Responsive Thermal Storage
Cleantech to Market Final Report
University of California, Berkeley

David Lewis, Andrew McKibben, Jay Taneja
5/16/2011
## Contents

- **Introduction** ......................................................................................................................................................................................................................................................................................................................... 4
- **Technology Overview** .................................................................................................................................................................................................................................................................................................................. 5
- **Competitive Advantages** ......................................................................................................................................................................................................................................................................................................... 8
- **Regulatory and Market Drivers** ........................................................................................................................................................................................................................................................................................................... 9
- **Potential Applications** ................................................................................................................................................................................................................................................................................................................... 15
  - **Peak Cost Avoidance** .................................................................................................................................................................................................................................................................................................................. 15
  - **Ancillary Services** ............................................................................................................................................................................................................................................................................................................. 20
    - **Capacity Curtailment** ........................................................................................................................................................................................................................................................................................................... 22
    - **Day Ahead Demand Response** ................................................................................................................................................................................................................................................................................................... 22
    - **Load Following** ................................................................................................................................................................................................................................................................................................................. 23
    - **Non-Spinning Reserve** ........................................................................................................................................................................................................................................................................................................ 24
    - **Spinning Reserve** ............................................................................................................................................................................................................................................................................................................... 25
    - **Frequency Regulation** ......................................................................................................................................................................................................................................................................................................... 25
- **Deployment Considerations** ...................................................................................................................................................................................................................................................................................................... 28
  - **Retrofit versus Replace** ........................................................................................................................................................................................................................................................................................................ 28
  - **Maximizing Adoption** ...................................................................................................................................................................................................................................................................................................... 30
  - **IP Strategy** ......................................................................................................................................................................................................................................................................................................................... 34
  - **Application Rollout** ............................................................................................................................................................................................................................................................................................................ 36
- **Recommended Next Steps** ....................................................................................................................................................................................................................................................................................................... 37
- **Appendix** .............................................................................................................................................................................................................................................................................................................................. 39
  - **Adoption Model Assumptions** ........................................................................................................................................................................................................................................................................................ 40
  - **Time of Use Model Assumptions** ........................................................................................................................................................................................................................................................................................ 41
  - **Interviews** ............................................................................................................................................................................................................................................................................................................................. 43
Figures
Figure 1: Estimation of Temperature and Power for Typical Residential Refrigerator Unit .................. 6
Figure 2: Estimated Temperature and Power for Augmented Residential Refrigerator Unit .............. 7
Figure 3: RPS Policies in May 2011, DSIRE .................................................................................. 10
Figure 4: Regulation Effectiveness of an "Ideal Resource", Beacon Power ........................................ 11
Figure 5: Advanced Meter Penetration by Sector, EIA ..................................................................... 14
Figure 6: Potential Cost Savings for a Residential Customer .............................................................. 17
Figure 7: Potential Cost Savings for a Commercial Customer ......................................................... 20
Figure 8: Load Following and Regulation ......................................................................................... 24
Figure 9: Economic Potential (GWh) by End Use and Segment, PG&E ........................................... 32
Figure 10: Estimated Market Penetration in CA – Commercial Retrofits and Residential Replacements. 34

Tables
Table 1: E-6 TOU Rate Schedule as of May 2011, PG&E ................................................................. 16
Table 2: E-19 TOU Rate Schedule as of May 2011, PG&E ................................................................. 18
Table 3: Ancillary Services Overview ............................................................................................... 21
Table 4: Frequency Regulation Capacity Requirements and Estimated Market Size, CAISO 2009 .... 26
Table 5: Frequency Regulation (Up/Down) Requirements, CAISO 2009 ........................................ 27
Table 6: Residential and Commercial Refrigeration Market Characteristics .................................. 28
Introduction

Faced with an evolving electrical grid, energy storage has always been an imagined yet financially infeasible technique for dealing with supply and demand variability. Our technology aims to bridge this divide by providing responsive thermal energy storage inexpensively by augmenting compressor-based freezer units that are distributed throughout the electricity grid. By inserting a reservoir of phase change material coupled with an embedded communicating controller, we can create an “ice battery” that can be used to preferentially absorb and release thermal energy, enabling load shifting by controlling when grid electricity is consumed.

