Title

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MOBILIZING THE ANTI-DUCK BRIGADE: TECHNOLOGY AND MARKET PATHWAYS FOR LOAD-SHIFTING DEMAND RESPONSE IN CALIFORNIA

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ABSTRACT

With rapidly increasing renewable power generation, the California electricity system is experiencing the impacts of the so-called "duck curve," with occasional over-generation in the middle of the day, followed by rapid ramping of net demand producing a sharp evening peak. Mitigating this pattern will require novel demand-side management approaches to shifting demand away from high net demand periods and toward high renewables generation periods. In this paper, drawing from more than 200,000 individual residential, commercial, and industrial customers' hourly smart meter data, we disaggregate load shapes for certain key end-uses and then average the results across a highly granular set of customer segments by sector, building type, demand profile and geographic region, to yield a library of characteristic daily load profiles ("clusters") for different end-uses and seasons. By categorizing the library into particularly desirable or undesirable load shapes in the context of mitigating the duck curve, we can gain insight into specific technologies, seasonal effects, or site-level attributes that may serve as helpful levers to use in developing future load-shifting programs. Based on these insights, we develop recommendations on technologies and new market structures and incentives that can create a future demand curve that more closely matches renewable generation patterns.

Introduction

Increasing penetration of variable renewable generation heightens the need for grid flexibility and poses challenges to market operators, including additional variability, uncertainty and the inherent difficulty in forecasting maximum power output (Ela et al. 2014). In the Electric Reliability Council of Texas (ERCOT), nearly half of the contingency reserve needed is supplied by demand-response resources that curtail when system frequency reaches some level below nominal frequency. Batteries can also provide flexibility as operating reserves and thus reduce power system operating costs to a traditional electric utility operating under high penetrations of solar photovoltaic (PV) generation (Denholm et al. 2015).

The problem of over-generation occurring at increased solar photovoltaics (PV) penetrations in California is often referred to using the name of the chart that was published by the California Independent System Operator (CAISO) in 2013 and called the "duck curve" (CAISO, 2013). This chart showed the potential for PV generation to exceed system demand, especially considering the host of technical and institutional constraints on power system operation. As the State approaches a generation portfolio including 50% renewable resources, there are new and evolving challenges for balancing generation and loads.

Some of these challenges can be tackled by fully enabling demand response (DR) as a flexible grid resource in a variety of scenarios beyond peak demand events, and a large effort has been underway in California to evaluate the future economic and technical potential of DR, culminating most recently in Phase 2 of the California Demand Response Potential Study (Alstone et al. 2017[1],,Alstone et al. 2018). In this paper, we make use of the full set of analytical results produced by this study to explore a variety of questions related to load-shifting DR. Alstone et al. 2017 identified four broad categories of DR resources, including the "canonical" *Shed*[2] DR, which refers to traditional load-reducing DR for peak load reduction; *Shimmy DR,* which refers to fast-responding DR that can rapidly modulate loads on timescales of seconds to minutes; *Shift* DR*,* which refers to customers actions that *move* the timing of loads from one time to another; and *Shape* DR, which refers to long-term persistent changes in the daily demand profile in response to time-varying rates, e.g. time of use (TOU) rates or other behavioral incentives.

This paper sheds light on the potential for *Shift* DR in helping to meet California's grid needs under increasing levels of variable renewable generation. We start by giving a brief overview of the modeling approach taken in the CA DR Potential Study. We then describe how *Shift* DR modifies energy consumption during the day, and how grid operators can to rely on its service. Next, we examine how the *Shift* DR potential can vary across different end-uses, and how it varies throughout the year. Last, we present preliminary considerations for further research into the deployment of *Shift* DR.

Modeling Methodology

The CA DR potential study modeled future potential for deployment of *Shift* DR and other California grid DR resources using a bottom-up modeling framework called **DR-Futures**. This framework leverages detailed calendar year 2014 data on hourly electricity consumption for hundreds of thousands of customers across the three California investor-owned utilities (IOUs). The first step for estimating DR resource availability is to group customers in similar cohorts, or "clusters" and look at their load shapes, representing the anonymized consumption of a customer subgroup. These load shapes are disaggregated into constituent end-uses, and the end-use baseline load shapes are forecasted to the study year of 2025. The DR Futures model is divided into two core analytical capabilities:

- **LBNL-Load** is an end-use load-forecasting approach that capitalizes on the demographic and hourly load data for IOU customers. Using these data, we developed approximately 2,700 representative customer clusters characterized by a typical demographic profile, location, and hourly end-use load forecasts over a full year.
- **DR-PATH** is a DR capability analysis model that estimates the potential DR resource across a diverse set of future technology pathways. The possible pathways consider the predicted end-use load (from LBNL-Load), technology capabilities and costs, market design parameters and expected customer participation rates.

