## Title
Are Load Flexible Technologies Affordable? A Population-Scale Cost-Benefit Analysis



**Authors**
Grahovac, Milica
Smith, Sarah Josephine
Agarwal, Shreya
et al.

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# Are Load Flexible Technologies Affordable? A Population-Scale Cost-Benefit Analysis

***Milica Grahovac, Sarah Smith, Shreya Agarwal, Vlada Dementyeva, Brian Woo-Shem, and Mary Ann Piette***
***Lawrence Berkeley National Laboratory***
**2026 ACEEE Summer Study in Buildings, Pacific Grove, CA**

## ABSTRACT

Customer end-use load flexibility enhances grid reliability and infrastructure affordability, yet quantifying the value proposition for continuously price-responsive technologies remains challenging given uncertainties in rates, device costs, and performance capabilities. We analyzed customer economics for five residential and one commercial load-flexible technology—ranging from mature to developmental—addressing space/water heating, space cooling, pool circulation, and EV charging.

Cost-effectiveness hinges on two drivers: initial investment and operating savings. We compiled comprehensive purchase and installation costs for each technology and determined annual electricity bill savings using a robust analysis framework. This framework considers hourly price design scenarios and resulting demand shifts away from high-priced hours, informed by technology field performance testing.

Using Monte Carlo simulation, we allocated technologies to all eligible California customers in 2030. Customers are characterized by sector, utility, building type and size, load shape, and climate zone. We evaluated trade-offs between operating cost savings from dynamic electricity pricing and upfront technology acquisition and installation costs, leveraging annualized life-cycle cost savings, payback periods, and cost limit development. We quantified individual customer economics by each customer characteristic and technology.

The paper illustrates ranges of resulting costs and benefits for customers and the State, discussing key drivers of each technology's affordability. Understanding these drivers is essential for identifying barriers to adoption and successful market evolution. Our findings provide insights for dynamic tariff design, flexible technology financing, product design, and marketing.

## Introduction

California has an increasing potential to shift electrical loads into times of affordable electricity generation (Specian and Aquino 2026; Gerke et al. 2024). Load shifts can reduce the cost of grid electricity generation, transmission, and distribution; offset new capacity development or free it for use in other applications (Specian and Aquino 2026). The cost savings realized by the grid and the utilities can be reflected directly on the customer bills, invested in load shifting infrastructure, or used elsewhere.

Load Flexible Technologies (LFTs) are technologies capable of, in the presence of a customer-facing hourly dynamic electricity tariff, shifting electrical loads away from highly priced time periods. We analyzed the customer side affordability of LFTs for several end-uses suitable for load shifting, such as commercial and residential space heating and cooling, and residential water heating, EV charging, and pool circulation. While all studied LFTs can perform demand response (DR), this analysis is specific to continuous hourly price response capability.

We developed a representative sample of potential LFT customers in California in year 2030 based on the customer segmentation introduced in the DR potential study (Gerke et al. 2024), using the sampling methodology presented in (Grahovac et al. 2020). We assumed that all customers with a suitable electric basecase technology (BCT) have potential for an LFT upgrade. Then, we simulated the state-wide range of LFT adopters' costs and benefits.

We studied the customer side affordability of the following LFTs, for two sectors:

- Commercial building model predictive controls (MPC), and
- Residential control technologies for:
    - Space heating, cooling, and water heating, specifically heat pump (HP) and heat pump water heater (HPWH) MPC.
    - Flexible level 1 (L1) electric vehicle (EV) charging.
    - Flexible level 2 (L2) EV charging.
    - Pool pumps for pool water circulation.
    - Space heating and cooling connected thermostats.
    - HPWH at two control modalities.

Commercial building MPC is well-established in research and pilot settings but has yet to find its optimal market pathway, with studies showing operating cost savings (OCS) of up to 61% (Zanetti et al. 2025; Blum et al. 2022; Morovat et al. 2025). The residential HP and HPWH MPC LFT is largely still under R&D. Flexible EV charging has been implemented in aggregator and utility programs, reducing peak load by up to 90% (Singh, Vaidya, and Mouftah 2022; Biesecker, Pivirotto, and Havenar-Daughton 2024). Pool pump controls are regulated by California's Flexible Demand Appliance Standards (FDAS) and require connectivity (Struven, Helft, and Hwang 2023). Wi-Fi-enabled residential thermostats are readily available on the market (PG&E 2026) and widely used in demand flexibility programs (Murphy et al. 2024). Previous studies have demonstrated significant load-shifting potential for HPWH, particularly with mixing valves that increase energy storage in existing hot water tanks (Grant et al. 2025; Gabriel et al. 2024).

Most of the residential technologies described, such as connected thermostats, EV chargers, pool pumps, and HPWHs, already have DR-capable versions on the market.

This work was part of California Load Flexibility Research and Development Hub (CalFlexHub) [1], a five-year project to identify, evaluate, develop, and demonstrate reliable load flexible technologies. An LFT's potential monthly bill savings depend on its capacity to shift or shed an amount of load. Our assumptions on shift duration and load shed depth stem from the DR potential study (Gerke et al. 2024) and are refined based on a recent literature review and CalFlexHub field testing and simulation results. We collected upfront and maintenance costs for each of the LFTs. The LFTs market readiness ranged between active market participants, such as thermostats, and those still in development, such as MPC. Aided by Guidehouse, Inc., we consulted several market actors and numerous resources that we reference later.

