Frequency Regulation from Flexible Loads: Potential, Economics, and Implementation$^{\pi}$

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Abstract— **Thermostatically Controlled Loads (TCLs) such as air conditioners, heat pumps, water heaters and refrigerators have a great potential for providing regulation reserve to the grid. This paper aims to provide a foundation for a practical method of enabling TCLs to provide regulation service. We study the economic, regulatory, and practical aspects to realize such a vision. We show that the potential of TCLs in California is more than enough for both current and predicted near-future regulation requirements. Moreover, we estimate the cost and revenue of TCLs, discuss the qualification requirements and participation incentive methods, and present a practical control framework for TCLs to provide regulation service. Numerical experiments are also provided to illustrate the efficacy of our methods in addressing practical issues such as short cycling of units, latency in communications, and dynamics modeling errors.**

I. Introduction

In the electrical power grid, balance between supply and demand must be maintained on a second-to-second basis, which otherwise will result in catastrophic consequences. Ancillary services such as frequency regulation and load following play an important role in achieving this power balance under normal operating conditions. While load following handles more predictable and slower changes in load, frequency regulation mitigates faster changes in system load and corrects unintended fluctuations in generation [1]. In this paper, we aim to provide a foundation for a practical method of enabling Thermostatically Controlled Loads (TCLs) to provide this frequency regulation service.

Frequency regulation has been traditionally provided by relatively fast-responding generators. However, the ramping rate of these generators is generally slower than that of the regulation signal, which results in poor power quality and high regulation procurements [1], [2]. The regulation requirements can be lowered if faster responding resources are available [3]. It has been shown if California Independent System Operator (CAISO) dispatched fast responding regulation resources, it could reduce its regulation procurement by as much as 40% [4]. This issue has been recognized in the power and energy system community. The recently issued FERC orders 784 and 755 require considering the speed and accuracy of regulation resources when procuring regulation services.

In accordance to FERC order 755, CAISO has introduced a mileage product to provide compensation for faster and more accurate regulation resources [5]. Moreover, CAISO's definition of a Non-Generator Resource (NGR) with Regulation Energy Management (REM) allow non-generator resources with limited energy capacities, such as batteries and flywheels, to competitively bid in the regulation market. REM resources can bid to provide power based on their 15-minute energy capacity into the day-ahead regulation market, and CAISO will dispatch these resources so that their state of charge limits are respected [6]. These regulatory developments have roused a growing interest in tapping the potentials of fast-responding and more precise regulation resources.

A. Main Contributions

In this paper, we argue that a collection of TCLs has a great potential for providing fast regulation service, due to their large population size and the ability of being turned ON/OFF simultaneously. In our recent work [7], [8], we have shown that the aggregate flexibility offered by a collection of TCLs can be succinctly modeled as a generalized battery. Moreover, we characterized the power limits and energy capacity of this battery model. Based on this battery model, we estimate in this paper the potential of TCLs in California for regulation service provision. We show that conservative estimates of the available power capacity is larger than twice of the current maximum regulation procurement (600 MW). Moreover, it is larger than the predicted maximum regulation requirement of CAISO with 33% of renewable penetration (1.3 GW) [9]. The potential of TCLs in California is more than enough for provision of regulation service for now and in the near future.

We further estimate the cost and revenue of TCLs for providing regulation service to the grid. Due to the stringent telemetry and metering requirements of CAISO, the real-time power measurement of each individual TCL is required to be reported to the ISO every 4 seconds. This requirement imposes a non-trivial cost on each unit to satisfy the qualification requirements. Moreover, CAISO currently requires the minimum resource size to be 0.5 MW, and no aggregation of loads is allowed. We comment that these rules must be changed in order to allow an aggregator to profitably provide regulation service using TCLs in the California regulation market. Additionally, we show that the annual revenue per TCL is not very attractive if the total revenue is split evenly

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to each unit. Therefore, a fair and attractive incentive method needs to be designed to encourage customer participation.

A controller strategy is needed to coordinate the TCL aggregation so that the power deviation from baseline follows the desired regulation signal. A priority-stack-based control framework was proposed in [7], [8]. The priority of a TCL is measured by the temperature distance to its switching boundary. The purpose of this control strategy is to minimize any rapid switching between the ON and OFF states of each unit. In many cases, there is a minimum ON/OFF time that must elapse between any switch to avoid equipment damage. This is called a no-short-cycling constraint. In this paper, we extend the priority-stack-based control strategy in [7], [8] to incorporate such a constraint. In our companion paper [10], we also derive an explicit characterization of the constraints on upward and downward movement of feasible regulation signals under the no-short-cycling requirement. Furthermore, we show by numerical experiments that our priority-stack-based control strategy is robust against latency in communications, dynamics modeling error and external disturbance from occupants, and satisfies the tracking accuracy requirement of CAISO.

B. Related Work

The proof of concept of using TCLs to provide regulation reserve and load following were reported in [11]–[14]. Time-based and temperature-based priority control methods that are similar to our work were developed in [12] and [13]. The work of [15], [16] are closely related to the present paper. In [15], the authors used simulation-based method to estimate the potential and revenue of TCLs for providing regulation reserve and load following services. In [16], the authors reviewed the historic ancillary service price, market size, and discussed the ancillary service qualification requirements for various ISOs in the United States. The analysis in the present paper is based on an analytical characterization of feasible regulation signals, and we focus on the regulation market in California, estimating the potential and revenue using historic data of CAISO.

C. Paper Organization

The remainder of the paper is organized as follows. Section II presents the potential of TCLs in California. In Section III, we study the cost and revenue of TCLs for regulation service provision, and discuss the qualification requirements and customer incentive methods. Section IV describes a priority-stack-based control framework to enable TCLs to provide regulation service. The paper ends with conclusions and future work in Section V.

