Zero-Emission Retrofit Assessment Model

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ABSTRACT

Reducing health risks and environmental damage requires switching from emission-producing equipment to zero-emission ready alternatives. But to be effective, rules and policies must reflect the real-world conditions in buildings. To cut emissions from millions of buildings, we need to understand key details about each building, like how much roof space it has, whether it has space for ventilation in mechanical rooms, and how much space is left on the electrical panel. These details all affect whether a building can switch to zero-emissions ready equipment.

Current data sources often list building features one by one. However, they usually do not show how these systems interact, especially across different end uses like space heating, water heating, cooking, pools, and laundry. A building's readiness to switch to zero-emission ready equipment depends on how these systems work together. It does not depend on each system by itself. Any equipment that is already electric is assumed to be zero-emissions and so no update is needed.

This paper introduces a modeling approach TRC developed with CARB to support zero-emissions regulations. We start with NREL's ComStock (2024 Release 1) dataset to simulate a realistic set of buildings. We include important building details, how different end uses interact, and differences by location. Then we apply an engineering method to estimate what upgrades each building needs and whether it is ready for zero-emissions equipment.

Early results show that our model can find patterns that are not clear when looking at building features on their own. This joint approach gives policymakers better information and helps identify building types that may need more support during the electrification process.

Introduction

Decarbonizing California's buildings plays a key role in meeting the state's climate goals. In non-residential buildings, this effort depends on using zero-emissions ready equipment across many systems, such as space heating, water heating, cooking, pool heating, and laundry. Switching to zero-emissions equipment reduces greenhouse gas emissions, improves indoor and outdoor air quality, and helps reduce long-term energy costs. However, we still know little about how ready buildings are to make this change in practice.

To support the shift to zero-emission ready equipment, policymakers and program designers need better data. They need to understand which buildings are ready to adopt zero-emissions equipment and which buildings face technical barriers. This includes checking things like electrical panel capacity, roof space, and access to outside air for heat pumps. They also need to know how different systems interact inside buildings; for example, a building might have enough roof space for a heat pump water heater but not for both water and space heating systems.

This paper introduces a new modeling approach to address this gap using the ComStock database as the foundation. ComStock is a comprehensive, open-source database of building energy models developed by National Renewable Energy Laboratory (NREL). It represents a wide range of building types, sizes, vintages, and technologies across the United States. The dataset combines public survey data, energy codes, engineering assumptions, and simulation outputs to create detailed building prototypes that capture real-world variability in building characteristics and energy use. ComStock has 39,346 building prototypes modeled in California, each with space heating system type, water heating and cooking fuel, and other building characteristics. TRC uses a version of NREL's ComStock (2024 Release 1) dataset to simulate a representative group of non-residential buildings in California. Then, we apply engineering-based rules to estimate how many buildings are ready to install zero-emissions equipment. The model combines building characteristics with end-use requirements to estimate retrofit levels across the full population.

By analyzing these combined effects, the model shows patterns that are hard to see when looking at one system at a time. This approach gives decision-makers more useful insights and helps them design better policies and programs.

Methodology

Zero-Emissions Retrofit Assessment Model

As described in the 2022 State SIP Strategy, the scope of the zero-emission GHG standards is that all new space and water heaters sold and installed in new and existing residential and nonresidential buildings must be zero GHG emission starting in 2030. CARB staff are also exploring the inclusion of other end uses, such as clothes drying, cooking, and pool heating, in the zero-emission appliance standards. TRC developed a zero-emissions retrofit assessment model to understand how buildings can upgrade to zero-emissions equipment across five main end uses: space heating, water heating, cooking, pool and spa heating, and laundry.

Retrofit levels depend on how all these systems interact. For example, a building might have enough electrical panel capacity to upgrade space heating or cooking alone, but not both. Because of this, the model looks at the combined impact of upgrading multiple systems. It does not rely on separate statistics for each system. Instead, it uses individual, representative buildings to test whether upgrades are possible. This approach allows us to assess whether each building can upgrade based on its own set of features.

We also use the model to test how building retrofit levels might change under different scenarios. For example, we can test the impact of a new regulation or a change in market trends by simulating a new population. This flexibility helps us explore how different conditions affect upgrade feasibility. The model runs in R, an open-source statistical programming language.

In this paper, "simulation" means building a population of buildings based on weights from ComStock and other data sources. It does not mean simulating building energy use with tools like EnergyPlus or eQuest. ComStock already includes energy-modeled archetypes. The building archetypes in ComStock are based on such building simulation models and building stock data; this model is using those, not developing new ones.