Whether LFTs are affordable for end-use customers depends on a variety of factors, including dynamic tariff composition (Murphy et al. 2024), customer behavior and expectations, BCT communicability, LFT market pathways, optimization algorithms, building conditions, and climate. We addressed the uncertainties by generating ranges of LFT affordability results across the state, informing not only technology developers, funders, and users, but also adjacent market and policy stakeholders. Comfort impacts, thermal resilience, or perceived loss of control are not

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[1] CalFlexHub, calflexhub.lbl.gov

discussed in the paper. Applicability to other states depends on the local climate, electricity generation mix, electricity demand, legislative framework, electrification level, current DR programs, and types and penetration of current end-use technologies upgradeable to LFTs.

The paper is organized as follows. The Methodology section describes the LFT affordability framework. The Assumptions, Inputs, and Scenarios section provides LFT cost and performance information and introduces the scenarios analyzed in the Results and Discussion section.

## Methodology

We developed the LFT Affordability Framework to analyze the customer-side costs and benefits of LFTs across California. This section presents the framework and its elements: the LFTs and their underlying BCTs, followed by the LFT performance, customer population sampling, LFT upfront and operating cost deltas, and key affordability metrics.

### The Affordability Framework

The framework's main components, as outlined in Figure 1, are:

1. BCT and LFT characterization.
2. Formation of the LFT customer sample.
3. LFT cost/benefit analysis for each customer in the eligible population.

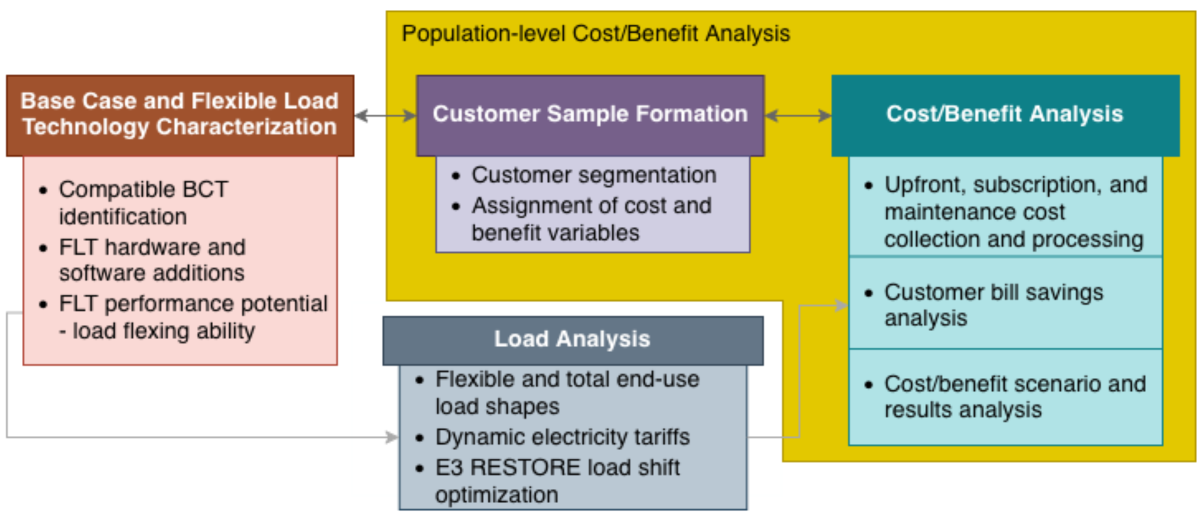


Figure 1. Affordability framework schematic overview: population-level cost/benefit analysis. The framework relies on the inputs from the BCT and LFT characterization and load analyses.

The customer load analysis, key to determining bill savings inputs, will be described in detail in a separate forthcoming publication (Smith 2026). The framework components are further described in the following subsections.

### Flexible Load Technologies as Addition to Basecase Technologies

LFTs often function as add-ons to a BCT, such as dynamic control software or an app. The BCT is the technology the customer already uses to meet a given end-use demand. Customers eligible for an LFT upgrade are those with a suitable BCT. For example, an HP load-controlling LFT requires the customer to already have a HP.

LFTs require internet or other networking capability to receive external control signals such as dynamic electricity prices and weather data. If the BCT lacks this capability, we consider it part of the LFT cost (Figure 2, left); otherwise, connectivity is already available through the BCT (Figure 2, right). The customers may have previously obtained communicable BCTs for remote control, internet-of-things (IoT), or to participate in DR programs.

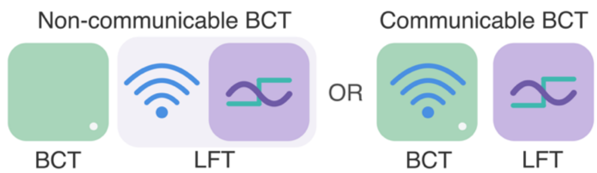


Figure 2. Difference between adding an LFT to the communicable vs. non-communicable BCT. Left: LFT includes the communicability and the load flexibility software. Right: BCT is communicable, therefore the LFT refers primarily to the load flexibility software.

Commercial building MPC LFTs may leverage existing (for retrofits) or planned (for new construction) rule-based control (RBC) infrastructure, or require additional networking, data storage, and instrumentation. Well-networked buildings may need only software additions, while others may require significant hardware upgrades (Blum et al. 2022; Ham et al. 2024). For flexible EV charging, the existing L1 or L2 charger or the vehicle itself is typically already connectable; otherwise, customers can obtain a Wi-Fi-connectable charger. Customers with non-connectable pool pumps require a connected controller or variable-speed pump with built-in Wi-Fi (Struven, Helft, and Hwang 2023). Wi-Fi-enabled thermostats are widely available (PG&E 2026). If a customer already has one, the LFT upgrade requires only connecting to an app or service capable of sending load-shifting signals, similar to how the existing DR is performed, otherwise a thermostat replacement is needed. Most HPWHs on the market are Wi-Fi-connectable, so the associated LFT is typically limited to software and signal exchange services.