II. POTENTIAL OF TCLS

A. Thermostatically Controlled Loads

In this paper, we consider a collection of Thermostatically Controlled Loads (TCLs). The temperature evolution of each TCL is described by a standard hybrid-system model

$$\dot{\theta} = \begin{cases} a(\theta_a - \theta) - bP_m + w, & \text{ON state, } q(t) = 1, \\ a(\theta_a - \theta) + w, & \text{OFF state, } q(t) = 0. \end{cases} \tag{1}$$

The parameters that specify this TCL model are $\chi = (a, b, \theta_a, \theta_r, \Delta, P_m)$, where $a = \frac{1}{CR}$, and $b = \frac{\eta}{C}$. See Table I for parameter definitions and [7], [8], [11], [12] for more details on the model. The term w accounts for external disturbances from occupancy, appliances, and so on. We consider four types of TCLs: air conditioner, heat pump, water heater and refrigerator. Table I describes the parameters and their typical values [15]. Each TCL has a temperature setpoint θ_r with a hysteretic ON/OFF local control within a deadband $[\theta_r - \Delta, \theta_r + \Delta]$. The operating state $q(t)$ evolves as

$$\lim_{\epsilon \to 0} q(t+\epsilon) = \begin{cases} q(t), & |\theta(t) - \theta_r| < \Delta, \\ 1 - q(t), & |\theta(t) - \theta_r| = \Delta. \end{cases}$$

The average power consumed by a TCL over a cycle is

$$P_o = \frac{P_m T_{\text{ON}}}{T_{\text{ON}} + T_{\text{OFF}}}, \tag{2}$$

where T_{ON} and T_{OFF} are respectively the ON and OFF state durations per cycle.

For a large collection of TCLs that is uncoordinated, the instantaneous power drawn by this collection will be very close to the combined average power requirement, because any specific TCL will be at a uniformly random point along its operating cycle. Consider a diverse collection of TCLs indexed by k. The baseline power of a collection of TCLs is given by

$$n(t) = \sum_k P_o^k,$$

where the average power P_o^k is given in (2). Additionally, their aggregated instantaneous power consumption is

$$P_{\text{agg}}(t) = \sum_k q^k(t) P_m^k.$$

B. Generalized Battery Model of TCLs

During a cycle, each TCL can accept perturbations around its average power consumption that will still meet user-specified comfort bounds. Define

$$\mathbb{E}^k = \left\{ e^k(t) \middle| \begin{matrix} 0 \le P_o^k + e^k(t) \le P_m^k, \\ P_o^k + e^k(t) \text{ maintains } |\theta^k(t) - \theta_r^k| \le \Delta^k \end{matrix} \right\}.$$

This set of power signals represents the flexibility of the k^{th} TCL with respect to nominal. The *aggregate flexibility* of the collection of TCLs is defined as the Minkowski sum

$$\mathbb{U} = \sum_k \mathbb{E}^k.$$

The geometry of the set $\mathbb{U}$ is, in general, unwieldy. In [7], [8], we showed the aggregate flexibility $\mathbb{U}$ could be captured by two generalized battery models.

Definition 1: A *Generalized Battery Model* $\mathbb{B}$ is a set of signals $u(t)$ that satisfy

$$-n_- \le u(t) \le n_+, \quad \forall\, t > 0,$$
$$\dot{x} = -ax - u,\ x(0) = 0 \ \Rightarrow |x(t)| \le C, \quad \forall\, t > 0.$$

The model is specified by the non-negative parameters $\phi = (C, n_-, n_+, a)$, and we write this compactly as $\mathbb{B}(\phi)$. □

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TABLE I: Typical parameter values for air conditioner, heat pump, water heater and refrigerator.

Parameter	Description	Unit	*Air Conditioner*	*Heat Pump*	*Water Heater*	*Refrigerator*
C	thermal capacitance	kWh/°C	$1.5-2.5$	$1.5-2.5$	$0.2-0.6$	$0.4-0.8$
R	thermal resistance	°C/kW	$1.5-2.5$	$1.5-2.5$	$100-140$	$80-100$
P_m	rated electrical power	kW	$4-7.2$	$4-7.2$	$4-5$	$0.1-0.5$
η	coefficient of performance		2.5	3.5	1	2
θ_r	temperature setpoint	°C	$18-27$	$15-24$	$43-54$	$1.7-3.3$
Δ	temperature deadband	°C	$0.125-0.5$	$0.125-0.5$	$1-2$	$0.5-1$
θ_a	ambient temperature	°C	variable	variable	20	20

We can regard u as the power drawn from or supplied to a battery, and $x(t)$ as its state-of-charge. This battery model provides a succinct and compact framework to characterize the aggregate power limits and energy capacity of a population of TCLs. We next summarize the main results of [7], [8] in Theorem 1.

Theorem 1: Consider a collection of *heterogeneous* TCLs parameterized by χ^k. Fix $a > 0$, and define $f^k = \Delta^k/(b^k(1+|1-a/a^k|))$. The aggregate flexibility $\mathbb{U}$ of the collection satisfies

$$\mathbb{B}(\phi_1) \subseteq \mathbb{U} \subseteq \mathbb{B}(\phi_2),$$

where the parameters $\phi_2 = (C, n_-, n_+, a)$ of the necessary battery model are given by

$$C = \sum_k \left(1 + \left|1 - \frac{a^k}{a}\right|\right) \frac{\Delta^k}{b^k},$$
$$n_- = \sum_k P_o^k, \quad n_+ = \sum_k P_m^k - P_o^k,$$

and the parameters $\phi_1 = (C, n_-, n_+, a)$ of the sufficient battery model are given by

$$C = \min_k \frac{f^k}{\beta^k}, \quad n_- = \min_k \frac{P_o^k}{\beta^k}, \quad n_+ = \min_k \frac{P_m^k - P_o^k}{\beta^k},$$