Modeling Steps

The model proceeds through the following five steps:

1. Generate the simulated population of buildings.
2. Determine existing equipment types and building characteristics.
3. Identify replacement zero-emissions equipment.
4. Assess retrofit levels at the end-use level.
5. Aggregate retrofit levels at the building level.

Generate the Simulated Population of Buildings

The first step is to generate a population of non-residential buildings that represents California's building stock. We use the ComStock dataset, which includes 39,346 modeled building prototypes in

California. Each prototype has associated characteristics (e.g., HVAC system type, water heating fuel, cooking fuel) and an assigned weight representing its prevalence in the statewide building stock.

At the low end, two rare building prototypes in Alpine County (weight = 5.18) represent 262,005 square feet, while three prototypes in Sierra County (weight = 11.3) represent 42,342 square feet. At the high end, 10,251 prototypes with a weight of 42,601.6 represent 1.66 billion square feet.

Overall, the total weighted square footage is 6.5 billion sq ft, which is somewhat less than the 8.8 billion sq ft estimated by the California End-Use Survey (CEUS) (CEUS 2024). This discrepancy likely reflects differences in covered building types and sampling methodology.

ComStock does not contain data on pool and spa heating as well as clothes drying end use. Data from additional sources, including CEUS, CBECS, and DEER, is used to supplement these end uses.

- Space heating and cooling data include both heating and cooling systems as the existing cooling system impacts the ease of adopt a heat pump for heating.
- Water heating data are classified as heat pump and non-heat pump hot water heater.
- Cooking data is separated into different types of equipment such as broiler, fryer, griddle, oven, range and steamers. We collected various data on these end-uses such as energy consumption, energy savings, fuel type as well as equipment capacity, efficiency, count, etc.
- Pool and spa heating were collected from external sources such as TripAdvisor listings. These sources provided the prevalence of heated pools across different building types.
- Clothes drying data were supplemented using CEUS, CBECS, and DEER. These sources provided information on fuel type (emissive system or electric), prevalence across building types, and typical equipment sizes.

To generate the population of buildings based on the set of building prototypes, we randomly generate a set a buildings replicating the building prototypes at the US Census Tract-level using the multinomial distribution and the associated weights. The multinomial distribution allows us to model different types of buildings (e.g., office, retail, restaurant) according to their relative frequencies across each area. The multinomial distribution represents the likelihood of observing a set of outcomes with a fixed percentage for a known set of trial, such as pulling a specific number of red, yellow, and blue beads out of a jar with known percentages of each color. In this case, we will randomly generate the number of buildings in each tract equal to the sum of the weights in each tract, with probability for each building prototype equal to the proportion of total weight in that tract. We randomly generate buildings rather than deterministically duplicating the building prototypes in order to better reflect the weighting structure that underlies the ComStock output data. Deterministic duplication would mean copying each prototype exactly as many times as its weight suggests, creating a fixed set of buildings. In contrast, the random method preserves the overall distribution but introduces variability at the individual level, which better reflects uncertainty and prevents overly uniform clusters in small areas.

Determine Existing Equipment Types and Building Characteristics

Once the population of buildings has been developed, we determine the existing building characteristics. There are multiple elements to this step: determining specific equipment or system types, determining overall system sizes/capacities, and determining building characteristics.

For space heating system, ComStock provides the system type, so no further determination is necessary. For water heating, ComStock provides a fuel type, but not a specific system type. If the fuel type is electric, it is already considered zero emission and so the specific system type (electric resistance, heat pump, or hybrid) is not further investigated. If the fuel type is gas, we assume it is either boiler or a tanked water heater, depending on capacity. ComStock also provides fuel type for cooking equipment, but for specific types of cooking equipment, such as fryers and griddles. We do not attempt to distinguish between different styles or models of cooking equipment beyond the overall equipment type and fuel type.

Pool and spa heating and laundry are much less common end uses in commercial buildings and are not included in ComStock building prototypes. We expect these to be primarily concentrated in hotels, colleges and universities, and laundromats. These end uses were determined by leveraging data sources outside of ComStock, including CEUS, CBECS, CASE, and DEER.

In addition to system type and fuel, we determine system capacity/size to determine the overall retrofit levels as larger systems will require larger replacement systems that may require more power, more space, or more structural support. ComStock includes the number of space and water heating units in a series of capacity bins; for cooking, it provides number of pieces of each type of equipment, as well as total energy use.

We also need to determine building characteristics, in particular, roof space, and electrical panel capacity. For roof space, we are relying on the exterior roof area provided by ComStock.

For electrical panel capacity, we are relying on expert input from ICI Engineers, electric code rules, and typical panel sizes to estimate current panel size.