LBNL-Load outputs a set of customer clusters, full representative annual hourly load shapes, disaggregated across multiple end-uses and forecasted to 2025. DR-PATH couples each

[1] Hereafter called the CA DR Potential Study
[2] Throughout this paper we will use capitalized and italicized terms (*Shift, Shed*, etc.) when referring to categories of DR product, to distinguish between the DR categories and the specific actions (e.g., "shifting a load") taken by participants.

cluster and end-use with a suite of different DR-enabling technologies, having different costs and capabilities, and calculates the potential of that cluster-technology combination to provide the different categories of DR. In the following sections, we use the outputs of LBNL-Load and DR-PATH, as computed for the CA DR Potential Study, to discuss the need for *Shift* DR in California, and to explore potential future customer-targeting approaches that can help develop the resource.

A Brief Overview of *Shift* Demand Response

Why is *Shift* DR needed?

California grid operators must accommodate increasing levels of renewable energy, which can help reduce the grid's carbon footprint and achieve the State's policy goals. At the same time, however, some challenges to the greening of the grid remain and may be exacerbated by further expansion of renewable energy. As a result of that, we identify four key operational challenges that can be addressed with the help of DR:

- **Downward ramping**: Thermal resources must ramp or shut-down rapidly as the sun rises and solar generation picks up the load on the grid.
- **Minimum generation**: Dispatchable thermal generators run in the middle of the day at a minimum power level to maintain power system reliability, and "over generation" by renewables in these peak solar generation times is curtailed.
- **Upward ramping**: Thermal resources must ramp up rapidly in the late afternoon as the sun sets to replace solar generation and carry the evening peak.
- **Peaking capacity**: The generation portfolio must have sufficient peak capacity to meet the evening peak.

As mentioned in the Introduction, *Shift* DR refers to an approach in which electrical loads are moved from one time to another to align with available renewable generation and to mitigate ramping. At the site level, *Shift* DR is manifested as a load reduction (a "shed") at a time when aggregate demand is high relative to available renewable generation, coupled with a load increase (a "take") at a different time beforehand, or afterward, when renewable generation is high relative to demand. Depending on the end-uses involved and power system conditions, this shed/take cycle can occur over a period of a few hours, over a diurnal (AM/PM) cycle, or even across several days (e.g., shifting peak weekday loads to the weekend). It is worth noting that load sheds in traditional *Shed* DR may also be partially offset by a take at a different time to make up the lost energy service (so-called "snapback"). One of the primary aims of *Shift* DR is to change the timing of loads in a controlled manner to ensure that the shed/take cycle serves to mitigate, not exacerbate, the duck curve. Furthermore, the opportunity to use *Shift* DR to mitigate renewables curtailment or fast ramping may occur much more frequently than the need to use traditional *Shed* DR for mitigating extreme peak loads (Alstone et al. 2017).

Figure 1 shows an example future load shape that summarizes the need for *Shift* DR in its various manifestations. The diagram shows the demand profile (solid curve) for ten days in May 2025, as forecast by the LBNL-Load model for the CA DR Potential Study, along with a generation stack broadly categorized into minimum generation (i.e., inflexible base generation) in gray, flexible generation (i.e., resources that can support rapid ramping) in blue, and variable renewable generation (specifically solar and wind) in green. As shown, when the net load