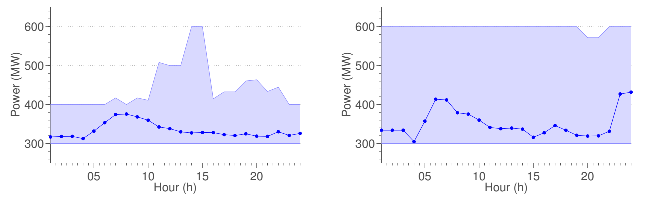
in which $\beta^k \geq 0$ satisfying $\sum_k \beta^k = 1$. □

Note that the gap between the sufficient battery model $\mathbb{B}(\phi_1)$ and the necessary battery model $\mathbb{B}(\phi_2)$ decreases as TCLs become homogeneous. The above theorem is used to estimate the potential of TCLs in California.

C. Potential of TCLs in California

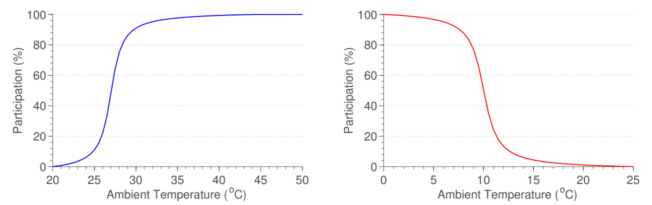
Prior to October of 2009, the amount of upward and downward regulation the CAISO procured were respectively about 375 MW and 500 MW [17]. More recently, the amount of regulation has increased, with the maximum upward and downward regulation that the CAISO procured in 2012 of about 600 MW [18]. In particular, the hourly minimum, average, and maximum in-market capacity procurements are depicted in Fig. 1. Furthermore, it has been predicted that if California achieved its 33% of renewable penetration target by 2020, both the maximum upward and downward regulation procurements would increase to 1.3 GW [9].

Using the generalized battery model, we estimate the regulation capacity for the four types of TCLs listed in Table I. Note that the ambient temperatures of refrigerator and water heater are assumed to be $20°C$. This makes their power limits and energy capacities constant, independent of the outside temperature. This is not the case for other types of TCLs such as air conditioners and heat pumps. In addition, the percentage of participation of air conditioners and heat pumps is also a function of ambient temperature. For example, in the case of air conditioners, there is low participation when the ambient temperature is low, and more participation when the ambient temperature is high. We assume the functions of participation percentage over ambient temperature for air conditioners and heat pumps are of inverse tangent functions, which are depicted in Fig. 2.



(a) Upward regulation (b) Downward regulation

Fig. 1: Hourly minimum, average, and maximum capacity procurements for upward and downward regulation in California. The plots are based on historic data of CAISO in 2012.



(a) Air Conditioners (b) Heat Pumps

Fig. 2: The functions of participation percentage over ambient temperature for air conditioners and heat pumps.

Based on the census result in 2011, there are 13.7 million households in California [19]. The saturation rates for the four types of TCLs are summarized in Table II based on a survey [20]. For each type of TCL, we estimate their aggregate flexibility using parameter values as the mean of the values listed in Table I. We then estimate their aggregate upward and downward power limits and the energy capacities for each type of TCLs using Theorem 1, together with the corresponding participation functions given in Fig. 2. The estimated average power limits and energy capacities of TCLs using the annual hourly average temperature profile in Sacramento are depicted in Fig. 3. In Table III, the peak values for the power and energy capacities are shown using the annual hourly average temperature profiles for 5 different cities: Sacramento (SA), San Francisco (SF), San Jose (SJ), Los Angeles (LA) and San Diego (SD). The final

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TABLE II: Saturation rates of air conditioner, heat pump, refrigerator, and water heater in California.

	AC	Heat Pump	Refrigerator	Water Heater
Percentage	46.5%	1%	122.3%	6.5%
Numbers	6.37×10^6	0.14×10^6	16.75×10^6	0.89×10^6

TABLE III: Potential of TCLs using different temperature profiles in Sacramento (SA), San Francisco (SF), San Jose (SJ), Los Angeles (LA) and San Diego (SD).

		SA	SF	SJ	LA	SD
AC (peak)	Reg up (GW)	5.18	0.15	1.21	0.44	0.36
	Reg down (GW)	8.68	0.53	3 .94	1.93	1.78
	Capacity (GWh)	0.62	0.03	0.22	0.10	0.09
Heat Pump (Peak)	Reg up (GW)	0.11	0.01	0.09	0.03	0.02
	Reg down (GW)	0.22	0.20	0.20	0.09	0.08
	Capacity (GWh)	.011	.009	.010	.004	.003
Water Heater	Reg Up (GW)	0.21	0.21	0.21	0.21	0.21
	Reg down (GW)	3.79	3.79	3.79	3.79	3.79
	Capacity (GWh)	0.53	0.53	0.53	0.53	0.53
Refrigerator	Reg up (GW)	1.63	1.63	1.63	1.63	1.63
	Reg down (GW)	3.38	3.38	3.38	3.38	3.38
	Capacity (GWh)	3.78	3.78	3.78	3.78	3.78
Total (minimum)	Reg up (GW)	1.93	1.87	1.89	1.85	1.85
	Reg down (GW)	7.42	7.27	7.34	7.30	7.34
	Capacity (GWh)	4.33	4.31	4.31	4.30	4.30

row shows the minimum values of the total power limits and energy capacity over the 24 hour period. We observe that even using the most conservative temperature profile (LA), the power limits are more than double the current maximum regulation procurement (600 MW). Furthermore, it is larger than the predicted regulation procurement (1.3 GW) if California achieved its 33% of renewable penetration by 2020. Additionally, assuming the regulation signal in CAISO has similar pattern as that in the Pennsylvania-New Jersey-Maryland (PJM) Interconnection, we use the regulation signal of PJM to estimate the maximum energy requirements using Definition 1. The estimated maximum energy requirements for regulation with 600 MW and 1.3 GW procurements are respectively 150 MW-h and 325 MW-h, which are much smaller than the energy capacity from TCLs shown in Table III. Altogether, these results show that the potential of TCLs in California is more than enough for provision of regulation service for now and in the near future.