We start by converting building's hourly peak electric demand (in kW) to apparent power (in kVA) using a power factor of 0.9. A power factor of 0.9 is a common assumption for commercial buildings because it reflects typical mixed-use electrical loads with some inductive equipment. Other power factors, such as 0.85 or 1.0, are also used in practice, but 0.9 offers a reasonable balance between conservative and efficient design. For example, a peak load of 150 kW becomes roughly 167 kVA (150/0.9).

We then select the smallest standard panel size that can handle this demand with at least 20% buffer capacity. The panel must have at least 20% spare capacity to allow for safety and future load growth, following typical design practice. In this example a 200 kVA panel would cover 167 kVA but not provide the required buffer (since 167 kVA is more than 80% of 200 kVA). Therefore, we assumed a 400 kVA panel would be provided, meeting the buffer typically provided and representing the next common size available from manufacturers larger than a 200 kVA panel.

We need to understand if there is enough roof space available in these buildings, since there is a space impact requirement. We reviewed the documentation that ICI had developed and concluded that most of the space heating upgrades do not have space impact. Some do have a 30% or 50% impact however, these are not significant numbers unless the ratio of roof area to number of floors is too low.

Determine replacement zero-emissions equipment

Based on the existing equipment, the next step is to determine the necessary replacement equipment. We estimated the diversity of a building's potential replacement equipment, prioritizing options that minimize the need for other building upgrades. Where there is more than one likely zero-emissions replacement option, the team estimated the likelihood of each system based on the project team's judgment and validated through review by our engineering subcontractor ICI. Any existing electric equipment is assumed to be zero-emission, and so a zero-emission replacement does not need to be considered.

For gas and propane emissive systems, we mapped the replacement system type to the existing system type based on a review of several data sources and the experience of our engineering team. (Houssainy 2024)(CBE 2022) For some systems, like rooftop single-zone packaged air conditioners with emissive furnaces, the most likely replacement system is a direct replacement with a rooftop single-zone packaged heat pump and requires minimal consideration of alternative system types. However, for service hot water applications and multizone heating, the project team developed probabilities for various replacement options, accounting for factors such as building type (small/large, use, etc.), climate, retrofit scope and cost, and replacement system complexity level.

For pool and spa heating, laundry, and cooking which only have electrical retrofit criteria when converting to zero emission equipment. there are no additional retrofit needs related to physical space, heat source, or structural needs. The project team only needed basic information about the existing bulk emissive appliance usage to make an estimate about the zero-emission alternative appliance electrical usage, and considering of various options were unnecessary

End use level retrofit needs

For each end use and retrofit criteria, a building will be categorized into a retrofit level that describes the level of additional retrofit needed to install zero-emission equipment replacements. The retrofit levels are defined in Table 1.

Table 1. Retrofit level categories and definitions

Retrofit threshold	Interior space and exterior space	Structural	Electrical	Heat source
No retrofit	Limited or no changes required for zero-emission equipment in comparison to a like-for-like replacement.	No structural impact.	<10% increase of existing electrical capacity will be needed. Most if not all existing circuits, breakers, and other infrastructure are adequate for zero-emission equipment replacement.	No additional ventilation needs.
Minor	Estimated cost increase over a like-for-like replacement of approximately 10-50%.	Structural review. May require additional structural support.	10-40% increase in existing electrical capacity. New circuits and breaker installation necessary. Subpanels, low voltage devices, or power control devices can avoid a service upgrade.	Ventilation to mechanical room on exterior wall.
Moderate	Estimated cost increase over a like-for-like replacement of greater than 50%, a combination of the existing mechanical room, roof, or adjacent ground-level is anticipated to meet the need.	Moderate reinforcement necessary.	40-200% increase in existing electrical capacity. New circuits, breakers, panel, and likely a new electrical service will be necessary.	Ventilation to interior mechanical room.
Major	Significant cost increase and existing occupancies are likely needed to be repurposed to house zero-emission equipment or infrastructure needs.	Significant reinforcement necessary.	>200% increase in existing electrical capacity. New circuits, panels, electrical service, and likely modifications to the electrical room.	Ventilation to interior mechanical room.
Already zero-emission	Buildings and end uses that are already zero-emission, therefore they can install zero-emission replacement equipment with no additional retrofit needs.			
Not applicable	End uses that are not applicable to the analysis because 1) the end use is not present in that building and therefore a replacement is not applicable, and 2) fuel type (district) is not within the scope of the assessment.			