In this report, we present a market assessment for this responsive thermal energy storage technology. Key market and regulatory forces are driving the adoption of energy storage technologies, including widespread renewable portfolio standards (RPS) targets throughout the US; FERC rulemaking increasing the value of energy storage; California legislation mandating the availability of storage resources on the grid; utilities encouraging adoption of time-of-use electricity pricing structures for consumers; and the accelerated deployment of advanced metering technology throughout the grid.

The confluence of these trends coupled with the capabilities of this technology presents opportunities in two application areas: peak electricity cost reduction for residential and commercial consumers and aggregation of storage resources to provide grid ancillary services to electrical utilities. Our analysis of residential and commercial refrigerator operation using time-of-use rate schedules from a utility indicates the ability to save approximately 17% of refrigerator electricity costs with no need for behavior or service changes, and minimal requirements for grid communication. We have also identified that by aggregating resources, this technology coupled with equipment for two-way communication with the utility can provide valuable ancillary service resources to electrical utilities. Among these services, this technology is best suited for the provision of frequency regulation, a large market with growth primarily driven by the realization of RPS goals.

Concerns about violating refrigerator warranties and more restricted volume considerations dictate that the best path for deployment in residential refrigerators is through cooperating with appliance
manufacturers to influence design of future models. For commercial freezer units, a high degree of unit customization, lesser volume constraints, and a more fragmented manufacturing base indicate that a retrofit model is more appropriate. The ability to aggregate capacity more quickly via commercial retrofits is a more suitable near to medium-term goal. The long design cycle for new residential refrigerator models (8-10 years) indicates that it could be a potential long-term goal.

Last, the strategy for deployment of the technology has important ramifications for licensing and patenting. We recommend that the technology inventors decide how involved they desire to be in proliferating the technology, a choice that can guide the selection of IP strategy.

**Technology Overview**

Our technology augments refrigeration units by placing a reservoir of phase-change material into the unit’s freezer that can be controlled to absorb and release thermal energy preferentially. This technology was developed in the research lab of Professor David Culler in the Computer Science department at UC Berkeley.

Many refrigerators operate using an electricity-consuming compressor unit to remove warm air from the inside of the refrigerator and freezer compartments. These compressors typically have one of two modes of operation: bang-bang control, where the compressor runs at a single speed and is either on or off, or variable drive control, where the compressor modulates its operation continuously within its acceptable range. Though this technology was developed using a refrigerator that employs bang-bang control, it may be applicable in both scenarios. For the remainder of the report, we will refer to bang-bang control refrigerators.

The idea for this technology arises from the observation that refrigerators have some amount of energy storage inherent in their operation. A refrigerator typically operates in a periodic fashion, where each period is composed of both a shorter “forced” cooling phase in which the compressor is operating and a longer “natural” warming phase in which the compressor is not operating. In this warming phase, warm air is entering the device via the conduction process at a rate governed by the difference in temperature inside and outside the device as well as the thermal mass of the contents of the refrigerator and freezer. As the difference in these two temperatures decreases, the warming process slows. It is important to
note that as the thermal mass increases, the overall rate of both the warming and cooling process slows – this is a form of thermal energy storage. By increasing this thermal mass, the amount of energy storage the refrigerator can contain also increases. Figure 1 shows the temperature and power draw over the course of a day of an empirically-driven model of a refrigerator created for this report.