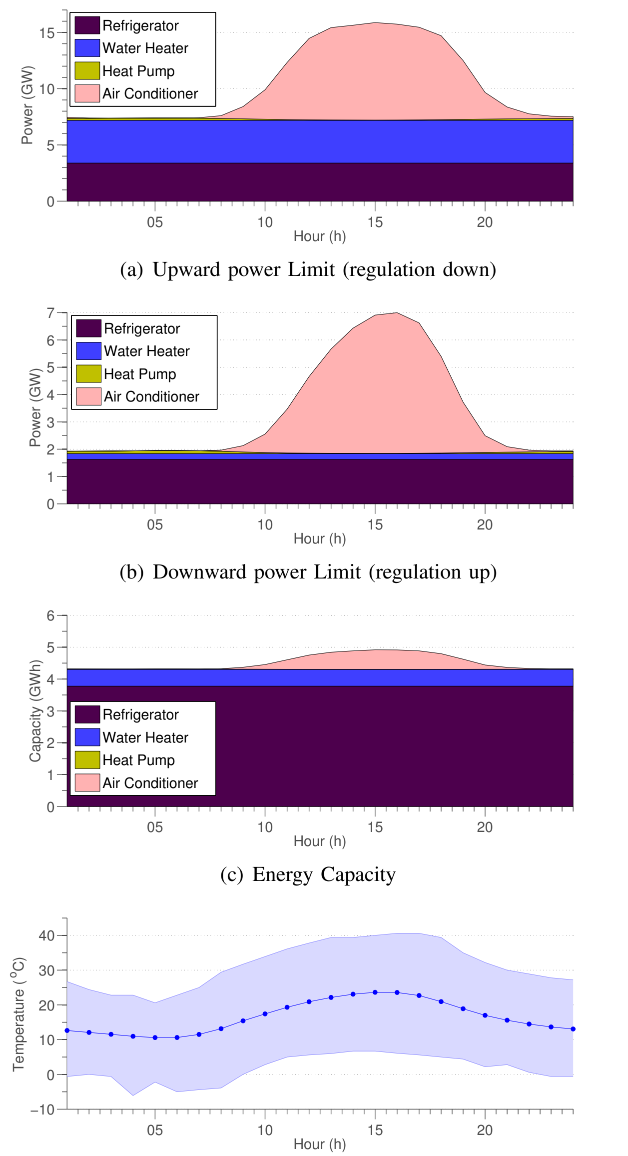
III. Qualification, Cost, Revenue, and Participation Incentives

We estimate the capital cost and potential revenue of using TCLs to provide regulation service, and discuss incentive methods to encourage customer participation. Before we proceed further, we present the regulation qualification requirements, which have a substantial impact on the capital cost and revenue of TCLs to provide regulation.

A. *Qualification for Regulation Service*

To qualify for regulation service, a provider must meet the following requirements.

a) Telemetry and metering: Telemetry refers to real-time measurement data that is sent to the ISO for operational visibility, and metering refers to revenue metering sent to the ISO for settlement purpose. In CAISO, the sampling rate of telemetry is 4 seconds. The 1) maximum and minimum operating limits (MW), 2) instantaneous resource output (MW), 3) charge and discharge ramp rates (MW/min), 4) the state of charge of the NGR, 5) connectivity status (ON/OFF), and 6) AGC Control Status (Remote/Local), are sent to the ISO's energy management system every 4 seconds. More detailed requirements on telemetry data point for non-generator resources can be found in [21]. The metering accuracy is required to be 0.25%. Moreover, the measurement data should be directly from the resource instead of an aggregation. These requirements impose a non-trivial cost on power measurement and communication on each TCL. We comment that a change on the sampling frequency and aggregation rule and enabling low cost communication such as using internet is necessary to lower the capital cost of



(a) Upward power Limit (regulation down)

(b) Downward power Limit (regulation up)

(c) Energy Capacity

(d) Outside Temperature

Fig. 3: Hourly average upward (a), downward (b) power limits, and energy capacity (c) in California. The temperature profile used is that of Sacremento for the year of 2012, where the hourly minimum, average, and maximum temperature is depicted in (d).

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TCLs to provide regulation.

b) Minimum available power: CAISO requires the regulation resource has at least 0.5 MW power capacity to be able to participate in the frequency regulation market. This corresponds to an aggregate of about 200 air conditioners, heat pumps, and water heaters, or a population of 3000 refrigerators. However, aggregation of distributed energy resources is not allowed in CAISO's ancillary service market. It is suggested that this rule on aggregation also needs to be changed to encourage more participation of distributed energy resources into the ancillary service market.

c) Minimum continuous energy delivery time: In CAISO, the minimum continuous energy delivery time in the day-ahead and real-time regulation market are respectively 60 and 30 minutes. However, for NGR with REM, the resources are allowed to bid their 15-min energy capacities into the regulation market and adjust their states of charge to the desired values in the real-time energy market. This scheme takes advantage of the fast ramping potential of regulation resources such as TCLs and allow those resources with limited energy capacities to be able to bid larger capacity and achieve more revenue in the regulation market than the case without REM.

d) Minimum performance threshold: CAISO requires a 50% of tracking accuracy for both regulation up and regulation down measured over a calendar month. Re-certification is required within 90 days if the resource fails the minimum performance requirement. As demonstrated in Section IV-C, this requirement can be easily met by a collection of TCLs.