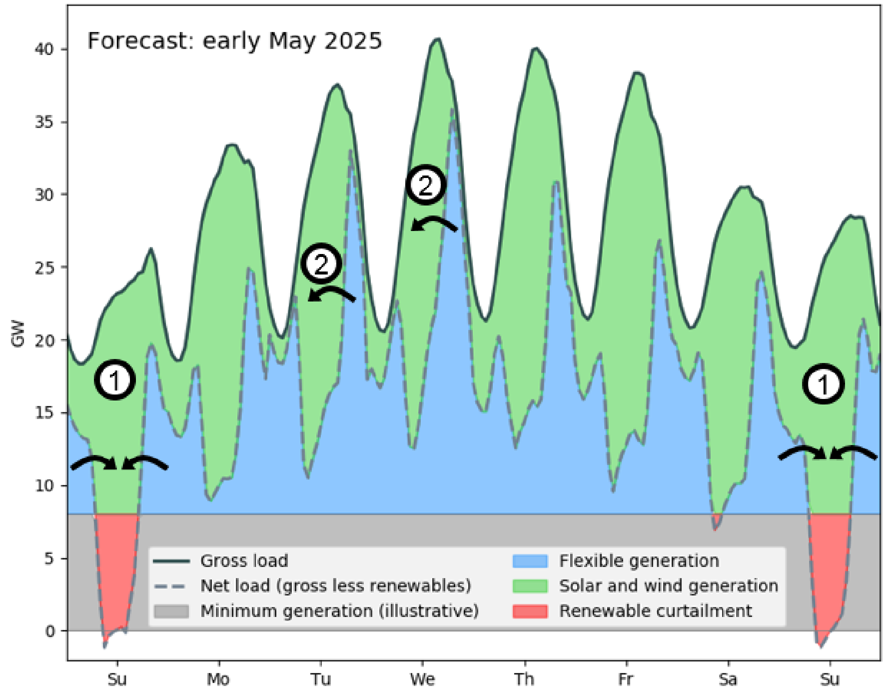

Figure 1: Demand and generation stack for ten days in May 2025, as forecast by the LBNL-Load model. Annotations show example periods when Shift DR would be valuable for mitigating renewable curtailment (1) and fast ramping (2).

(defined as gross demand less renewable generation) falls below the minimum generation level (red shaded regions), it is necessary to curtail renewables. The minimum generation level of 8 GW shown here is for illustrative purposes only: the precise value in 2025 is unknown, and it can vary over timescales of days as inflexible generators come online and offline. Thus, in some cases, some of the curtailment periods could be less substantial than shown. Notably, however, in two instances during the period shown (label 1 Figure 1**Error! Reference source not found.**), the net load curve falls below zero; in those cases, curtailment would occur even if all non-renewable generation could be turned off completely. *Shift* DR could be used to fill in those gaps.

Error! Reference source not found. Figure 1 also indicates example periods (label 2) when *Shift* DR can be valuable to mitigate ramping and sharp peaks, even when there is no curtailment. Importantly, rapid ramping of flexible resources occurs on every day shown, in response to changes in renewable generation at sunrise and (especially) sunset. This ramping profile occurs, to at least some extent, on every day of the year. Using *Shift* DR to ease these ramps could provide value to the grid on every day of the year, since it can eliminate the need for some peak and flexible generation capacity. The value may be greatest, however, on days with substantial renewable curtailment or with especially large evening peaks in the net load, since this impacts the total amount of generation infrastructure that is needed to provide adequate capacity.

When is *Shift* DR needed?

In the DR Potential Study, the DR-PATH model estimated the potential *Shift* DR resource by modeling it is a DR product that was perfectly **energy neutral** at the customer's site, over some

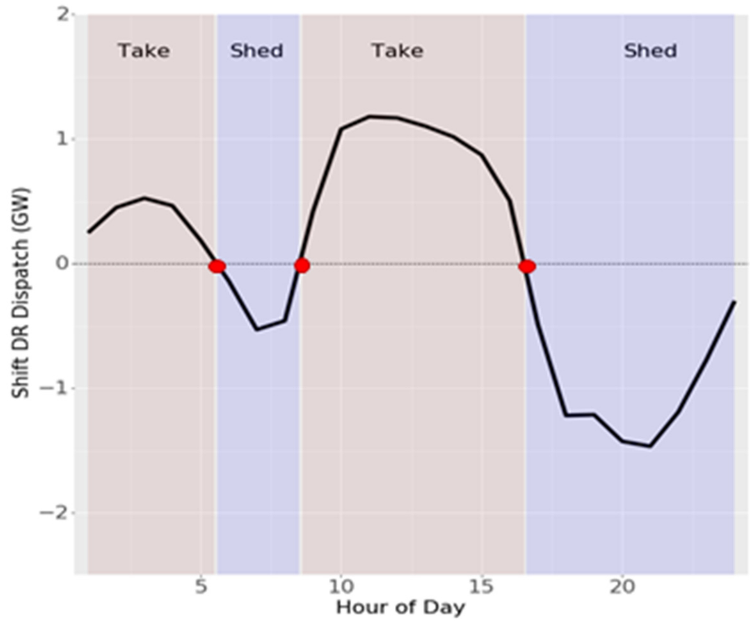

Figure 2: Average daily dispatch signal to which Shift DR would respond. To estimate the Shift resource, the DR-PATH model identifies loads that could be shifted within symmetrical, multi-hour windows about the zero points (red dots).