Figure 1: Estimation of Temperature and Power for Typical Residential Refrigerator Unit

The material chosen to augment the thermal mass of the contents of the refrigerator and freezer should have a high heat capacity. Our scientists have selected an aqueous salt-based solution that has a number of advantages. First, water has a relatively high specific heat, allowing a large amount of thermal energy to be stored by changing its temperature. The key observation, though, is that a much larger amount of energy can be stored by managing the phase-change process of the material, via the heat of formation of the freeze/thaw process, enabling the “ice battery” to store a significant amount of thermal energy. This thermal energy can then be distributed throughout the refrigeration unit using a small fan and pump. This storage can be used for the preferential consumption of energy - by operating the compressor at times when electricity is in surplus, compressor operations during times of electricity shortage can be avoided.

In order to manage this thermal energy storage resource, some amount of computation and communication is needed. Our scientists have developed a method to manage this storage using a small embedded microcontroller with sensors measuring liquid and air temperatures inside the freezer, as well as a load switch on the compressor’s electrical connection. By monitoring these environmental

---

1 Laboratory estimates
parameters, the microcontroller can easily switch between grid electricity to power the compressor or locally-stored thermal energy from the ice battery. Additionally, this embedded controller, in its prototype form, has an IEEE 802.15.4-compliant radio coupled with an IPv6 compatible network stack for communication using the Internet. Though this communication is not needed in all applications (i.e., peak cost avoidance does not require data communication with the electrical grid), its inclusion enables this technology to be used for utility-scale applications, such as the provision of grid ancillary services. Furthermore, the selection of the communications technology can be made to fit the application; the controller can be made to communicate with advanced metering infrastructure (AMI) or other networking equipment.

The result of combining phase-change material with an embedded communicating controller is a thermal energy store that is capable of preferentially avoiding refrigerator compressor operation while maintaining the temperature within the refrigerator and freezer. An example of this type of operation using our refrigerator model is included in Figure 2; in this scenario, the refrigerator unit seeks to avoid consuming electricity between the hours of 12 PM and 6 PM to avoid higher “peak” electricity costs. At the beginning of that interval, the thermal store is actuated, allowing energy to be released to maintain the cool temperature within the unit. When the “peak” period is over, the refrigerator can return to its normal periodic cycle using its compressor.

Figure 2: Estimated Temperature and Power for Augmented Residential Refrigerator Unit
Competitive Advantages

This technology has a number of advantages versus traditional forms of energy storage.

**One-way energy conversion:** Since this thermal storage technology is applied specifically to a system that can consume thermal energy, electrical energy is only converted once. This is unlike thermochemical, kinetic, and hydroelectric storage systems, which convert electrical energy to be stored in another form, only to be converted back to electrical energy, which produces inefficiencies in both directions.

**Distributed storage:** With the host refrigeration/freezer devices spread throughout the electricity grid, this technology could be deployed widely, allowing the resource to be deployed to the locations within the grid that are the most constrained, limiting the burden on the electricity transmission and distribution systems. Other forms of energy storage such as pumped hydroelectricity, compressed air, and flow batteries have significant site related constraints/concerns, limiting the set of feasible locations, and necessitating fewer, larger energy storage repositories.

**Scalable:** Thermal storage units spread throughout the gird with communication capabilities aggregate easily. Because of their ability to communicate with and be controlled by the resource operator, there is limited effort and impact associated with the addition (or removal) of units. Thus, as the network of storage devices grow, its fundamental operation remains the same.

**Inexpensive:** By leveraging compressors that are already deployed or would otherwise be deployed and augmenting them with cheap, earth-abundant materials, energy storage could be added to the grid to buffer supply and demand variability at a fraction of the cost of traditional forms of energy storage. Though the cost of managing this resource increases the overall deployment cost, this may be partially offset by leveraging existing and future advanced metering infrastructure to provide communication capabilities.

**Long discharge duration:** With 1 kWh of storage in a typical residential refrigerator, generation can be avoided for up to 20 hours. This duration is beyond other forms of energy storage, allowing for extreme flexibility in charge and discharge patterns, even without a fully “charged” ice battery. Additionally, this
ability provides a competitive advantage over traditional forms of non-generation resources, such as demand response reliant on interruptible loads, which have much shorter durations.