### Population Sampling

The load database developed for the CPUC DR Potential Study (Gerke et al. 2024) clusters customers based on an array of customer characteristics. In this work we further processed the 5,434 clusters as follows:

- Extracted subsets of each cluster customers that have the affected end-use(s) and a BCT eligible for an upgrade to LFT in year 2030 (selected analysis year). This step included electrification and BCT market share increase to meet state targets (Smith et al. 2026a).
- Grouped such processed clusters by climate zone, sector, utility, building size and type, and load shape, resulting in 66 to 240 distinct cluster groups per LFT. Figure 3 shows the share of climate zones, utilities, and building types for each LFT.

Figure 4 illustrates the Monte Carlo sampling process used to draw a representative customer sample for each LFT. For each customer, we first randomly selected a customer segment weighted by segment population, then sampled the LFT lifetime from a Weibull distribution around the expected average. We assigned discount rates by customer sector. Then, we sampled costs and bill savings uniformly from identified ranges, as detailed in the Cost and Benefit Analysis subsection and the Assumptions, Inputs, and Scenarios section. Finally, we calculated cost/benefit metrics and stored the results. The process repeated 10,000 times per LFT and scenario to generate a representative sample.

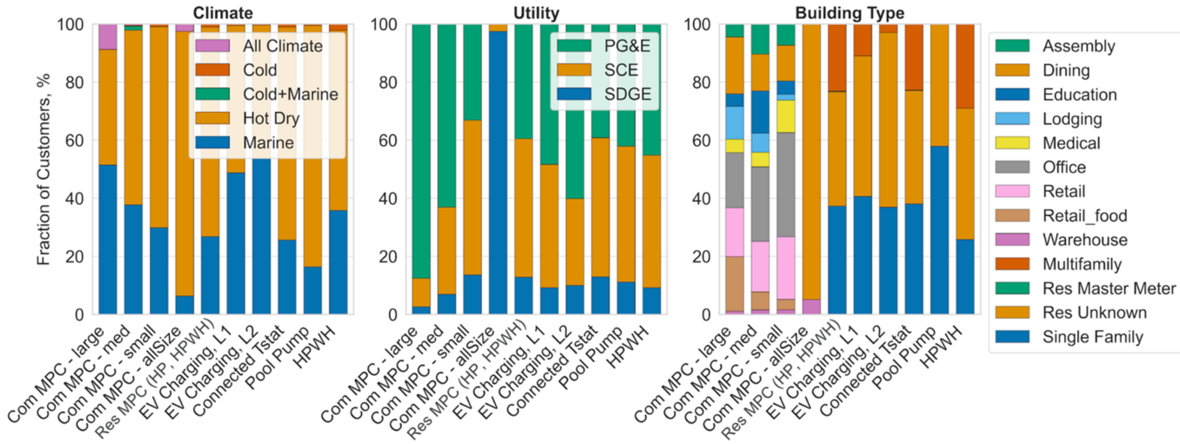


Figure 3. Breakdown of customers for each technology by climate zone, utility company, and building type.

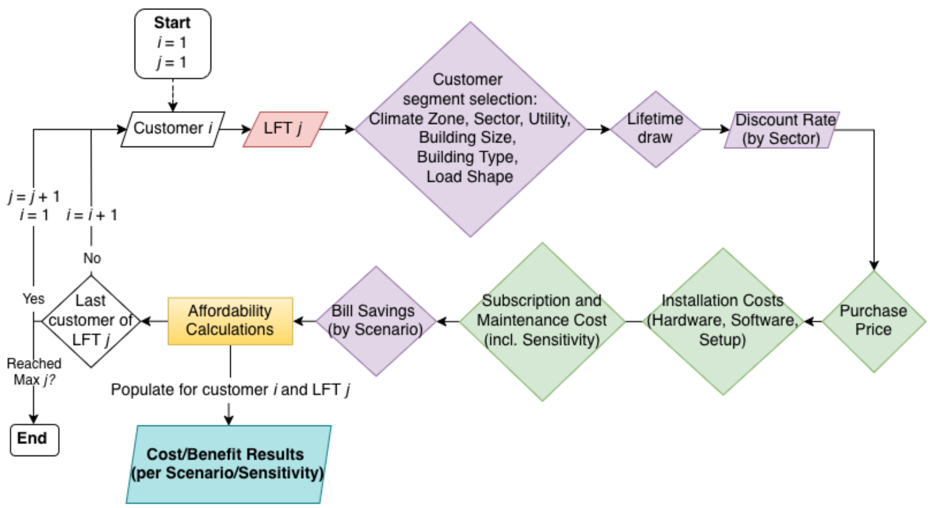


Figure 4. LFT customer population Monte-Carlo sampling algorithm.

## Cost and Benefit Analysis

The key drivers of the LFT affordability are the added upfront cost (total installed cost – TIC) and the OCS. Figure 5 provides the overall schematic of the affordability metrics calculation.

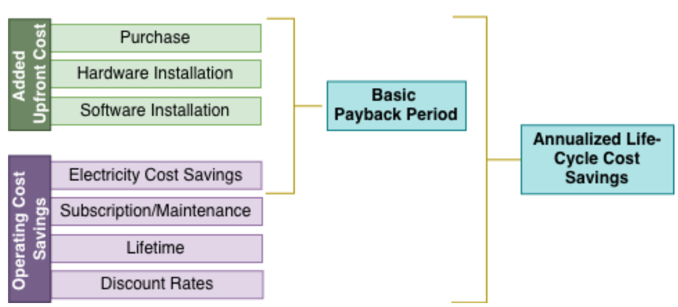


Figure 5. Affordability metrics calculation flowchart for individual customers. Costs and benefits represent the delta between a BCT and an LFT delivering the same utility.

The cost and savings components, as well as the affordability metrics are further described in the subsections below.

