of energy sufficiency (Fournier et al., 2020; Malik et al., 2024).

There is currently significant interest among researchers to better understand the frequency and duration of times in which customers encounter worst-case concurrent load conditions. This is a topic which will become of increasing importance as the implications of all these new power-hungry electrical devices for grid transmission and distribution infrastructure capacity upgrades come into focus. Along these lines, more work is needed to assess when, where, and why different customers do or do not make full use of their service panel’s existing capacity. It is possible that such work could glean new insights into structural drivers of high-power demand that could guide revisions to future iterations of NEC panel sizing guidelines. These could hopefully be more nuanced than blanket calls for ever larger panel sizes over time. It would also be interesting to see how smart panel capabilities might be integrated with demand response programs or even rate tariffs to ensure that the infrastructure costs of high-power users are properly allocated to them. There are meaningful equity implications associated with both the quantity of power that is accessible to a home as well as what proportion of this capacity ultimately gets utilized.

A final take home message of this analysis is the need to seriously think through how the electrification transition and any corresponding needs for panel upgrades will be realized within the MF sector. The estimated percentages of MF properties with panel sizes that are likely insufficient to support full electrification without substantial building energy system retrofits are extremely high in many areas throughout the state. Moreover, there simply aren’t strong incentives for MF property owners to undertake such costly and intensive retrofit work at this time.

More concerted efforts should be taken to better understand the costs and complexities associated with the technical implementation of panel upgrades within different MF contexts. Moreover, different incentive structures to promote the rate at which this work is occurring need to be proposed and evaluated using seed grants, pilot programs, and other mechanisms. Failure to adequately address the conditions of these MF structures will result in an inequitable distribution of both the costs and benefits associated with this transition.

CRediT authorship contribution statement

Eric Daniel Fournier: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Robert Cudd:** Writing – review & editing, Writing – original draft, Conceptualization. **Samantha Smithies:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis. **Stephanie Pincetl:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Eric Daniel Fournier reports financial support was provided by California Air Resources Board. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1
Breakdown of total parcel counts and relative coverage rates for the panel size estimation procedure by county.

County	Single-Family Properties			Multi-Family Properties		
	Total	Modeled	Coverage Percent	Total	Modeled	Coverage Percent
Alameda County	327,245	316,236	96.64	29,307	25,383	86.61
Alpine County	829	713	86.01	19	17	89.47
Amador County	10,322	9784	94.79	86	81	94.19
Butte County	58,103	54,179	93.25	2029	1992	98.18
Calaveras County	20,737	17,520	84.49	216	185	85.65
Colusa County	4836	4645	96.05	147	136	92.52
Contra Costa County	297,548	295,948	99.46	9040	8789	97.22
Del Norte County	3982	2391	60.05	196	179	91.33
El Dorado County	50,519	48,228	95.47	1885	1819	96.50
Fresno County	199,356	161,885	81.20	7396	2789	37.71
Glenn County	4634	4488	96.85	191	191	100.00
Humboldt County	30,809	12,137	39.39	4316	2657	61.56
Imperial County	33,922	3238	9.55	1231	609	49.47
Inyo County	5589	5142	92.00	148	145	97.97
Kern County	192,189	175,866	91.51	18,544	9941	53.61
Kings County	29,203	27,635	94.63	832	754	90.63
Lake County	22,553	16,448	72.93	374	342	91.44
Lassen County	6101	5412	88.71	333	319	95.80
Los Angeles County	1,476,464	1,462,897	99.08	240,137	237,456	98.88
Madera County	30,254	28,498	94.20	1212	1130	93.23
Marin County	59,658	58,416	97.92	4230	3465	81.91
Mariposa County	3520	1872	53.18	9	7	77.78
Mendocino County	11,471	1945	16.96	898	381	42.43
Merced County	57,546	56,451	98.10	3040	2523	82.99
Modoc County	2269	1920	84.62	3	3	100.00
Mono County	5814	5269	90.63	168	163	97.02
Monterey County	69,098	67,658	97.92	5613	4906	87.40
Napa County	27,354	27,056	98.91	2156	1700	78.85
Nevada County	25,710	23,684	92.12	190	170	89.47
Orange County	587,173	543,239	92.52	25,872	23,684	91.54
Placer County	117,104	112,480	96.05	2779	2684	96.58
Plumas County	12,366	10,605	85.76	178	161	90.45
Riverside County	599,744	585,799	97.67	7856	6898	87.81
Sacramento County	394,076	383,461	97.31	19,406	18,758	96.66
San Benito County	11,579	4037	34.86	744	458	61.56
San Bernardino County	489,179	478,866	97.89	12,109	10,600	87.54
San Diego County	545,159	507,499	93.09	42,144	28,151	66.80
San Francisco County	96,952	96,174	99.20	31,590	31,456	99.58
San Joaquin County	173,535	170,164	98.06	8887	8214	92.43
San Luis Obispo County	72,636	68,636	94.49	3975	3048	76.68