- For exterior roof space and electrical capacity, the retrofit level will be based on whether the increased capacity exceeds the available additional capacity. For heat source/ventilation needs, this will depend on system type, typical design, and location. For example, systems on the roof have access to atmospheric air and need no additional ventilation and relatively small buildings are likely to have mechanical rooms on an exterior wall that make ventilation straight-forward, but larger buildings may have interior mechanical rooms that require dedicated ventilation to provide sufficient air turnover for a heat source for heat pumps. Structural retrofit is based on whether a structural review is likely to be triggered due to a 10% or greater increase in weight, not whether the total roof load is likely to be exceeded without further reinforcement.

- Although the scope of this project does not include cost estimating, the project team believes that costs are the best indicator for defining certain retrofit thresholds because it can reflect all the resources a building owner may need to expend to convert an emissive appliance to a zero-emission appliance, including time, effort, and materials. The project team developed large bins for costs, akin to order-of-magnitude estimates, to represent our best-guess estimate for the increases in resources needed above a like-for-like replacement. These estimates were used only for gauging the retrofit levels of physical space and were reviewed with team member ICI engineers.

Building level retrofit assessment

We assigned one overall retrofit level for each end use and then one overall level for the building as a whole. To do this, we apply a retrofit level hierarchy that always selects the most restrictive level. Hierarchy of retrofit levels (from least to most impact)

1 Not applicable (end use or retrofit criteria is not applicable for this building or fuel type (district) if out of scope of the study)
2 Already zero-emission
3 No retrofit
4 Minor
5 Moderate
6. Major

End-use level

Each end use (space heating, water heating, cooking, pool and spa heating, and laundry) is first evaluated against four retrofit criteria: panel size, physical space, heat source and structural. We then determine a single overall retrofit level for that end use. If all criteria are marked not applicable, end use is considered not applicable. If the end use is already fully electrified, it is classified as already zero-emission. Otherwise, we assign the end-use level based on the most restrictive level based on all the criteria. For example, if space heating is rated minor for panel size, moderate for physical space, and no retrofit for the remaining criteria, the overall space heating retrofit level is moderate, since that is the highest on the hierarchy.

Building level

After the team determined retrofit levels for each end use, we assigned an overall building-level retrofit level by applying the retrofit level hierarchy. We determined the building's overall level by looking at the highest retrofit level present among its end uses. For instance, if a building has moderate space heating, minor water heating, and the rest are either already zero emission or not applicable, the building's overall retrofit level is moderate.

Model Outputs

The output of the model is a dataset with the simulated population of buildings, each with its current and upgraded equipment, building characteristics, existing space and excess electrical capacity, and capacity needs, and retrofit levels.

Results summary

The building-level outputs consider the retrofit level of each building in the simulated population for each end use and retrofit criteria, as well as the cumulative effect. A building could be zero-emissions ready for any specific retrofit criteria for each end use but have retrofit needs overall due to the combined effect.

Table 2 presents the percentage of the nonresidential building stock in California that meet each retrofit level, as defined in Table 1, for each end use individually and the building stock overall. This is the percentage of all buildings by end use that are either already zero-emission, a replacement is not applicable because the end use is not present in the building, or the building can upgrade to zero-emission equipment with some level of retrofit.

Table 2. Percent of buildings by retrofit level and end use

			Buildings with Emissive End Uses				
End use	Already zero-emission	Replacement not applicable	No retrofit	Minor retrofit	Moderate retrofit	Major retrofit	Minor, moderate, or major retrofit
Space heating	38%	1%	3%	20%	31%	7%	58%
Water heating	54%	0.5%	9%	28%	7%	2%	37%
Pool heating	54%	46%	0.1%	0.1%	0.1%	0.0%	0%
Cooking	2%	70%	24%	3%	1%	0.0%	3%
Laundry	0.3%	97%	3%	0.1%	0.1%	0.0%	0%
All	25%	0.4%	9%	24%	33%	9%	66%

The total percentage of nonresidential buildings in California that do not require additional retrofits to become zero-emission is the sum of the buildings that are already zero-emission, the buildings where replacements are not applicable, and the buildings that are emissive and able to upgrade to zero-emission equipment without retrofits. For all end uses in this case, 25% of buildings are already use zero-emission equipment, 0% are not applicable for Case 0, and 9% of buildings are emissive and able to upgrade to zero-emission equipment without retrofits, meaning that 34% of all buildings can accommodate zero-emission equipment for all end uses without additional retrofits across all categories.

Error! Reference source not found. Table 3 presents the percentage of all buildings by retrofit category and overall that have emissive end uses and can upgrade to zero-emission equipment without constraints on key retrofit criteria (the "No retrofit" category above). The results are further disaggregated by four retrofit criteria the electrical panel, heat source ventilation, space, and structural review which demonstrate four different key features that the model can produce.