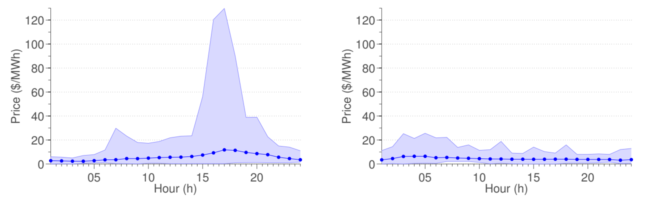
e) Ramping rate requirement: The participating resources are required to ramp to their maximum capacity in 10 minutes in CAISO. This requirement can also be easily satisfied by an aggregation of TCLs.

f) Others: To participate as NGR resource, the CAISO will require resources to sign participating agreements, conform to resource data template, use existing business processes. In addition, all market participants must be represented by a Scheduling Coordinator that is financially responsible for all interactions with the market and undergoes special certification. Moreover, CAISO requires that the scheduling coordinator must be a loads serving entity.

B. Capital Cost of TCLs for Regulation Provision

The major capital cost enabling TCLs to providing regulation service consists of 1) smart meters for real-time power measurement of TCLs, 2) control device that overrides a TCL's local control action, and 3) communication and control infrastructure that supports metering and telemetry, and can be integrated with CAISO's energy management system.

Measuring the power consumption of each TCL necessitates a nontrivial capital cost. Power meters are expensive. *In our view, this is unavoidable.* Other schemes have been proposed where the aggregate power is *estimated* using population models, or disaggregated from substation measurements [11], [12], [22]. These schemes face the challenges in meeting the stringent auditing, telemetry and metering requirements necessary to participate in the regulation ancillary service market.



(a) Upward regulation (b) Downward regulation

Fig. 4: Hourly minimum, average, and maximum market clearing price for upward and downward regulation in California. The plots are based on historic data in 2012.

The cost of a smart meter that is used in PG&E is about $200 [23], [24]. The smart meter can be combined with validated HAN (Home and Business Area Network) device to obtain near real-time residential power measurement [24]. For our purpose, we need real-time power measurement of each TCL unit every 4 seconds, in order to satisfy CAISO's telemetry requirement. A smart plug that measures the real-time power consumption of an appliance is about $50 [25]. Additionally, the price for a smart thermostat that could override a unit's local control actions is about $100 [26]. Regarding communication and control devices, various commercial Remote Telemetry Units (RTUs) that support internet, cellular and other types of communications are available [27]–[29]. It is to our opinion that the combined capital cost enabling TCLs to provide regulation service is less than $250 per unit. Assuming the lifetime of each unit is 20 years, the average capital cost for each unit per year is $12.50.

For some utility companies in California, the basic infrastructure that enables TCLs to provide regulation service is already in place. For example, PG&E (Pacific Gas and Electric Company) has installed over 9 millions smart meters throughout its service area, and plans to cover all customers by the end of 2013 [24]. Additionally, the SmartAC™ program of PG&E gathered 147, 600 residential customers for peak load shaving and managing emergency situations by remotely controlling their AC units [30]. Such programs can be upgraded to provide additional ancillary service such as regulation with low additional capital cost.

C. Potential Revenue of TCLs

In the ancillary service market, frequency regulation is the most expensive service. The market clearing prices of other ancillary services such as contingency reserves (spinning or non-spinning) and supplemental reserve are much cheaper, compared with frequency regulation [1].

The system operator in CAISO clears the regulation service market as follows. First, participating resources submit their offers. The system operator uses these offers together with the energy offers to determine the lowest cost alternative for these services by conducting an co-optimization. Within the co-optimization, an ISO dispatch profile is created along with Locational Marginal Pricings (LMPs). Using the dispatch profiles and foretasted LMPs, an opportunity cost is estimated for each resource that is eligible to provide regulation. The Market Clearing Price (MCP) for that oper-

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TABLE IV: Revenue of TCLs for providing regulation service in different regions (The unit is \$ per unit per year). UP and DN respectively represent regulation up and regulation down.

	AC		Heat Pump		Refrigerator		Water Heater	
	UP	DN	UP	DN	UP	DN	UP	DN
SA	27.5	16.4	16.7	36.0	4.8	7.8	11.8	164.0
SF	0.9	0.7	10.4	35.5	4.8	7.8	11.8	164.0
SJ	5.1	4.9	11.5	32.2	4.8	7.8	11.8	164.0
LA	0.9	3.6	2.6	12.5	4.8	7.8	11.8	164.0
SD	1.7	4.1	2.2	10.3	4.8	7.8	11.8	164.0

ating hour is the sum of the availability bid and opportunity cost associated with the most expensive resource awarded. All awarded resources in a reserve zone are paid the same MCP, regardless of their own bid and opportunity cost. Fig. 4 depicts the hourly minimum, average, and maximum market clearing price for upward and downward regulation in California for the year of 2012 [18]. In particular, the average MCP for regulation up and regulation down in 2012 were respectively \$5.65 and \$4.39 per MW-h.

To estimate the annual revenue for regulation service provision, we assume for air conditioners and heat pumps, the participation functions are as those depicted in Fig. 2. In addition, we assume water heaters and refrigerators are always participating. The estimated revenue for each type of TCLs is summarized in Table IV. We observe that water heaters have the largest potential revenue, while refrigerators have smaller potential revenue. This is because refrigerators have lower rated power (see Table I). In addition, the potential revenue of air conditioners and heat pumps are highly sensitive to weather. The reason why ACs in San Francisco (SF), San Jose (SJ), Los Angelos (LA), and San Diego (SD) have small revenue potential is because the weather in these regions is moderately cool, which means there is low participation of AC throughout the year. However, in the city of Sacramento (SA) where the summer is hot, ACs present a large revenue potential. Moreover, if a unit has combined AC and heat pump, and it is located in a region with hot summer and cold winter (e.g. SA), the potential revenue will be substantial. Compared to the results reported in [15], our revenue potential of TCLs is slightly smaller. This is mainly because no participation functions are considered for AC and heat pump units in [15], and the market clearing price for regulation used in [15] is slightly higher than the historic data in California.