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Table A1 (*continued*)

County	Single-Family Properties			Multi-Family Properties		
	Total	Modeled	Coverage Percent	Total	Modeled	Coverage Percent
San Mateo County	156,748	154,713	98.70	10,190	9718	95.37
Santa Barbara County	86,409	79,291	91.76	3746	1982	52.91
Santa Clara County	343,429	341,849	99.54	19,887	19,652	98.82
Santa Cruz County	56,796	44,432	78.23	4130	2726	66.00
Shasta County	40,771	38,422	94.24	2322	1949	83.94
Sierra County	2021	831	41.12	4	2	50.00
Siskiyou County	8859	6348	71.66	337	137	40.65
Solano County	114,648	112,104	97.78	3674	3056	83.18
Sonoma County	110,175	108,628	98.60	5934	5544	93.43
Stanislaus County	123,168	122,086	99.12	5657	5457	96.46
Sutter County	20,228	19,838	98.07	1111	989	89.02
Tehama County	9834	8485	86.28	515	461	89.51
Trinity County	5009	18	0.36	46	31	67.39
Tulare County	103,284	93,570	90.59	3748	3310	88.31
Tuolumne County	16,544	15,745	95.17	656	451	68.75
Ventura County	180,287	174,642	96.87	6264	5644	90.10
Yolo County	47,317	44,905	94.90	2087	1776	85.10
Yuba County	17,356	15,603	89.90	1159	1086	93.70
Overall	7,610,021	7,240,031	95.14	560,953	506,315	90.00

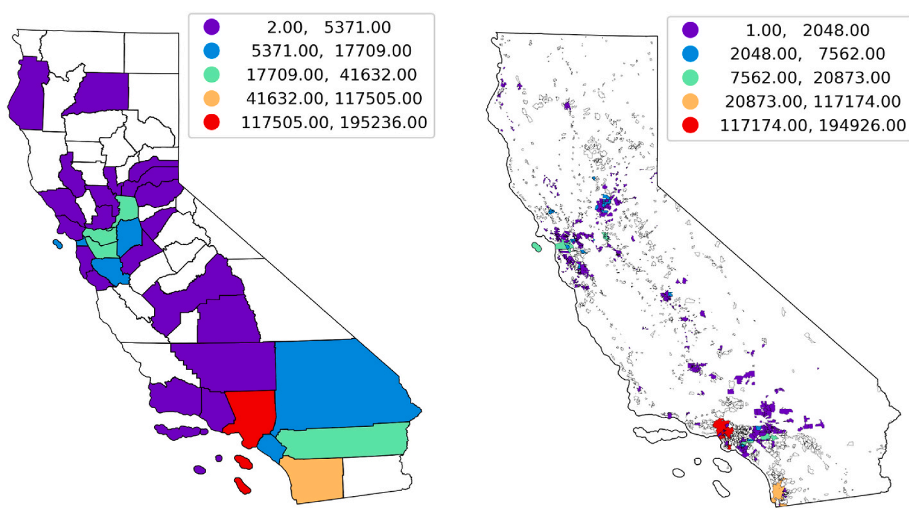

Fig. A1. Counties (left) and census designated places (right) for which permit data were obtained. In each, areas are colored according to the total numbers of collected permits.

Table A2
Breakdown of permit counts by source municipality and derived classification with min/max ranges for issue dates.