defined time window. The model assumed that *Shift* DR resources would be responding to a Shed and Take dispatch signal that is just the inverse of Generation-Up and Generation-Down dispatch signal communicated by the grid operator. The specific dispatch instructions used for the CA DR Potential Study were estimated using optimization of resources in E3 Consulting's RESOLVE model (see the CA DR Potential Study for further details). Figure 2 shows this dispatch signal averaged over all days in 2025. Shed periods occur during periods of peak net demand in the early morning and late evening, when demand is significant but solar generation is not available; while Take periods occur in the middle of the day, when solar generation is strong, and overnight, when loads are minimal but there is often significant wind generation (because of the variability of wind, however, an overnight Take period does not occur on every day).

We also note that, for the deepest curtailment periods in Figure 1 or in cases where significant wind generation dominates the generation mix over a multi-day period, there could be added value in shifting energy consumption over multiple days, such as by rescheduling discretionary loads from weekday evenings to weekend mornings. The potential for this kind of long-duration shifting over more than a few hours has not been thoroughly explored to date.

Which end-uses can provide *Shift* DR*?*

To estimate the available *Shift* DR resource, DR-PATH examines the forecasted cluster load profiles from LBNL-Load, disaggregated by end-use. For end-uses whose load can be shifted within a window of a given duration (e.g., 4 hours), the model calculates, within that window, the amount of shiftable load that is available to be moved across each of the zero-points of the *Shift* DR dispatch curve (red dots in Figure 2).

To serve as a *Shift* DR resource, a given end-use must meet two criteria:

1. It must have an inherent flexibility in timing, and
2. It must have a significant amount of load that would typically occur during times when there is need to reduce the system load, along with an ability to increase load at times when there are significant renewables available.

A wide variety of electrical end-uses meet these criteria. The DR Potential Study considered a subset of these that are expected to be common in California in 2025, limited by the ability to disaggregate those loads from the historical meter data and by the available information at the time related to end-use technology. The end-uses considered as *Shift* DR resources in the study are: industrial processes and pumping, warehouse refrigeration, electric vehicle (EV) charging, residential pool pumps, and residential and commercial HVAC, and behind-the-meter (BTM) battery storage.

BTM batteries naturally provide temporal load flexibility, and they may be a particularly large source of cost-effective *Shift* DR in the future, especially if prices fall further than was assumed in the CA DR Potential Study. However, the future adoption of storage technology remains highly uncertain, and it is a notable result of the CA DR Potential Study that there are many other end-uses already in use that provide comparable potential.

***Shift* DR's hourly availability.** Figure 3 shows the annually averaged daily load shapes for IOU-service areas, projected in 2025 for the different shiftable end-uses considered in the DR Potential Study (with the exception of batteries, whose expected load shapes are not well constrained). As mentioned, the study considered shifting within defined multi-hour windows centered on the daily Shed/Take transitions, and these periods are labeled as the pink (Take) and blue (Shed) shaded regions in Figure 3. As seen in Figure 3, HVAC and EV charging loads have