D. Participation Incentive

Existing demand response incentive methods offer limited financial value. For example, the SmartAC™ program of Pacific Gas and Electric Company (PG&E) offers a one-time signup bonus of \$50 to the customers [30]. The OnCall® program of Florida Power and Light Company (FPL) provides \$5/month incentive to participating customers for only 7 months in a year [31]. As an aggregator, how to incentivize the customers to encourage participation with small reward is a challenge.

As we showed in the previous section, although aggregation of a collection of TCLs presents a large potential for regulation provision, the annual revenue per unit is not very

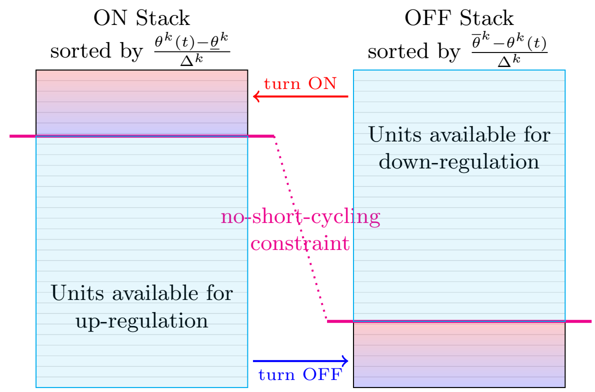

Fig. 5: Priority Stacks with no-short-cycling constaint. The lower and upper temperature bounds are given by $\underline{\theta}^k = \theta_r^k - \Delta^k$ and $\overline{\theta}^k = \theta_r^k + \Delta^k$.

attractive if the total revenue is split evenly. Therefore, it is essential to study innovative methods to incentivize residential customers to encourage participation. Studies show that customers prefer lower probability large award over a guaranteed small award [32]. A lottery-based incentive method has been shown to be very successful in reducing traffic congestion [33]. It is to our view that incentivizing methods such as lottery based incentive present a great potential to increase the participation for demand response.

IV. Implementation and Practical Considerations

A. Priority-stack-based Control Framework

In this section, we extend the priority-stack-based control framework proposed in [7], [8] to incorporate the aforementioned no-short-cycling constraint. In our companion paper [10], we also derive an explicit characterization of the constraints on upward and downward movement of feasible regulation signals under the no-short-cycling requirement. We adopt a centralized control architecture. This choice is dictated by the stringent power quality, auditing and telemetry requirements necessary to participate in regulation service market. At each sample time, the aggregator compares the regulation signal $r(t)$ with the aggregate power deviation $\delta(t) = P_{\text{agg}}(t) - n(t)$, where $P_{\text{agg}}(t)$ is the instantaneous power drawn by the TCLs, and $n(t)$ is their aggregate baseline power.

If $r(t) < \delta(t)$, the population of TCLs needs to "discharge" power to the grid, which means some of the ON units will be turned OFF. Conversely, if $r(t) > \delta(t)$, then the population of TCLs must consume more power. This requires turning ON some of the OFF units. To track a regulation signal $r(t)$, the system operator needs to determine appropriate switching actions for each TCL, so that the power deviation of TCLs, $\delta(t)$, follows the regulation signal $r(t)$.

In practice, it is more favorable to turn ON (or OFF) the units which are going to be turned ON (or OFF) by their local hysteretic control law. To this end, we propose a priority-stack-based control method. Imminence can be measured naturally by *temperature distance* to the switching boundary. For example, for the OFF units, priority can be measured by

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$\pi^k(t) = (\overline{\theta}^k - \theta^k(t))/\Delta^k$, where $\overline{\theta}^k = \theta_r^k + \Delta^k$, and smaller $\pi^k(t)$ implies higher priority. The temperature distance is normalized to account for heterogeneity. The unit with the highest priority will be turned ON (or OFF) first, and then units with lower priorities will be considered in sequence until the desired regulation is achieved. This priority-stack-based control strategy minimizes the ON/OFF switching action for each unit, which reduces wear and tear of the mechanical equipment. Moreover, to prevent short cycling, we impose no-short-cycling constraints to the priority stacks. Once a unit is turned ON or OFF, it must remain in that state for at least a certain amount of time (that is specified by the manufacture) before it is switched again. Priority stacks are illustrated in Fig. 5. We index the units available for manipulation in the ON stack from *bottom to top* by $\{1, 2, \cdots, N_1\}$, and the units in the OFF available unit from *top to bottom* by $\{1, 2, \cdots, N_0\}$.

The priority-stack-based control algorithm is summarized in Algorithm 1. Units are turned ON or OFF when their real time power consumption $P^k(t)$ (instead of rated power P_m^k) matches the difference between the regulation signal $r(t)$ and aggregate power deviation $\delta(t)$. We stress that this is a *feedback* control strategy which offers robustness against modeling errors in the dynamics of TCLs and latency in communications. Moreover, this feedback control strategy is dictated by CAISO's stringent telemetry requirement.