Permit Source Municipality	Total Permits	Permit Upgrade Observations		Permits for Other Related Work	Minimum Permit Issue Date	Maximum Permit Issue Date
		With Destination Panel Size	Without Destination Panel Size			
Los Angeles City	205,665	56,951	37,286	111,428	1996-10-03	2022-08-18
San Diego City	132,287	12,584	32,067	87,636	2002-06-19	2022-08-22
Sacramento County	47,126	7891	16,042	23,193	2007-01-02	2022-08-18
Contra Costa County	26,357	3500	7695	15,162	1986-09-26	2022-09-05
Oakland City	22,225	3327	3663	15,235	1982-09-16	2022-09-02
Moreno Valley City	20,266	2349	10,693	7224	2002-04-22	2022-11-02
Anaheim City	16,254	6251	1712	8291	1999-12-02	2022-07-29
Riverside City	13,977	5919	6150	1908	2013-01-02	2022-08-19
San Bernardino County	12,763	3040	5049	4674	2017-07-31	2022-07-20
San Francisco County	11,416	465	6868	4083	1981-04-10	2023-01-27
San Francisco City	11,416	465	6868	4083	1981-04-10	2023-01-27
Stockton City	9673	1754	888	7031	2005-05-09	2018-02-15
Santa Ana City	8061	1735	2843	3483	1963-12-27	2022-09-06
Pleasanton City	6302	221	1956	4125	2011-05-24	2022-08-03
San Mateo County	6236	991	2553	2692	1990-11-08	2022-07-28
Corona City	5478	567	1674	3237	2017-07-31	2022-07-25
Marin County	5091	779	440	3872	2017-04-12	2022-08-22
Rancho Cucamonga City	5026	24	537	4465	2017-04-26	2022-07-20

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Table A2 (*continued*)

Permit Source Municipality	Total Permits	Permit Upgrade Observations		Permits for Other Related Work	Minimum Permit Issue Date	Maximum Permit Issue Date
		With Destination Panel Size	Without Destination Panel Size			
West Sacramento City	4934	514	362	4058	1998-04-21	2022-07-21
Santa Rosa City	4593	3469	244	880	2010-07-26	2022-07-21
Roseville City	4577	542	234	3801	2013-07-01	2023-01-26
Yuba City	4348	534	994	2820	2017-01-17	2022-07-21
Garden Grove City	4106	1113	2135	858	2018-04-11	2022-09-02
Yorba Linda City	4014	10	36	3968	2014-12-10	2022-07-21
Alameda City	3970	713	1141	2116	1935-09-23	2020-05-22
Clovis City	3113	1095	1033	985	2011-07-06	2022-09-19
Placer County	1998	443	924	631	2022-02-16	2022-03-25
San Mateo City	1934	656	658	620	2015-06-04	2022-07-20
Humboldt County	1534	369	160	1005	2018-09-23	2022-07-21
Nevada County	1510	212	166	1132	2005-11-10	2022-07-12
Redding City	1404	313	51	1040	2011-12-19	2022-07-19
Paso Robles City	1393	2	0	1391	2018-01-03	2022-08-29
Lake County	1375	138	103	1134	2019-01-15	2022-08-04
Victorville City	1178	193	32	953	2018-02-12	2022-05-12
Los Gatos Town	1131	409	108	614	1995-07-06	2022-07-27
Ceres City	1074	153	122	799	1998-04-06	2022-08-03
San Rafael City	1009	189	45	775	2003-06-10	2022-07-22
Kern County	948	9	747	192	2014-03-31	2022-07-20
Fresno City	543	432	55	56	2020-02-18	2021-02-16
Santa Monica City	329	19	120	190	2016-06-24	2022-08-09
Ojai City	300	118	78	104	2018-02-20	2022-07-18
Elk Grove City	116	45	6	65	N/A	N/A
Tulare County	105	12	13	80	2011-09-01	2015-10-22
Fairfield City	24	0	0	24	2014-08-13	2019-11-08
Richmond City	10	4	1	5	N/A	N/A
El Dorado County	8	0	0	8	2018-05-17	2018-07-27
Yolo County	3	2	1	0	N/A	N/A
Overall	617,200	120,521	154,553	342,126	1935-09-03	2023-01-27