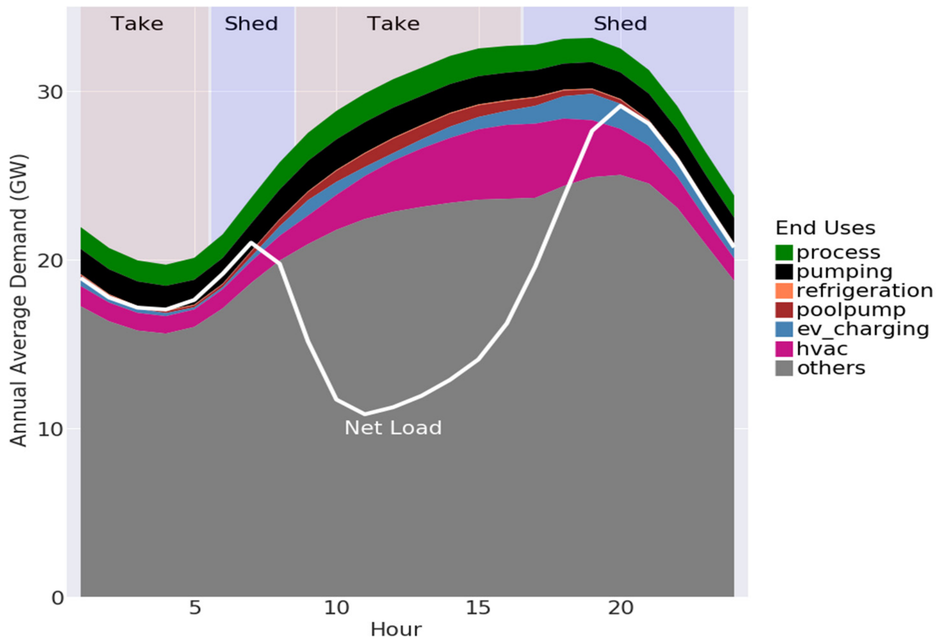

Figure 3: Annual average daily load shape in 2025, as forecast by LBNL-Load, with analyzed shiftable end-uses disaggregated (colored bands) and set in the context of the daily Take/Shed cycle from Figure 2 and the daily average net load (white curve).

natural peaks near the transition between Shed and Take periods; hence they are likely to have a high *Shift* DR potential. By contrast, pool pump loads have their peak during the middle of the day, where it is already largely aligned with system needs. Industrial process and pumping loads have flatter profiles, suggesting that they may have potential to shift a portion of their load. In essence, the opportunity to participate in *Shift* DR comes from a misalignment between the "natural" timing of loads that is incumbent in the power system and the emerging dynamics of variable renewable generation.

***Shift* DR's seasonal availability**. Just as the potential for a given end-use to provide *Shift* DR depends on its daily load profile, there is also a strong seasonal component to each end-use's value as a *Shift* DR resource. Figure 4 shows the daily statewide load shapes in 2025 by season, disaggregated into estimated end-use contributions, similar to the annual average load shapes in **Error! Reference source not found.**. A strong seasonal variation is apparent in the amount of shiftable load, driven primarily by seasonal variation in HVAC load. The DR Potential Study reported annual averages for *Shift* DR that reflected the accumulated opportunity and value to shift loads. When planning for the deployment of *Shift* DR resources, it will be essential to account for seasonal variation, since the largest available end-uses may not align with times of critical system need.

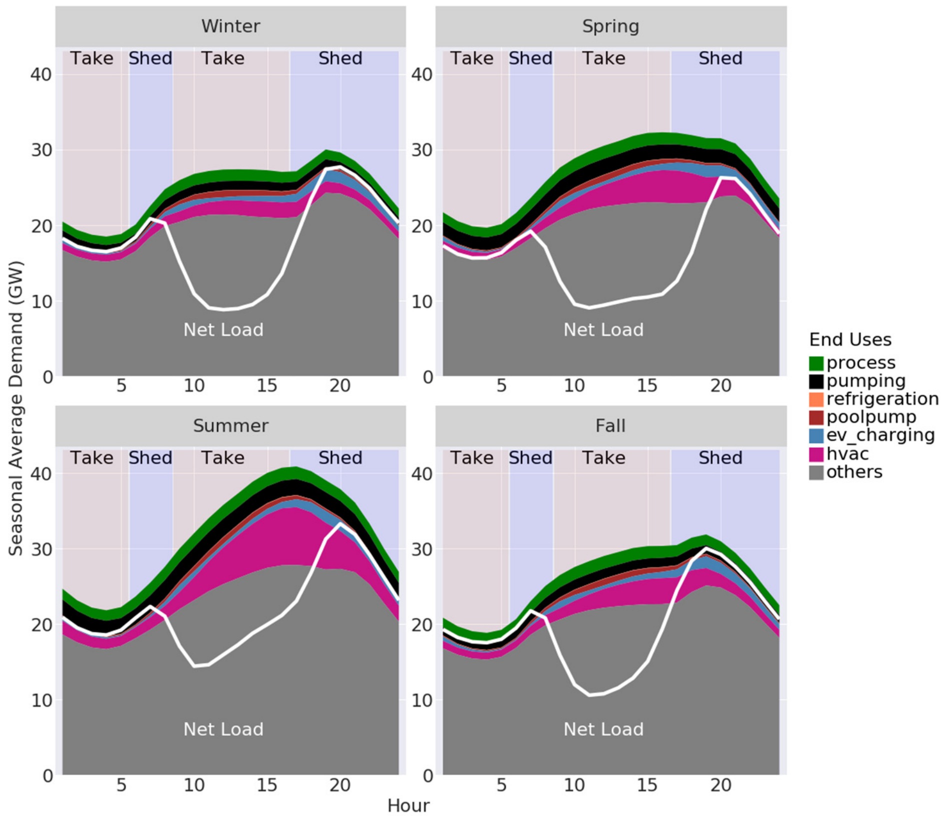

Figure 4: Seasonal average daily load shapes in 2025, as forecast by the LBNL-Load model. The loads are broken down by end-use and set in the context of the daily net load (white curve) and Shed/Take periods, as in **Error! Reference source not found.**.