Algorithm 1 Priority-stack-based control algorithm

loop
  receive $\pi^k(t)$, $P^k(t)$, and availability of unit k;
  construct priority stacks;
  read $r(t)$;
  compute $\delta(t) = P_{\text{agg}}(t) - n(t)$;
  if $\delta(t) < r(t)$ **then**
    find $j^* = \min\{j \mid j \le N_1, \sum_{i=1}^{j} P^i(t) \ge r(t) - \delta(t)\}$;
    turn ON units indexed by $\{1, 2, \cdots, j^*\}$.
  else if $\delta(t) > r(t)$ **then**
    find $j^* = \min\{j \mid j \le N_0, \sum_{i=1}^{j} P^i(t) \ge \delta(t) - r(t)\}$;
    turn OFF units indexed by $\{1, 2, \cdots, j^*\}$.
  end if
end loop

To implement the proposed direct load control strategy, we require (at a minimum) measurements of real-time power $P^k(t)$ and temperature $\theta^k(t)$ at a sampling rate of 0.25 Hz for each TCL. While $\theta^k(t)$ and the set-point θ_r^k are directly available from the thermostat, measuring the power $P^k(t)$ requires additional hardware infrastructure. For each TCL, run-time system identification algorithms can be used to estimate the operating state $q^k(t)$, availability for manipulation, the ambient temperature θ_a^k, and model parameters a^k, b^k, Δ^k from the temperature time series $\theta^k(s), s \le t$. Using this information, a local embedded controller computes $\pi^k(t)$ for each TCL. The priority criterion $\pi^k(t)$, power consumption $P^k(t)$, and availability of each TCL are transmitted to the aggregator. The aggregator forms the priority stack from the collated data and computes the control action. This is broadcasted to the TCLs where the local controller implements the action. This scheme has modest computation and communication overhead.

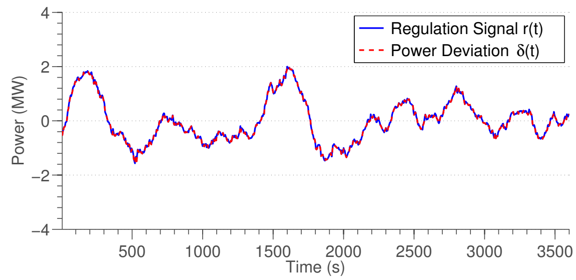

Fig. 6: Tracking performance of TCLs subject to modeling errors of transient power and external disturbances. The regulation signal is obtained from PJM [34].

B. Robustness of Priority-Stack-based Control Strategy to Modeling Errors

We now examine the robustness of our priority-stack-based control strategy to modeling errors in the thermal dynamics of each TCL by numerical simulations. In particular, we consider the case that the power consumption when a unit is ON is a not a constant. We assume there is a large inrush current immediately when a unit is turned ON, and the power consumption gradually converges to a constant value as time elapses. Additionally, we add a Gaussian noise w to the thermal dynamics (1) of each unit to account for the external disturbances from occupancy, internal appliances and so on. In the simulation, we discretize the thermal dynamics with a discretization step of 4 seconds. Moreover, we let the mean of the Gaussian noise to be zero, and its standard deviation to be $0.005\ ^\circ C/s^{0.5}$ [11]. Fig. 6 shows the tracking performance of TCLs with modeling errors in their thermal dynamics. We observe that good tracking is achieved regardless of the modeling errors. This showcases the robustness of our feedback control strategy.

C. Effect of Latency on Tracking Performance

We next examine the effect of latency on the tracking accuracy and ramping rate of TCLs. Latency in the control loop will determine the quality of the offered regulation service. We study the effect of communication latency on the tracking accuracy. The accuracy performance in CAISO is measured by the ratio of the sum of the AGC setpoint for each 4-second regulation interval less the sum of the tracking error for each regulation interval to the sum of the AGC setpoint. The accuracy percentage is calculated every 15 minutes. Fig. 7 depicts the average tracking accuracy as a function of the communication delay for tracking a 24-hour long regulation signal of PJM. We observe that even with up to 20-second communication delay, the tracking accuracy of TCLs satisfies the CAISO accuracy performance threshold (50%). Moreover, additional simulations (not reported) show that TCLs are able to ramp to their power limits in 10 minutes with up to 20 seconds communication latency, which satisfies the ramping rate requirement of CAISO.

V. Conclusions and Future Work

We presented a practical treatment of enabling TCLs to provide frequency regulation service to the grid. In particular,

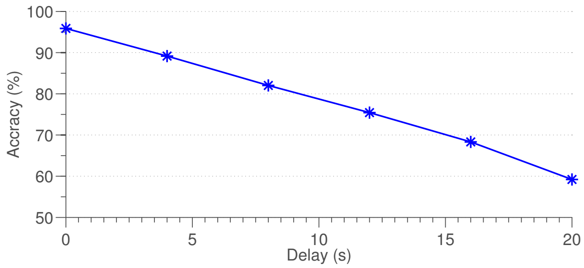

Fig. 7: Tracking accuracy vs. communication delay.

we estimated the potential, cost, and revenue of TCLs, discussed the qualification requirements, recommended policy changes and incentive methods, and presented a practical control framework for TCLs to provide regulation service. Our results showed that the potential of TCLs in California was more than enough for provision of regulation service for now and in the near future.

There are several important future research issues that must be addressed. These include: (a) an exploration of suitable and low-cost hardware, firmware and communication infrastructure to implement direct-load control, (b) conducting pilot programs to showcase the feasibility of the proposed method, and (c) developing fair schemes to incentivize TCL owners for participating in regulation services.