**Bidirectional:** Energy storage in general presents a valuable service to the electricity grid that demand response cannot – the capacity to both release as well as absorb energy. Though many services seek to increase available energy either by adding generation or reducing demand, other applications would benefit from the ability to preferentially absorb energy, such as frequency regulation up and exploitation of negative locational marginal pricing.

**No behavior or service change:** In demand response scenarios, service levels are often diminished. Our technology responds differently because the refrigeration unit experiences no change in service level – the unit’s thermostat remains the ultimate arbiter of temperature, maintaining conditions within the allowable maximum and minimum of the device. Thus, the end-user is able to realize the benefits of the thermal storage without changing how and when they use their refrigeration unit.

**Regulatory and Market Drivers**

There are a number of regulatory and market trends which make energy storage increasingly timely and valuable. The progression of these trends will be instrumental in shaping the demand and potential markets for both this technology and energy storage in general.

**Renewable Portfolio Standards**

The increase of renewable energy sources strengthens the case for energy storage on the grid. Renewable energy sources, unlike coal and gas, are typically both intermittent and unable to be dispatched on demand. This makes it increasingly difficult for utilities to match supply and demand. Energy storage provides a potential solution since it enables excess renewable energy to be stored and distributed when needed. This is relevant for both macro supply/demand management and for the more specialized ancillary services designed to smooth the constant variations in supply and demand. For these latter services, the variability of energy supplied by renewables will dramatically increase ancillary service capacity requirements. As traditional forms of energy supply become more expensive, non-generational resources, such as storage, may be increasingly used to provide ancillary services to the grid.
Renewable portfolio standards (RPS) are targets set by each State for the percentage of a utility’s capacity or generation that must be provided by alternative or renewable energy. The types of energy that qualify differ by state and certain states have “carve-outs” which mandate a certain portion of the RPS be provided by a specific energy source. RPS have been enacted by states since the 1980s, however, many have been revisited and strengthened within the last decade. In 2009, California enacted the most aggressive RPS in the country other than Hawaii’s target for 2030, increasing the 20% RPS target for 2012 to a 33% target for 2020. The following map by the Database of State Incentives for Renewables & Efficiency portrays the RPS set by each state in the US.

Figure 3: RPS Policies in May 2011, DSIRE

To manage the increased reliance on renewable energy, many States plan to not only significantly increase their requirements for ancillary services, but also to incorporate energy storage into their standard programs.\(^2\) International adoption of renewable energy will also likely fuel demand for energy storage abroad. Countries such as China, India and Germany have implemented or plan to implement aggressive renewable goals in the future.\(^3\)

\(^2\) CAISO, ISO-NE, PJM
\(^3\) EIA
Federal Energy Regulatory Commission Proposes “Pay-for-Performance”

In 2011, the Federal Energy Regulatory Commission (FERC) issued a notice of proposed rulemaking for pay-for-performance. The pay-for-performance proposal recommends that technologies that provide more responsive frequency regulation should be compensated based on their ability to quickly and efficiently respond to the needs of the grid. FERC’s proposal is agnostic to the technology that provides the frequency regulation. Traditionally, energy storage technologies that are most able to respond quickly to the imbalance between supply and load are also typically the most expensive and capital intensive. To illustrate this point, the two most responsive storage technologies currently used for frequency regulation, flywheels and hydro power.

![Figure 4: Regulation Effectiveness of an "Ideal Resource", Beacon Power](image)

While the FERC ruling makes the provision of existing, expensive storage technologies more economical, it should also drive demand for technologies with equal or higher responsiveness that are also more cost effective. Given that a responsive thermal storage device could potentially meet both these criteria, the potential opportunity for such a solution will grow as compliance with the FERC ruling trickles through ISO and RTOs’ ancillary service markets.