For example, solar curtailment may be most problematic in the spring, when there is relatively high daily insolation but low temperatures limit the total mid-day HVAC load; however, the reduced HVAC load also means there is less *Shift* DR resource available to offset the curtailment than is available in summer.

Pathways to Implementing *Shift DR*

How do we get *Shift* DR on the grid?

As discussed above, a future grid with increased renewable energy is likely to have a consistent need for load shifting from evening to midday hours on nearly every day of the year. Beyond this consistent pattern, the day-to-day variability in renewables leads to different specific needs for load shifting each day. Therefore, it may be most effective to implement *Shift* DR using a two-tiered approach as follows.

First, for load shifting is consistently needed, it may be least costly to achieve it through approaches that drive persistent changes in consumer behavior, such as through *Shape*-DR approaches (see Alstone et al, 2017). These approaches fall into two broad categories:

- **TOU pricing.** Using retail rates to shape load will be foundational to achieving the needed daily shift, since this can drive permanent daily load shifts that help mitigate the effects of duck curve. There are many competing concerns that must be considered in developing retail electricity rates, but modifications to current TOU practice that could enhance the load-shifting impacts include increasing the number of daily and seasonal periods (e.g., four daily periods, as in **Error! Reference source not found.**, varying across four seasons, instead of two or three periods and two seasons), and increasing the difference in price between Take and Shed periods.

- **Modified approaches to programs, codes, and standards.** In California and elsewhere, substantial infrastructure already exists that is devoted to gross load reduction through energy efficiency (EE), in the form of utility programs, building codes, and appliance/equipment standards. The value of EE is enhanced if it delivers energy savings at times when it is most valuable to the grid (Boomhower and Davis 2017); thus, it may be valuable to restructure market and policy incentives toward load reshaping in addition to gross load reduction.[3] TOU rates having a larger differential between Shed/Take periods will naturally create pressure in this direction, since the consumer value proposition for EE rests on cost savings achieved at the meter.

Even with maximum permanent load reshaping, daily variability in renewables suggests that there will likely also be a value in having a dispatchable *Shift* DR product in the energy market. We envision three broad categories of market-based approaches to *Shift* DR that might enable load shifting in California, and the challenges that must be overcome before wide deployment can be achieved.

- **Real-time price tariff.** This approach would pass through real-time or day-ahead energy prices to the consumer, enabling load shifting consumers to shift their consumption in response. Studies have shown that customers may be more willing to shift their consumption depending on the hedging options they are offered, and more broadly, more financial benefits than those offered by fixed price tariffs (see Barbose et al., 2005). Wide deployment of this approach would require substantial customer engagement and/or technological support (e.g., automated price-responsive devices) to be successful; nevertheless, there are some real-world examples of this approach today[4].
- **DR bidding as a generator.** The traditional approach to *Shed* DR is to bid DR into the energy market as a generator, and to respond to the same dispatch instructions. It may be possible to develop *Shift* DR type products that participate similarly, allowing DR participants to respond to both generation-up (Shed) and generation-down (Take) signals (as in Figure 2). However, if *Shift* DR is dispatched on a near-daily basis, there are challenges to establishing a baseline against which to measure performance.
- **DR bidding as a load.** An alternative wholesale market approach to *Shift* DR participation would be to enable bidding flexible loads into the market as loads resources. Currently, fixed loads are bid into the CAISO market as price-takers, but there may be may be approaches that allow price-conditional bids, thus introducing some demand

[3] Notably, some load-reshaping incentives already exist or are under development. For instance, California Title 24 already makes use of time-dependent valuation in developing building energy efficiency standards (CEC 2016), and the CalTRACK initiative v2.0 (www.caltrack.org/caltrack-20.html) envisions measuring changes in hourly load shapes at the meter as an option for pay-for-performance evaluation of EE programs.
[4] For example, the Commonwealth Edison RTP program – see hourlypricing.comed.com/live-prices/

elasticity into the market.[5] This could eliminate some of the baselining issues that arise with requiring DR to bid like a generation-type resource, but establishing this fundamentally new means of interfacing with the market will be challenging.