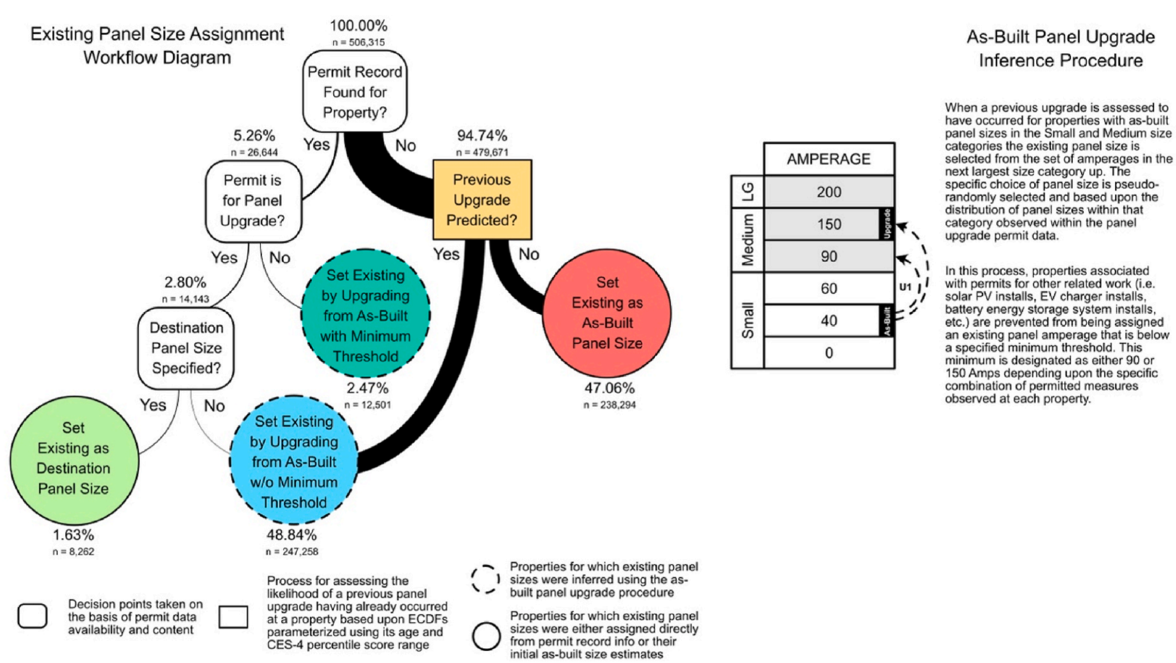

Fig. A2. Multi-family property workflow diagram and as-built upgrade procedure summary.

Table A3
Inferred single-family as-built panel size ratings based upon construction vintage year and floor area value ranges.

Inferred As-Built Panel Size Rating	Illustration	Construction Vintage Year Range	Floor Area Range (ft^2)
None	None	(0, 1879]	0 - >20,000

(*continued on next page*)

Table A3 (*continued*)

Inferred As-Built Panel Size Rating	Illustration	Construction Vintage Year Range	Floor Area Range (ft^2)
30 Amps		(1879,1950]	<1000
40 Amps		(1879,1950]	1000–2000
60 Amps		(1879,1950]	2000–3000
		(1950,1978]	<1000
100 Amps		(1879,1950]	3000–4000
		(1950,1978]	1000–2000
		(1950,1978]	2000–3000
		(1978,2010]	<1000
		(1978,2010]	1000–2000
125 Amps		(1879,1950]	4000–5000
		(1950,1978]	3000–4000
		(1978,2010]	2000–3000
150 Amps		(1879,1950]	5000–8000
		(1950,1978]	4000–5000
		(1978,2010]	3000–4000
200 Amps		(1879,1950]	8000–10,000
		(1950,1978]	5000–8000
		(1978,2010]	4000–5000
		(2010,2023]	<2000
225 Amps		(2010,2023]	2000–3000
320 Amps		(1879,1950]	10,000–20,000
		(1950,1978]	8000–10,000
		(1978,2010]	5000–8000
		(2010,2023]	3000–4000
400 Amps		(1879,1950]	>20,000
		(1950,1978]	10,000–20,000
		(1978,2010]	8000–10,000
		(2010,2023]	4000–5000
600 Amps		(1950,1978]	>20,000
		(1978,2010]	10,000–20,000
		(2010,2023]	5000–8000
800 Amps		(1978,2010]	>20,000
		(2010,2023]	8000–10,000
1000 Amps		(2010,2023]	10,000–20,000
1200 Amps		(2010,2023]	>20,000

Table A4
Inferred multi-family as-built tenant unit panel size ratings based upon construction vintage year.

Inferred As-Built Panel Size Rating per Unit	Illustration	Construction Vintage Year Range
0 Amps	None	(0,1879]
40 Amps		(1879,1950]
60 Amps		(1950,1978]
90 Amps		(1978,2010]
150 Amps		(2010,2023]