**Added Upfront Costs.** Upfront costs include purchase, hardware installation, and software setup. The purchase price refers to any additional hardware beyond the existing BCT, or the price difference if a full BCT replacement is needed to achieve flexibility. Hardware installation costs apply to any LFT components absent in the BCT, such as replacing a non-communicable thermostat with a connected one. Often no additional hardware is required. Some LFTs, such as MPC, may require specialized software setup, which is accounted for as a separate cost component. LFT costs are typically higher for customers with a non-communicable BCT, leading to two distinct price range levels, as presented in the Results section.

**Operating Cost Savings.** OCS stem from the achieved electricity bill savings reduced in any potentially added subscription or maintenance costs.


Figure 6. High-level schematic of the electricity bill savings calculation model

Figure 6 outlines the bill savings model. Starting with the 8760 flexible end-use and total customer load shapes, derived from the DR potential study load database, we assumed optimal deployment of LFT technologies against a dynamic tariff. We then compared the customer bill on the same dynamic tariff with and without the LFT. The resulting annual customer bill savings value represents an average by customer type. The optimization was performed using E3[2] RESTORE model, assuming idealistic controls within each LFT performance ability. Additional details regarding the methodology are provided in (Smith et al. 2026a).

LFT operation may require a service subscription or incur additional maintenance costs.

**Key Affordability Evaluation Metrics.** In this paper we analyzed the LFT affordability measured by the basic payback period (PBP), calculated as a ratio between the TIC and the first-year bill savings, and the annualized life-cycle cost (LCC) saving. Additionally, we provided ranges of LFT total installation costs that would keep the PBPs under three years.

## Assumptions, Inputs, and Scenarios

This section describes the underlying assumptions and provides the analytical inputs related to LFT performance, field use, and costs.

### Flexible Load Technology Performance

Performance parameters were obtained from literature review and CalFlexHub field-testing and simulation results, as presented in Table 1. The medium performance scenario represents how the technology would likely perform if deployed across the market using currently-available controls and equipment, based on field testing and simulation performance.

[2] Energy + Environmental Economics, E3, ethree.com/

The upper performance scenario represents the potential with further development, using best-case scenarios from field results and input from technology developers on how the technologies could likely be improved as they move toward wider deployment. We selected as input into the bill savings model two key performance metrics per LFT:

- The shift window, defined as the number of hours over which a load-shifting event is balanced between load shedding and load taking. The shift hours in Table 1 are the duration of the typical load shed, or half of the shift window.
- The shed fraction, defined as the maximum fraction of nominal capacity that the controlled equipment can reduce during a shed event.

Table 1. Performance assumptions for each technology.

| Load Flexible Technology | Upper Performance | | Medium Performance | | Round-Trip Efficiency | Sources and Notes |
|---|---|---|---|---|---|---|
| | Shift Hrs | Shed (%) | Shift Hrs | Shed (%) | | |
| Res. MPC for HP and HPWH, Space Conditioning | 4 | 90 | 2 | 70 | 0.90 | CalFlexHub preliminary field-testing results.* |
| Res. MPC for HP and HPWH, Water Heating | 7 | 52 | 4 | 41 | 0.98 | Based on field demonstration results for unitary HPWHs (Gabriel et al. 2024). |
| Com. MPC, Large Buildings | 8 | 65 | 4 | 65 | 0.90 | Field demonstration results (Zanetti et al. 2025) |
| Com. MPC, Medium Size Buildings | 6 | 65 | 3 | 65 | 0.90 | Assumes 75 % of shift window compared to large buildings. 3-hour window was demonstrated in (Morovat et al. 2025). |
| Com. MPC, Small Buildings | 4 | 65 | 2 | 65 | 0.90 | Assumes 50 % of shift window compared to large buildings. Values are similar to residential thermostats, but MPC can modulate load over longer periods in the upper performance case. |
| Res. EV Charging, L1 | 6 | 80 | 4 | 70 | 1.00 | (Biesecker, Pivirotto, and Havenar-Daughton 2024; ev.energy corp 2021; Singh, Vaidya, and Mouftah 2022; Almaghrebi et al. 2024). |
| Res. EV Charging, L2 | 6 | 100 | 4 | 90 | 1.00 | |
| Res. Connected Thermostat | 3 | 90 | 2 | 60 | 0.85 | CalFlexHub preliminary field-testing results. |
| Res. Pool Pump | 12 | 90 | 10 | 90 | 1.00 | No change in efficiency as the pump can run at the same speed, just at a different time. |
| Res. HPWH, Basic Flex Control | 7 | 52 | 4 | 41 | 0.98 | Field demonstration results (Gabriel et al. 2024). |
| Res. HPWH, ALU** | 8 | 100 | 6 | 98 | 0.73 | Additional modeling using methodology in (Grant et al. 2025). |

* https://calflexhub.lbl.gov/wp-content/uploads/sites/41/2026/04/CFH-2026-Symposium-Project-Showcase.pdf

** Advanced load up (ALU) control relies on a temporary raise in HPWH tank temperature.

The LFT lifetime introduces an additional level of uncertainty to the analysis. The average lifetime assumptions, derived using data from California Technical Forum, 2026, were conservative.

### Flexible Load Technology Costs

Table 2 provides the upfront and subscription cost differential ranges by LFT.