Where is the *Shift* DR resource?

Targeting customers with a high *Shift* DR potential to participate in DR programs is an essential component needed to maximize the cost effectiveness of any *Shift* DR resource. Targeting could be used to identify a valuable combination of sites that can provide *Shift* DR during times of need, for recruitment into either dispatchable DR or *Shape*-based programs.

To explore various approaches to customer targeting for *Shift* DR, we used the outputs of DR-PATH to compute several different statistics for each customer cluster, which might be relevant to targeting.

- The ***Shift* DR potential per Site** is the maximum amount of *Shift DR—i.e., the* number of shiftable kWh available on an average day[6] at times of system need—that could be enabled in each cluster (using an optimal mix of technologies and incentives), divided by the customer count of the cluster.
- The **Total Consumption per Site** is the cluster's average daily total energy consumption, computed either annually or seasonally, divided by the customer count. In what follows, we will sometimes use the term site size to refer to this quantity.
- The **Peak Consumption** is the total consumption during the peak hours of net load in the evening (5 to 8 pm, and the **Off-peak Consumption** is the total consumption during midday hours (12 to 33 pm), either annually or seasonally, divided by the site size. We considered various ratios of peak to off-peak or peak to total consumption as a way to provide compressed information about the overall load shape for each cluster.

Based on the previous investigation where we observed that shiftable load shapes tend to show seasonal patterns, we then looked at the total consumption over each season relative to its shift potential by sector (see Figure 5). With this analysis we test whether, for example, the assumption that one expects promising sites would be those with large evening peaks that could be shifted slightly earlier to utilize solar generation was true or not.

[5] This bidding approach is available in PJM Interconnection (see: https://bit.ly/2GQ2dr6), and ISO New England's new price-responsive demand structure goes into effect in June 2018 (see https://bit.ly/2IP7YqQ).
[6] The CA DR Potential Study, Phase 2, did not consider seasonal variation in the DR resource, so the values we explore here are annual averages only. Exploring a seasonal metric could give more nuanced results and reveal new approaches to targeting.

Error! Reference source not found. shows that site usage is highly correlated with its shift potential, with an especially tight relation evident in the commercial and industrial sector. In those sectors a fairly trivial customer targeting strategy that simply pursued the largest sites would be highly effective in identifying the largest *Shift* DR resources. In the commercial sector in particular, we see a clump of very large commercial customers (consumption between 10^3 and 10^4 kWh) that appear to have a higher *Shift* DR potential than the trend from the rest of the clusters. A simple threshold in site size can very effectively isolate these customers for targeting.

In the residential sector, by contrast, the relation between usage and *Shift* DR potential has a much larger scatter, and some very large sites have a very small *Shift* DR potential, so a size-based targeting strategy would be less effective. It is also worth noting from **Error! Reference source not found.** that the maximum *Shift* DR potential per site in the residential sector is smaller by several orders of magnitude than the maximum potential for industrial or commercial sites. Since residential sites are quite numerous, however, it may still be valuable to target residential sites that have an especially high *Shift* DR potential using different metrics than site usage.

Another targeting metric to consider is the ratio between peak and off-peak consumption, which can tell us something about the relative amounts of load that are in use during typical Shed and Take periods. As shown in Figure 6, however, this metric represents a fairly poor statistic for targeting specific clusters given the high data variability. The figure shows the relation between *Shift* DR potential and peak/off-peak ratio in the residential sector, by season. In every case, there is little relation evident between the two variables: simply because a site has a relatively large peak-period load, this does not necessarily mean the load is shiftable; conversely, a relatively small peak-period load may still represent a large potential shift. (We also find little to no correlation between these two variables in the industrial or commercial sectors.)

Interestingly, however, the targeting quality of the peak/off-peak ratio varies by season: in the summer, selecting sites with a peak-to-off-peak ratio greater than 1.5 would tend to yield