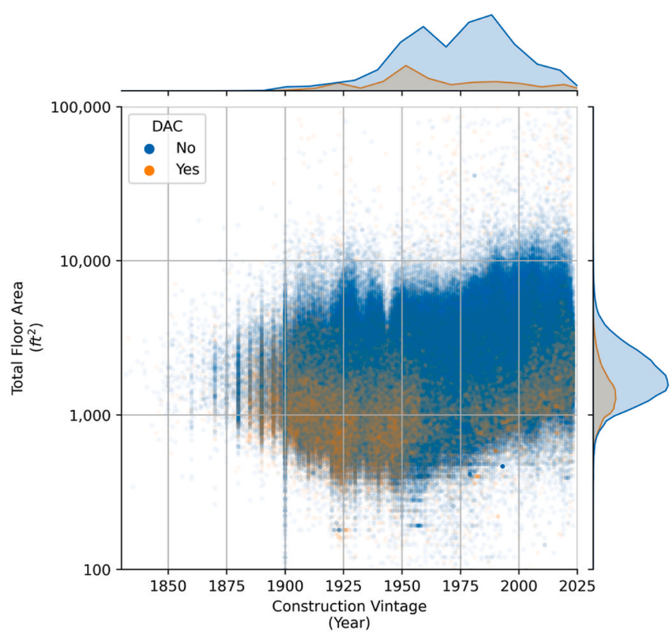

Fig. A3. Joint-distribution plot of the total floor area and construction vintage of California single-family housing stock, separated by DAC status (Note the log-scale of the y-axis).

Table A5
Cross tabulation of single-family properties analyzed by floor-area range and construction vintage year range.

Construction Vintage Year Range	(0, 1950]	(0, 1950]	(1950, 1978]	(1950, 1978]	(1978, 2010]	(1978, 2010]	(2010, 2023]	(2010, 2023]
DAC Status	No	Yes	No	Yes	No	Yes	No	Yes
Floor Area Range (ft^2)								
(0, 1000]	159,697	149,248	127,122	61,844	34,692	12,251	1541	447
(1,000, 2000]	512,517	292,249	1,606,200	420,341	1,089,575	270,698	81,814	36,527
(2,000, 3000]	133,872	24,146	493,132	34,959	816,604	80,215	134,733	33,605
(3,000, 4000]	32,399	3067	73,152	2545	274,784	15,846	51,142	7667
(4,000, 5000]	9436	565	14,930	321	67,028	1689	14,727	1032
(5,000, 8000]	5861	241	5877	132	31,772	421	7683	270
(8,000, 10,000]	713	31	393	20	2933	36	991	17
(10,000, 20,000]	429	45	232	37	1809	33	814	19
(20,000, 1,000,000]	38	26	77	3	202	2	139	1

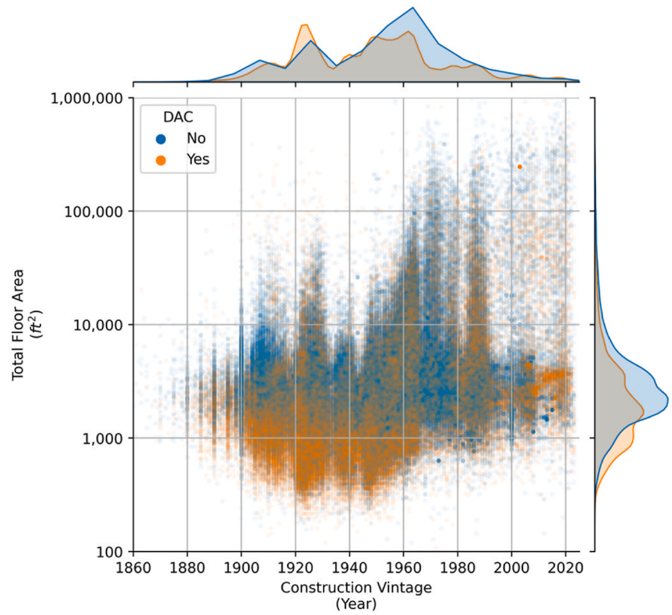

Fig. A4. Joint-distribution plot of the total floor area and construction vintage of California multi-family housing stock, separated by DAC status (Note the log-scale of the y-axis).

Table A6
Cross tabulation of multi-family properties analyzed by total number of units and construction vintage year range.

Construction Vintage Year Range	(0, 1950]	(0, 1950]	(1950, 1978]	(1950, 1978]	(1978, 2010]	(1978, 2010]	(2010, 2023]	(2010, 2023]
DAC Status	No	Yes	No	Yes	No	Yes	No	Yes
Number of Units Range								
(0, 3]	68,233	75,163	33,512	21,356	8782	5896	772	1979
(3, 5]	15,193	16,124	16,086	10,540	2092	2275	173	497
(5, 10]	7676	6028	12,818	9677	1983	2624	132	156
(10, 25]	3550	2264	6891	4702	1650	1628	172	137
(25, 50]	713	573	2237	1603	799	759	142	173
(50, 100]	198	145	826	440	503	423	117	132
(100, 250]	52	32	399	184	501	158	164	71
(250, 500]	2	8	69	26	130	22	99	30
(500, 1000]	5	1	17	1	14	4	10	5

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