Table 2. LFT upfront and maintenance/subscription cost differential ranges compared to the BCT

| Load Flexible Technology | Basecase Technology | Upfront Cost | | | Annual Maintenance/ Subscription Cost |
|---|---|---|---|---|---|
| | | Purchase Price | Installation Cost (Hardware) | Installation Cost (Software) | |
| Res. MPC for HP and HPWH | HPWH (100% connectable) | $0 | $0 | $0 | $0 |
| | Connectable HP (45%) | $0 | $0 | $97-$152* | $12-50* |
| | Non-connectable HP (55%) | $96-$166 | $0-$200 | $97-$152* | $12-50* |
| Com. Building MPC | Connectable building (80/50/50/50% for large/medium/small/all size) | 8¢/sqft to 12¢/sqft | | | $0 |
| | Non-connectable Building (20/50/50/50% for large/medium/small/all size) | 10¢/sqft to 49¢/sqft | | | 2.4¢/sqft to 3.6¢/sqft* |
| Res. EV Charging, L1 | Connectable EV (90%) | $0 | $0 | $0 | $0-$180* |
| | Non-connectable EV (10%) | $150-$300 | $0 | $0 | $0 |
| Res. EV Charging, L2 | Connectable EV (90%) | $0 | $0 | $0 | $0-$180* |
| | Non-connectable EV (10%) | $354-$750 | $0 | $0 | $0 |
| Res. Connected Thermostat | Connectable Thermostat (45%) | $0 | $0 | $0 | $0 |
| | Non-networked non-programmable thermostat (55%) | $96-$166 | $0-$200 | $0 | $0 |
| Res. Pool Pump | Non-connectable pool pump - controller replacement (25%) | $130-$170 | $0 | $0 | $0 |
| | Non-connectable pool pump - pump replacement (25%) | $462-$694 | $28 | $0 | $15.2 - $22.8 |
| | Connectable pool pump (50%) | $0 | $0 | $0 | $0 |
| Res. HPWH, Basic Flex Control | Connectable Non-optimized HPWH (100%) | $0 | $0 | $0 | $0 |
| Res. HPWH, ALU | Connectable Non-optimized HPWH (100%) | $0 | $0 | $0 | $0 |

* This cost is $0 in the cost sensitivity analysis, reflecting potential role for utility programs.

The customer bill savings are distributed uniformly across individual customers, within 20% of the cluster group average.

The residential discount rate is 3.93% and the commercial discount rate is 7.38% (The Fed 2023, Fujita 2025).

**Purchase Price.** Effective January 1, 2026, California Building Code (CEC 2025) will require residential HPWHs to include an EcoPort, a built-in technology that enables connectivity.

For residential HPs, we assume 45% of households have a compatible Wi-Fi-enabled thermostat in 2030, incurring no additional connectivity cost, while 55% incur the cost of installing a Wi-Fi-enabled thermostat (TECH 2025).

The incremental cost between a $20 non-networked thermostat and the $96-$166 cost of the networked version is $76–$146 (Nubbe et al. 2020). For commercial buildings, we combine the purchase and installation costs into a single cost that scales linearly with the building square footage. This cost varies based on the building's existing network for RBC. Well-networked buildings, needing minimal sensor/system upgrades, are assumed to incur 8 ¢/sqft to 12 ¢/sqft

(Anonymous 2025. Interview conducted by Guidehouse, Inc.). Poorly networked buildings incur a higher cost of 10 ¢/sqft to 49 ¢/sqft (RBC, Nubbe et al. 2020), assuming that the MPC would not be more expensive than installing RBC to compete in the market. We estimate, based on expert advice, that 80% of large commercial buildings are well-networked, and 50% of all other building sizes are well-networked.

We categorize residential EV charger customers into two groups based on vehicle age. For the 90% of EVs sold since 2018 (BTS 2025) we assume the vehicle's baseline connectivity is sufficient for demand response via manufacturer connectivity software. The remaining 10% require a connected charger. Wi-Fi-controllable residential L1 EV chargers cost approximately $150-$300 (Lectron 2026; Tesla 2026). Wi-Fi-controllable residential L2 chargers have a higher upfront cost, ranging from $354-$750 (ev.energy 2026).

As FDAS took effect in September 2025 and pool pump lifespans average 10 years, we project 50% of 2030 installed pumps to be FDAS compliant, requiring no extra cost. For the remainder, we assume 25% of all consumers will replace their pump with a communication-enabled variable speed drive model with an incremental cost range of $463–$694, and 25% purchase a Wi-Fi connected switch, costing $130–$170 (Struven, Helft, and Hwang 2023).

**Hardware Installation Costs.** We assume no additional hardware costs for HPWH as the majority of HPWH installed in 2030 are expected to be DR compatible via EcoPort and have a mixing valve. Wi-Fi-enabled thermostat installation can be done by the customer or professionally for up to $200 (Nubbe et al. 2020). We assume no installation cost for all residential EV chargers. While L2 chargers require a non-standard 240V outlet, the BCT already satisfies this requirement. For residential pool pumps, we assume no added installation cost as the installation process for a pool pump is the same regardless of flex capability (Struven, Helft, and Hwang 2023). Users can install a simple pool pump controller themselves at no cost.

**Software Installation Costs/Programming.** For residential MPC, we estimate the cost of the model and system integration, beyond a Wi-Fi-enabled thermostat, to be $97–$152 (Nubbe et al. 2020). We assume all residential EV chargers and connected thermostats require no software installation or programming costs, as app installations are simple. For residential pool pumps, we assume a $15.20 – $22.80 annual incremental maintenance cost due to additional motor maintenance for the 25% of consumers choosing to replace their pool pump (Nubbe et al. 2020).

**Subscription/Maintenance Costs.** Subscription costs represent fees for the use of software apps or services, to ensure customer support and regular updates. For residential MPC for HP, we assume an annual subscription cost of $12-$50 (Anonymous 2025. Interview conducted by Guidehouse, Inc.). For connected thermostats, we assume no subscription cost as manufacturers offer control software at no cost and we anticipate the same for HPWH.

