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Resource and revenue potential of California residential load participation in ancillary services ☆

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HIGHLIGHTS

- California's energy storage mandate requires 1.325 GW of energy storage by 2020.
- Residential loads such as refrigerators have thermal energy storage.
- California's residential loads could provide 10-40 GW/8-12 GWh of storage.
- Loads participating in ancillary services markets could earn up to $56/load/year.
- Consumer choices and policy mechanisms could increase revenue potentials.

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ABSTRACT

Increasing penetrations of intermittent renewable energy resources will require additional power system services. California recently adopted an energy storage mandate to support its renewable portfolio standard, which requires 33% of delivered energy from renewables by 2020. The objective of this paper is to estimate the amount of energy storage that could be provided by residential thermostatically controlled loads, such as refrigerators and air conditioners, and the amount of revenue that could be earned by loads participating in ancillary services markets. We model load aggregations as virtual energy storage, and use simple dynamical system models and publicly available data to generate our resource and revenue estimates. We find that the resource potential is large: 10–40 GW/8–12 GWh, which is significantly more than that required by the mandate. We also find that regulation and spinning/non-spinning reserve revenues vary significantly depending upon type of load and, for heat pumps and air conditioners, climate zone. For example, mean regulation revenues for refrigerators are $11/year, for electric water heaters are $24/year, for air conditioners are $0-32/year, and for heat pumps are $22–56/year. Both consumer choices, such as appliance settings, and policy, such as the design of ancillary service compensation and appliance standards, could increase revenue potentials.

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1. Introduction

To reduce greenhouse gas emissions many states have implemented renewable portfolio standards that require a certain percentage of electricity to come from renewable sources. Both wind and solar photovoltaics are expected to comprise a significant portion of new renewables (Loutan et al., 2007); however, both technologies produce intermittent and uncertain power. As a result, system operators will need to procure more ancillary services such as regulation and load following (Makarov et al., 2009; Halamay et al., 2011). Rather than using power plants to provide these additional services, it may be more cost-effective and/or environmentally beneficial to use alternative technologies, namely energy storage devices (e.g., batteries, flywheels, compressed gas,

Abbreviation: AC, air conditioner; CAISO, California Independent System Operator; CEC, California Energy Commission; EIA, energy information agency; EWH, electric water heater; GH, gas heater; GWH, gas water heater; HP, heat pump; LADWP, Los Angeles Department of Water and Power; MAEC, mean annual energy consumption; PG&E, Pacific Gas and Electric Company; RECS, residential energy consumption survey; RF, refrigerator; SCE, Southern California Edison Company; SDG&E, San Diego Gas & Electric Company; SMUD, Sacramento Municipal Utility District; TCL, thermostatically controlled load

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and pumped hydropower) and demand response resources.

In October 2013, California became the first state in the U.S. with an energy storage mandate (Sweet, 2013). The mandate requires 1325 MW of energy storage by 2020 (CPUC, 2013a), which is expected to support California's renewable portfolio standard goal of 33% of delivered energy from renewables by 2020 (CPUC, 2013b). California's definition of energy storage includes systems that “store thermal energy for direct use for heating or cooling at a later time in a manner that avoids the need to use electricity at that later time” (State of California, 2010). Therefore, demand response that shifts the power consumption of thermostatically controlled loads (TCLs), such as heating and air conditioning systems, electric water heaters, and refrigerators, which all store heat in thermal mass, may qualify as energy storage, and contribute to California's energy storage needs.

Residential TCLs are well-suited to load shifting on timescales of seconds to minutes. These loads generally operate with hysteresis, modulating temperature between an upper and lower limit, and so their power consumption is inherently flexible. Recent work has focused on the development of strategies to coordinate the power consumption of large aggregations of residential TCLs to provide power system services, e.g., (Callaway, 2009; Kundu et al., 2011; Perfumo et al., 2012; Bashash and Fathy, 2013; Mathieu et al., 2013b; Zhang et al., 2013; Totu et al., 2013), while ensuring that coordination actions are non-disruptive to electricity consumers, meaning that temperatures stay near or within existing temperature limits (Callaway and Hiskens, 2011). A variety of approaches have been shown effective in simulation; however, several key questions remain including: How well will loads perform in practice? What is the size of this resource? Is it large enough to play a meaningful role in intra-hour energy balancing? Will revenue earned from ancillary services participation be enough to cover the infrastructure and operational costs associated with non-disruptive load coordination? While answering the first question requires testbeds and pilot studies, we can begin to develop answers to the last three questions with data and models.