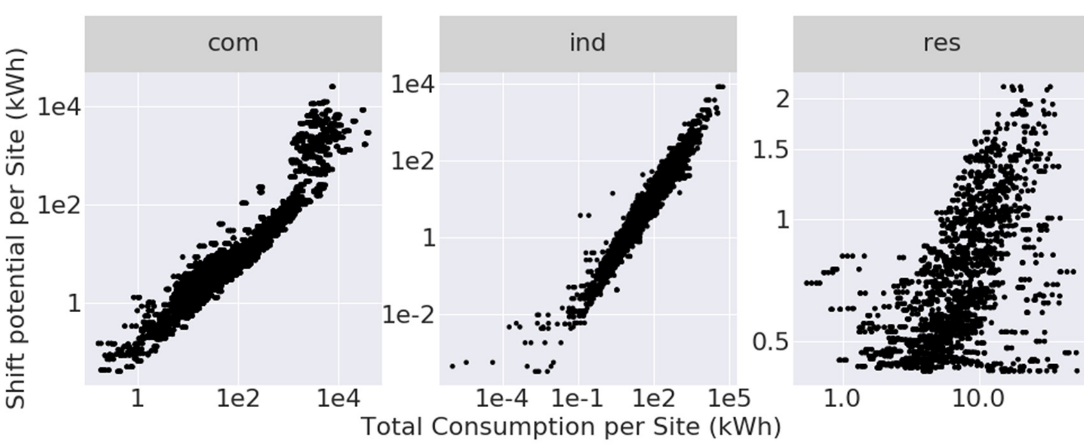

Figure 5. The relationship between the average daily site-level consumption and site-level Shift potential in each customer cluster, subdivided by sector. Note that all axes have a logarithmic scale.

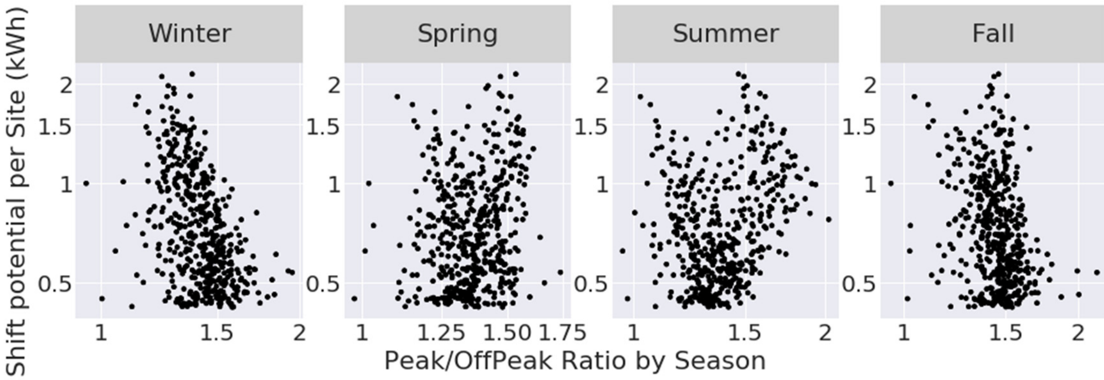

Figure 6. The relationship between Peak/Off-peak consumption ratio and *Shift* potential for each cluster in the residential sector, broken down by season. Note that all axes have a logarithmic scale.

sites with a larger *Shift* DR potential than average, although the scatter is still quite large. This initial exploratory analysis suggests that a much closer look and more granular investigation will need to be performed in order to identify and eventually enable a valuable portfolio of resources that can provide *Shift* DR to the grid.

Conclusions

With rapidly increasing variable renewable energy generation, the California electricity system today is already experiencing the impacts of the duck curve. Mitigating this pattern will require novel demand-side management approaches to shifting demand away from periods of high net demand and toward periods of high generation from renewables. Using a full set of analytical results produced by the CA DR Potential Study, we have explored a variety of questions related to *Shift* DR and its potential for meeting California's future grid needs. Specifically, we discussed how *Shift* DR may be needed both to mitigate occasional renewable curtailment as well as to ease steep ramps in non-renewable generation that occur on every day of the year. The latter situation means that there are likely to be fairly stable "Take" and "Shed" dispatch periods that we identify during a typical day, to which DR resources can respond. Because of this, while a wide variety of electrical end-uses can provide *Shift* DR, their potential availability is a function of their seasonal and hourly usage patterns.

In this context, we discussed various strategies for incorporating *Shift* DR into the future mix of grid resources. Persistent load shifting may be achievable through a combination of retail pricing mechanisms, potentially coupled with a suite of EE measures that can spur adoption of load-shifting technology. These efforts will have to be synchronized with energy markets, where DR resources will potentially see their efforts remunerated to achieve the residual daily need for load shifting. Targeting sites for participation is also a challenge. While the commercial and the industrial sectors end-uses that can provide the most *Shift* DR might be identified based on their size alone, more granular analysis will be needed for the residential sector. Many open questions remain on how future markets will incentivize *Shift* DR products to actively participate as a grid resource, and to enable a clean, reliable, and resilient energy grid.

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