Commercial building MPC maintenance costs, like upfront costs, depend on the existing RBC network and scale linearly with square footage. We assume no maintenance cost difference for MPC in well-networked buildings compared to RBC. For buildings requiring upgrades, we assume the added MPC maintenance cost over the simple RBC baseline would not exceed the maintenance cost difference between complex and simple RBC systems. We estimate the incremental maintenance cost between 2.4¢/sqft and 3.6¢/sqft (based on Trenbath et al. 2022).

EV charging connectivity can be enabled by either the charger or the car manufacturer. For the 90% of consumers with newer EV models, we assume a $0-$180 annual subscription cost for manufacturer connectivity software (Hodge 2026). For residential pool pumps, we assume there is no additional subscription cost.

### Electricity Prices

We deployed the LFTs to achieve maximal bill savings under two hourly dynamic tariffs:

- ACC rate: The marginal electricity price profile from the 2024 California Public Utilities Commission (CPUC) Avoided Cost Calculator (E3 2024).
- Dynamic rate: The realistic customer-facing dynamic tariff derived for the CPUC in the scope of the California Price Response Potential Study (Smith et al. 2026b).

### Scenarios

We calculated the affordability results for the following four scenarios:

- Medium LFT performance with the ACC rate (1) and Dynamic rate (2).
- Upper LFT performance with the ACC rate (3) and Dynamic rate (4).

In addition, we created a sensitivity analysis for all the scenarios assuming that the software installation and setup, as well as the subscription costs would be covered by an entity other than the customer, such as the utility or a third-party LFT service provider.

## Results and Discussion

We illustrate the range of customer results for the performance and electricity rate scenarios and cost sensitivities. In Figures 7 and 8, the boxes represent the 25th to the 75th percentile, and the whiskers the 5th to the 95th percentile, while large and medium size commercial building MPC is shown on a separate vertical axis to better represent the scale.

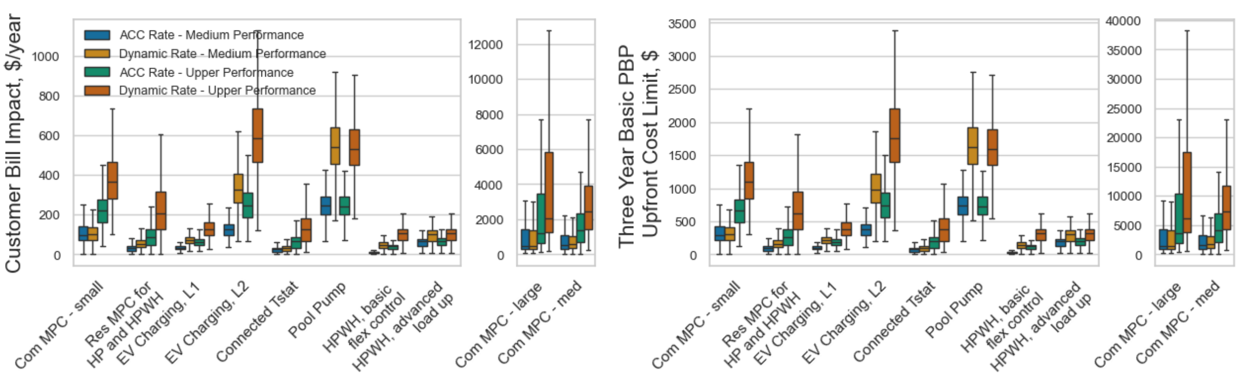


Figure 7. Left: Distributions of annual customer bill impacts by technology and scenario. Right: Distributions of three year basic PBP upfront cost limits by scenario and technology.

Figure 7, left, shows annual customer bill impacts. The bill savings represent the difference between the customer bills, on either the ACC or the Dynamic rate, between unmodified load and the load after the LFT has been optimally deployed. In real applications, the customers may get exposed to an hourly dynamic rate only after purchasing and installing an LFT. In that case the specific bill savings would depend on a customer's initial tariff, associated with their segment, such as sector, income level, or pre-existing DR-enabled technology.

Both the electricity rate and equipment performance significantly impact bill savings, with the upper performance limit and dynamic price typically driving higher savings potential. Office buildings require heating and cooling predominantly during work hours and are unaffected by evening peak prices, causing the medium performance parameters to produce similar savings regardless of the rate. Pool pump medium performance parameters are already high enough that extending them to the upper limit doesn't change the bill impacts range. The longer the shift duration, the higher the impact of rate selection, resulting in much higher savings on a dynamic rate for pool pumps and EVs. Figure 7, right, shows the range of upfront cost limits yielding basic PBPs of three years or less, with MPC reaching the highest values due to broad cost uncertainty, especially for non-connectable BCTs.

The distributions in Figure 8 show the LFT TIC, the achieved OCS, and the resulting annuity of the LCC savings for two customer BCT segments, connectable and non-connectable.