The objective of this paper is to develop order-of-magnitude estimates for the technical resource potential and ancillary service revenue potential of non-disruptive coordination of residential TCLs in California. To develop these estimates, we model TCL aggregations as virtual energy storage devices and first estimate the time-varying and location-dependent power and energy capacities of aggregations of four types of residential TCLs – central air conditioners, heat pump heating systems, electric water heaters, and refrigerators. We then generate statewide technical resource potential estimates (i.e., estimates of the time-varying aggregate power and energy capacity of all TCLs in California) for both 2014 and 2020, where in the latter we consider two scenarios: (i) electric appliance saturation levels equivalent to those today and (ii) increased electric appliance saturation levels due to a portion of consumers switching from gas to electric water and space heating. The latter analysis is not meant to be predictive but rather to explore the effect of increased appliance electrification as recommended by a California Council on Science and Technology report (CCST, 2011), which listed appliance electrification as one of the changes needed to achieve greenhouse gas emissions reductions to 80% below 1990 levels by 2050. With our resource estimates, we estimate the mean revenue per TCL per year for TCLs providing regulation and spinning/non-spinning reserve. This paper builds upon and updates our preliminary work in this area (Mathieu et al., 2012).

Our contributions are twofold. First, we develop methods to estimate resource and revenue potentials of TCL aggregations. These methods rely on simple models of TCL dynamics and publicly available data, and could be used to generate estimates for other regions. Second, our estimates inform energy policy. An understanding of the size of the resource and current financial incentives will help policy makers determine whether policy mechanisms are needed to achieve load participation in ancillary services markets.

This paper is organized as follows. In Section 2 we present our methods including appliance ownership, temperature, and price data sources; TCL model; technical resource potential calculation methods; and revenue potential calculation methods. Section 3 presents the results of our resource and revenues potential analyses, and Section 4 provides a discussion of these results in the context of energy policy. Section 5 gives concluding remarks.

2. Methods

2.1. Appliance ownership, temperature, and price data sources

We estimated the number of central air conditioners (henceforth “air conditioners” and abbreviated AC), heat pump heating systems (henceforth “heat pumps” and abbreviated HP), refrigerators (RF), electric water heaters (EWH), gas heating systems (henceforth “gas heaters” and abbreviated GH), and gas water heaters (GWH) in five utility districts in California: Pacific Gas and Electric (PG&E), Southern California Edison (SCE), San Diego Gas and Electric (SDG&E), Sacramento Municipal Utility District (SMUD), and Los Angeles Department of Water and Power (LADWP). We did not consider room air conditioners or space heaters because the resource is small and hard to control. To develop the estimates, we used appliance saturation rates from the 2009 California Residential Appliance Saturation Survey (Palmgren et al., 2010) and we extrapolated California Energy Commission (CEC) forecasts for the number of households in California in 2014 and 2020 (Marshall and Gorin, 2007). For air conditioners, heat pumps, and gas heaters, we used saturation rates by CEC Forecasting Climate Zone (listed in Table 1 and shown in Fig. 1a) since power consumption varies as a function of outdoor air temperature. For refrigerators, electric water heaters, gas water heaters, we used statewide saturation rates since power consumption varies as a function of indoor air temperature, which we assume is constant and uniform across the state. Table 2 shows estimates for the number of households per CEC Forecasting Climate Zone in 2014 and 2020 together with appliance saturation rates. Note that newer statewide forecasts are available (Kavalec and Gorin, 2009; Alcorn et al., 2013a, 2013b); however, these reports do not provide breakdowns of households by climate zone. The 2007 statewide household forecasts (13.14 million in 2014, 14.26 million in 2020)

Table 1
List of CEC Forecasting Climate Zones, mapping to California Building Climate Zones, and Associated CAISO Ancillary Service Zone.

CEC Forecasting Climate Zone	California Building Climate Zone	CAISO Ancillary Service Zone
1: PG&E North Coast Mountain	1: Arcata	North
2: PG&E Sacramento Area	12: Sacramento	North
3: PG&E Central Valley	12: Sacramento	North
4: PG&E East Bay	2: Santa Rosa	North
5: PG&E San Francisco	3: Oakland	North
6: SMUD	12: Sacramento	North
7: SCE San Joaquin	13: Fresno	South
8: SCE LA Basin Coast	6: Los Angeles	South
9: SCE LA Basin Inland	10: Riverside	South
10: SCE Inland Empire	14: China Lake	South
11: LADWP	10: Riverside	South
12: LADWP	10: Riverside	South
13: SDG&E	7: San Diego	South

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