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REFERENCES

[1] B. Kirby, "Ancillary services: Technical and commercial insights," Tech. Rep., July 2007.
[2] Texas Energy Storage Alliance, "Storage participation in ERCOT," January 2010. [Online]. Available: http://www.ercot.com/
[3] K. Vu, R. Masiello, and R. Fioravanti, "Benefits of fast-response storage devices for system regulation in ISO markets," in *IEEE Power Energy Society General Meeting, 2009*, july 2009, pp. 1 –8.
[4] Y. V. Makarov, L. S., J. Ma, and T. B. Nguyen, "Assessing the value of regulation resources based on their time response characteristics," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-17632, June 2008.
[5] CAISO, "Pay for performance regulation." [Online]. Available: http://www.caiso.com/informed/Pages/StakeholderProcesses/PayforPerformanceRegulation.aspx
[6] ——, "Storage technologies provide flexible resources in the market," 2012. [Online]. Available: http://www.caiso.com/participate/Pages/Storage/Default.aspx
[7] H. Hao, B. M. Sanandaji, K. Poolla, and T. L. Vincent, "A generalized battery model of a collection of thermostatically controlled loads for providing ancillary service," in *the 51th Annual Allerton Conference on Communication, Control and Computing, to appear*, October 2013. [Online]. Available: http://plaza.ufl.edu/hehao/publication.html
[8] ——, "Aggregate flexibility of thermostatically controlled loads," *IEEE Transactions on Power Systems, under review*, 2013. [Online]. Available: http://plaza.ufl.edu/hehao/publication.html
[9] U. Helman, "Resource and transmission planning to achieve a 33% RPS in California–ISO modeling tools and planning framework," in *FERC Technical Conference on Planning Models and Software*, 2010.
[10] B. M. Sanandaji, H. Hao, K. Poolla, and T. L. Vincent, "Improved battery models of an aggregation of thermostatically controlled loads for frequency regulation," in *American Control Conference, submitted*, September 2013. [Online]. Available: http://plaza.ufl.edu/hehao/publication.html
[11] D. S. Callaway, "Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy," *Energy Conversion and Management*, vol. 50, no. 5, pp. 1389–1400, 2009.
[12] S. Koch, J. Mathieu, and D. Callaway, "Modeling and control of aggregated heterogeneous thermostatically controlled loads for ancillary services," in *Proc. PSCC*, 2011, pp. 1–7.
[13] J. L. Mathieu, S. Koch, and D. S. Callaway, "State estimation and control of electric loads to manage real-time energy imbalance," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 430 –440, Feburary 2013.
[14] S. Kundu, N. Sinitsyn, S. Backhaus, and I. Hiskens, "Modeling and control of thermostatically controlled loads," in *the 17-th Power Systems Computation Conference*, 2011.
[15] J. Mathieu, M. Dyson, and D. Callaway, "Using residential electric loads for fast demand response: The potential resource and revenues, the costs, and policy recommendations," in *2012 ACEEE Summer Study on Energy Efficiency in Buildings*, 2012.
[16] J. MacDonald, P. Cappers, D. Callaway, and S. Kiliccote, "Demand response providing ancillary services," in *Grid-Interop 2012*, Irving, Texas, December 2012.
[17] CAISO, "AS procurement - regulation," Tech. Rep., December 2009. [Online]. Available: http://www.CAISO.com/
[18] "California ISO open access same-time information system (OASIS)." [Online]. Available: http://oasis.caiso.com
[19] United States Census Bureau, U.S. Department of Commerce, "California quickfacts." [Online]. Available: http://quickfacts.census.gov/qfd/states/06000.html
[20] C. Palmgren, N. Stevens, M. Goldberg, R. Barnes, and K. Rothkin, "2009 california residential appliance saturation study, cec-200-2010-004-es," Tech. Rep., Octobor 2010. [Online]. Available: www.energy.ca.gov
[21] CAISO, "Direct Telemetry and Metering Requirement for Non-Generator Resources." [Online]. Available: http://www.caiso.com/Documents/DirectTelemetryRequirement-Non-GeneratorResourcesV1-0.pdf
[22] J. Mathieu and D. Callaway, "State estimation and control of heterogeneous thermostatically controlled loads for load following," in *the 45th Hawaii International Conference on System Sciences*. IEEE, 2012, pp. 2002–2011.
[23] C. King, "How Much Do Smart Meters Cost?" [Online]. Available: http://www.emeter.com/smart-grid-watch/2010/how-much-do-smart-meters-cost/
[24] Pacific Gas and Electric Company, "Smart Meter." [Online]. Available: http://www.pge.com/en/myhome/customerservice/smartmeter/index.page
[25] PostScapes, "Smart Outlet Handbook." [Online]. Available: http://postscapes.com/smart-outlets
[26] Honeywell, "Wi-Fi Programmable Thermostats." [Online]. Available: http://wifithermostat.com/Products/
[27] S. Kiliccote, "Open automated demand response communications in demand response for wholesale ancillary services," in *Grid-Interop Forum 2009*, Denver, Colorado, November 2009.
[28] A. N. Brooks, "Vehicle-to-grid demonstration project: Grid regulation ancillary service with a battery electric vehicle," Tech. Rep., 2002.
[29] D. Todd, M. Caufield, B. Helms, A. Generating, I. Starke, B. Kirby, and J. Kueck, "Providing reliability services through demand response: A preliminary evaluation of the demand response capabilities of alcoa inc," *ORNL/TM*, vol. 233, 2008.
[30] Pacific Gas and Electric Company, "Smart AC program." [Online]. Available: http://www.pge.com/en/myhome/saveenergymoney/energysavingprograms/smartac/index.page
[31] Florida Power and Light Company, "On call savings program." [Online]. Available: http://www.fpl.com/residential/energy_saving/programs/oncall.shtml
[32] D. Kahneman and A. Tversky, "Prospect theory: An analysis of decision under risk," *Econometrica: Journal of the Econometric Society*, pp. 263–291, 1979.
[33] D. Merugu, B. S. Prabhakar, and N. Rama, "An incentive mechanism for decongesting the roads: A pilot program in Bangalore," in *Proc. of ACM NetEcon Workshop*. Citeseer, 2009.
[34] "PJM regulation data." [Online]. Available: http://www.pjm.com/markets-and-operations/ancillary-services/mkt-based-regulation/fast-response-regulation-signal.aspx

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