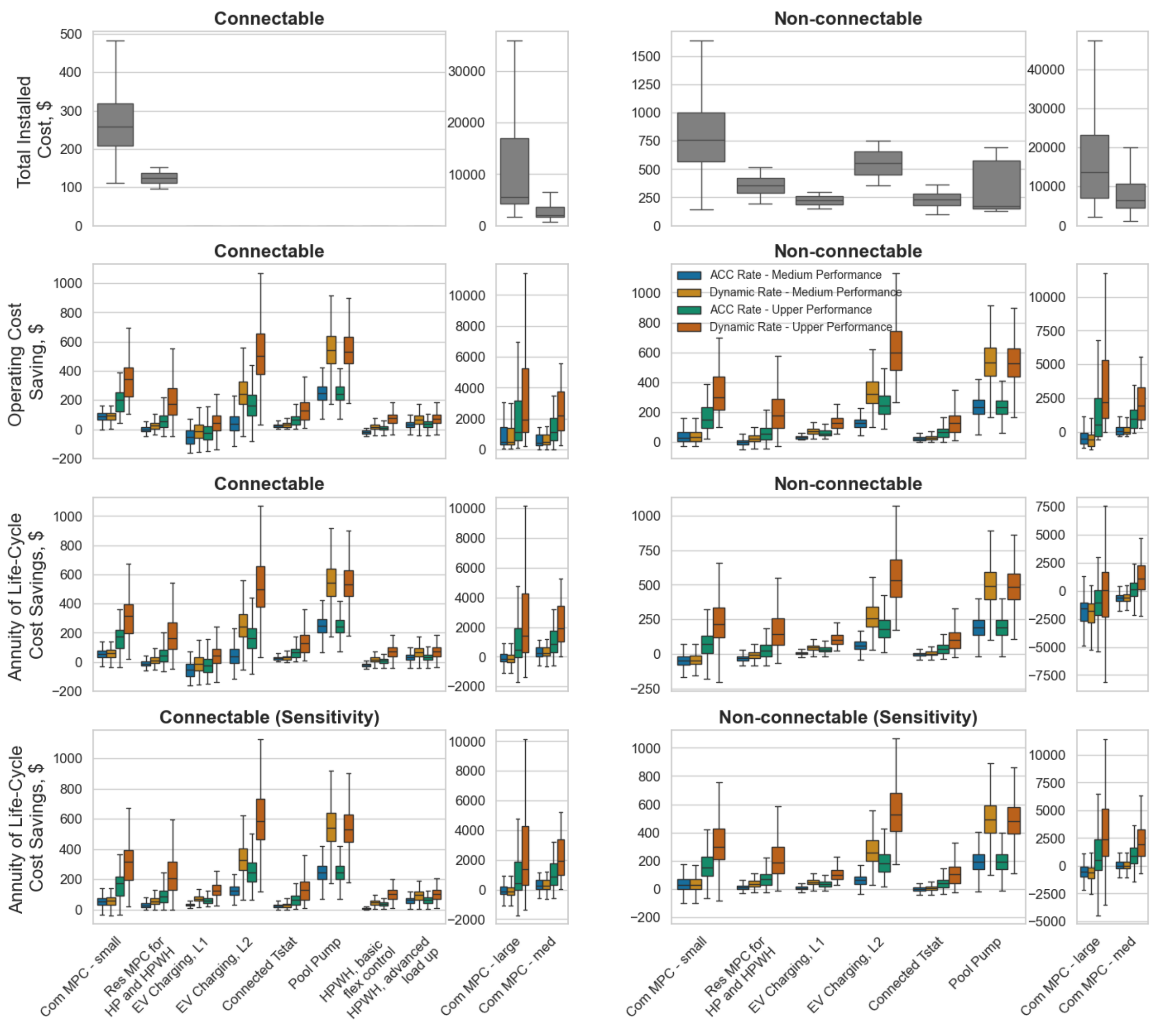


Figure 8. Resulting distributions by LFT and scenario for connectable (each row left) and non-connectable BCT (each row right) customer segment: TIC (first row); OCS (second row); Annuity of LCC savings (third row); Annuity of LCC savings in the cost sensitivity (fourth row).

The first row of Figure 8 shows that the upfront costs (TIC) are generally higher for LFT installations onto a non-connectable BCT. For the connectable BCT: several LFTs incur no additional TIC, such as residential EV charging, connected thermostats, HPWH, and pool pumps; while commercial MPC technologies are relatively more affordable for all building sizes.

The residential EV charging OCS are higher for the non-connectable BCT segment, assuming no subscription costs with the purchase of a smart charger. Otherwise, the LFT operating costs savings are typically higher if the BCT is connectable: the entire range of commercial MPC customers has positive OCS (second row left). All residential HPWH customers have a connectable BCT and all of them incur positive OCS. Connected thermostats consistently achieve positive savings, with the magnitude depending on the structure of the dynamic tariff and the LFT performance.

The third row in Figure 8 displays the annuity of LCC savings. Commercial MPC has high customer bill savings potential, especially for larger buildings, but as an R&D technology, its upfront and maintenance cost uncertainty remains high. In the connectable BCT segment, a large fraction of customers experiences positive LCC saving annuities, while in the non-connectable BCT segment that remains true only for select scenarios for the small and medium size buildings. Residential MPC customers may incur positive savings with medium LFT performance, with that fraction increasing with the LFT performance capability. Flexible EV charging for the connectable BCT assumes app subscription costs that reduce LCC savings, such that customers with a non-connectable EV on average achieve better savings by purchasing a smart charger. The connected thermostats incur benefits from the initial installation year for all customers in the connectable BCT segment regardless of the scenario. Furthermore, the LFT has potential to benefit most customers who upgrade to a Wi-Fi-enabled thermostat. Pool pump BCT may become increasingly connectable in the presence of the FDAS. Even when the pool pump connectivity is added on or fully replacing the non-connectable BCT, the LFT results in significant annual LCC savings. Residential HPWH controls LCC savings depend on the control strategy, with ALU customers likely to experience positive annuities.

The cost sensitivity (Figure 8, fourth row) assumes a utility or a third party covers the installation and subscription costs for residential MPC and EV charging customers. This is reflective of the currently existing programs, such as WatterSaver (PG&E), SmartShift (SCE), and MCE Sync. This leads to a large majority and all the customers of those LFTs achieving positive LCC savings annuities in the connectable and non-connectable BCT segments, respectively. It further assumes commercial MPC maintenance costs equal those of its BCT (RBC), yielding significant savings depending on the scenario, proportional to building size.