Table 3. Percent of emissive buildings with no retrofit needs, by end use and retrofit criteria

End use	Electrical panel	Heat source	Physical space	Structural	Overall
Space heating	56%	47%	5%	11%	3%
Water heating	37%	9%	19%	31%	9%
Pool heating	0.1%	0.3%	0.3%	0.3%	0.1%
Cooking	24%	28%	28%	28%	24%
Laundry	3%	3%	3%	3%	3%
All	59%	31%	12%	22%	9%

Table 2 shows that space heating and water heating are present in almost all buildings evaluated. For space heating, 38% are already zero-emission and 3% have no retrofit needs, as shown in the tables above. The retrofit criteria with the most buildings without retrofit needs are electrical capacity and heat source, with 56% and 47% respectively, and the criteria with the fewer buildings without retrofit needs are physical space and structural, with 5% and 11%, respectively. For water heating, 54% are already zero-emission and 9% have no additional retrofit needs. Electrical capacity has the most buildings requiring no retrofits at 37%, and heat source has the least buildings requiring no retrofits at 9%. For both space heating and water heating, and overall, electrical capacity is the criteria that most buildings can meet without retrofits. Trends vary for the other retrofit criteria between end uses.

For pool heating, cooking, and laundry end uses, nearly all buildings either already have zero-emission equipment or do not have this end use. For the remainder of buildings, electrical capacity is the only criteria which may need retrofits.

Table 4 presents similar results to Table 2 weighted by building square footage, using the floor area for each building in the ComStock dataset. We see similar patterns across retrofit categories, but with a higher retrofit level in each retrofit criterion, as well as overall.

Table 4. Percent of buildings with no retrofit needs, by end use and retrofit criteria, weighted by square footage

End use	Already zero-emission	Replacement not applicable	Electrical panel	Heat source	Physical space	Structural	Overall
Space heating	36%	3%	53%	39%	4%	5%	1%
Water heating	50%	1%	37%	5%	14%	24%	5%
Pool heating	50%	49%	1%	1%	1%	1%	1%
Cooking	2%	71%	27%	28%	28%	28%	27%
Laundry	0%	93%	6%	6%	6%	6%	6%
All	24%	1%	56%	23%	9%	15%	7%

Conclusions

The overall state of the market is that a significant portion of the buildings are already zero emission. Space heating is the main driver for overall building retrofit needs, with exterior space being the single biggest constraint. Cooking, pool, and laundry rarely drive overall building retrofit needs.

9% of the building stock has an overall major retrofit need, 33% has a moderate retrofit need, 24% has a minor retrofit need, 9% has no retrofit need, and 25% is already zero-emissions. Cooking, laundry, and pool don't apply to large portions of the building stock, while space heating and water heating apply to the vast majority of the building stock. Space heating and water heating generally drive a lot of the retrofit needs

For overall building major retrofit needs, 80% of those buildings have major space heating retrofit needs, 21% have major water heating retrofit needs, and less than 1% have major cooking, pool, or laundry retrofit needs.

Very few of the overall major retrofit buildings (<1%) require major retrofits for both space heating and water heating. The buildings that do have both major space heating and water heating retrofit needs have an average of 200,000 square feet of floor area, are mostly large office, large hotel, and schools, and mostly have existing central multi-zone VAV systems with boilers. These very large buildings have complex systems and are space-constrained, causing major retrofit needs.

Of buildings with overall moderate retrofit needs, 92% have a moderate space heating retrofit need, 21% have a moderate water heating retrofit need, and 14% require moderate retrofits for both space heating and water heating. Cooking is 2% and pool and laundry combined make up less than 1%. These buildings span a diverse range of building characteristics.

In general, cooking, pool, and laundry do not drive the overall building retrofit need in many buildings. Where they do drive the overall building retrofit need, they do so due to electrical requirements and are largely due to the large incremental electric panel capacity needed for the retrofit relative to the overall panel capacity.

There are only nine buildings out of the entire building stock where cooking requires a major retrofit and where cooking drives the overall major building retrofit level. these are all in quick service restaurants and are due to electrical requirements. A very small percentage of the building stock have moderate or minor retrofit needs due solely to cooking, and are mostly restaurants and are due to electrical requirements.

Similarly for pools, there are 54 buildings out of the entire building stock where pool requires a Major retrofit and where pool drives the overall major building retrofit level. these are all in hotels and are due to electrical requirements. Even fewer buildings have overall retrofit needs of moderate or minor due to pools.

Laundry drives only a handful of building retrofits, driving no major retrofit needs and only 65 moderate retrofit needs and 6 minor retrofit needs. These are all in laundromats and are all due to electrical requirements.

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