Figure 9 shows the range of population average basic PBP values over all scenarios. The non-connectable customer segment range, in dark blue, has on average longer PBPs than the connectable segment, in gold. The green shows the range of PBP results in the cost sensitivity for the residential MPC, a likely outcome based on the existing HPWH controls DR programs. The shortest population-average PBPs are consistently achieved under the Dynamic rate with the upper LFT performance, shown as the empty diamonds. The circles indicate the medium performance scenario averages. The longest resulting PBPs occurred on the Dynamic rate (empty circles) for the commercial, and on the ACC rate (full circles) for the residential sector LFTs.

With commercial MPC, the average basic PBPs for buildings that are well networked range from about one to 15 years, not exceeding seven years at the upper performance limit, with higher averages attributable to larger buildings. Small and medium buildings retain basic PBPs below five years in the connectable BCT segment. The residential MPC has PBPs ranging from about one to four years in the connectable BCT segment and two to 12 years for the non-connectable BCT. This significantly improves in the cost sensitivity: the non-connectable and connectable segments have a basic PBP of one to seven years and zero years, respectively. Connected thermostats have average basic PBPs of two to nine years if the customer needs to purchase a Wi-Fi-enabled thermostat, otherwise they are zero.

Pool pumps have average basic PBPs of one to two years. HPWHs are all connectable and do not have a payback period as the customer only incurs net benefits.

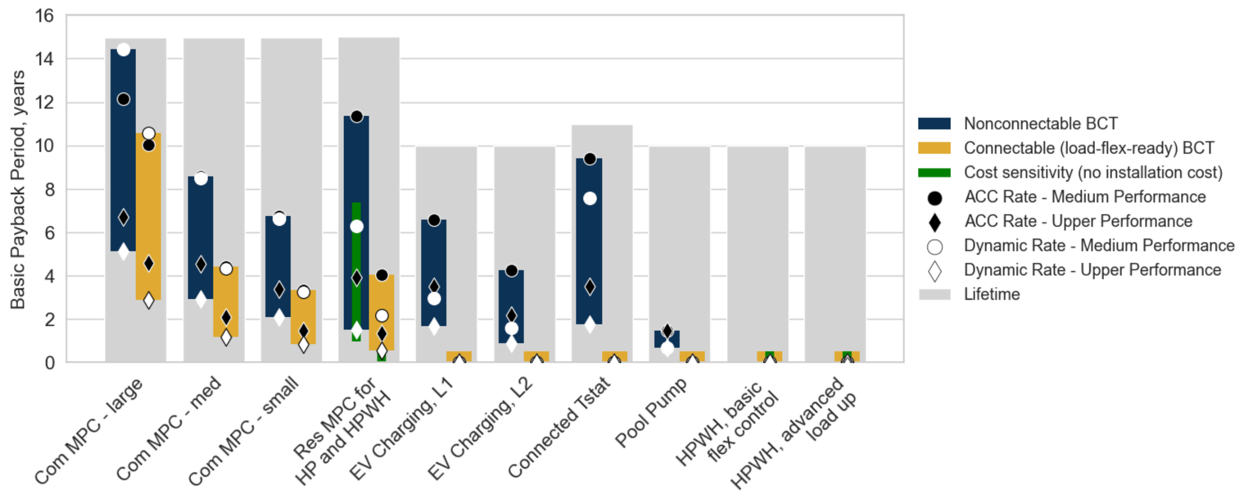


Figure 9. Range of population average basic PBPs across all rate and performance scenarios by LFT for non-connectable BCT (dark blue) and connectable (gold) customer segment. Cost sensitivity, in green, assumes utility or a third party covers installation costs. Full and empty circles and diamonds represent the average PBPs by sensitivity. Average LFT lifetimes are indicated in gray.

## Conclusion

We presented an LFT affordability framework and applied it to one commercial and several residential LFTs spanning a wide range of market readiness levels. Using a representative sample of potential California LFT customers, we combined current cost and performance data from market and R&D sources, segmented by customers with and without a connectable BCT, with two LFT performance scenarios derived from DR potential study and field metering results. Optimally load shifting against two dynamic price scenarios yielded customer bill savings, from which we calculated ranges of annualized LCC savings and average basic PBPs across all four scenarios.

While costs and benefits varied with the dynamic tariff structure and the performance of the LFT, most were more affordable in the connectable BCT (DR-ready) segment. The LFT is essentially an add-on representing an incremental step towards continuous dynamic price-responsiveness. It is free if the utility or a third party absorbs the service subscription costs. In California, there are existing DR programs doing this for residential Wi-Fi-enabled thermostats, EV chargers, and HPWHs. Where additional hardware is required, such as for customers with non-connectable residential integrated HPs and thermostats, the rate design and LFT performance, together with upfront cost rebates, can bring the PBPs below five years. When the right market segment is equipped with well-developed MPC, annual benefits for commercial building customers can be significant.

Broader benefits of the LFT affordability framework are to inform both program and technology development. The LFT affordability framework lends itself to cost sensitivity analyses that can inform program design by assessing the resulting range of customer impacts. Furthermore, the framework can aid the LFT development by providing a range of potentially feasible upfront cost targets, under various conditions, such as utility programs, dynamic tariffs, and norms. Additionally, it can be used to optimize the market pathways and improve LFT business strategies by identifying market segments most likely to achieve higher annual savings and low PBPs. Future R&D should focus on narrowing the uncertainty ranges towards lower customer PBPs. LFT performance benchmarks could be used to inform the dynamic tariff design by customer segment. LFT turnover models can be developed to study longer term impacts of LFT adoption on customer loads, dynamic tariff design, and market needs. Lastly, studying the service design to increase LFT adoption is key in driving the customer adoption.

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**AI-assisted Tools: Disclosures**

AI-assisted tools used: Anthropic Claude Sonnet 4.6, Google Gemini Pro.
Used for: editing text for conciseness, formatting references, debugging analysis code.

Extent: light editing, code review.
Human review: The authors reviewed and verified all content, calculations, and citations.