---

4 FERC Statement by Commissioner John R. Norris, February 17, 2011
California Energy Storage Bill (AB 2514)

California’s Assembly Bill 2514 was enacted into law in September 2010. The bill directs the California Public Utilities Commission (CPUC) to evaluate energy storage targets and establish energy storage procurement targets for 2015 and 2020. When originally proposed, the bill was an energy storage portfolio standard with hard targets of 2.25% of peak load by 2014 and 5% by 2020. Later in April 2010, the bill was amended and the hard targets were removed in favor of the CPUC establishing targets. Most recently, in March of 2011, the CPUC has moved ahead of schedule to begin proceedings to establish targets.

The bill states that targets are intended to be technology neutral and application neutral. All storage technologies installed after January 2010 will be eligible towards meeting the targets. Utility, customer, and third party owned storage is eligible, and only electrical corporations with less than 60,000 customers are exempt from meeting the targets.

A device enabled with responsive thermal storage would be eligible towards the CPUC’s target, so AB 2514 would likely help to spur adoption of this technology. Furthermore, the potential cost advantages of this technology over other storage technologies such as batteries and flywheels make it an attractive means to achieve compliance with these storage targets.

Time-of-Use Rate Structures

Time-of-use (TOU) pricing is a pricing structure in which utilities charge a higher price for electricity when demand is high (on peak) and a lower price when demand is low (off peak). There are two main purposes of implementing TOU pricing:

1. The cost of electricity paid by the consumer more closely represents the cost of producing the electricity as power sources with higher marginal costs are called upon as demand increases.
2. TOU pricing encourages consumers to shift energy consumption to times when demand is scarce and prices are lowest, thereby reducing the costs to produce energy during peak hours.

---

6 CESA, March 29, 2011
There are various degrees of time-of-use or variable pricing, ranging from higher prices during critical peak days of the year all the way to dynamic (real-time) pricing that fluctuates according to availability throughout the day.

Today, time-of-use pricing is more common for customers with larger electricity loads (e.g., >500KW) such as large commercial and industrial clients. Adoption of time-of-use pricing within the residential sector has thus far lagged other customer bases. According to Pacific Gas & Electric, only 1% of their residential customers are currently on TOU rate schedules as opposed to 30% of their commercial clients. The Rates group at PG&E believes that while all customer bases are eventually headed towards a high degree of TOU adoption, only the commercial and industrial sectors will achieve a high level of adoption in the near future. Slow residential adoption is partly due to difficulties associated with installing and connecting each customer via the advanced metering infrastructure required to record and communicate price and consumption information between the customer and the utility.

A device enabled with responsive thermal storage would allow customers to take advantage of TOU rate structures by shifting consumption from higher price to lower price time periods. As TOU rate adoption continues to rise, the potential customer base for a device enabled with responsive thermal storage would also grow.

**Smart Meters and Home Area Networks**

Smart meters and home area networks are two technologies that will enable the spread of TOU pricing, which would in turn increase the relevance of devices enabled with responsive thermal storage. Smart meters are advanced meters that allow for two-way communication between the customer and the utility. These smart meters have several benefits to the utility which include eliminating the need to physically travel to read meters, the ability to collect accurate and timely data on consumption, and knowledge of when outages occur. As TOU rate penetration increases, consumers will have the added benefit of knowing the price of electricity at various times and adjusting their energy consumption to avoid higher prices. This in turn benefits the utility again as smoother energy consumption will allow the utility to lower its capital costs for providing energy during peak periods.

---

7 Southern California Edison
8 Interview with Andrew Bell, PG&E, February 28 2011
According to a McKinsey study, smart meter penetration is growing rapidly in the US. Across all sectors, adoption of smart meters more than tripled between 2007 and 2009. McKinsey estimates that such rapid growth will continue – with adoption growing from 2 million in 2005 to 50 million by 2015. In some countries in Europe, smart meter penetration is close to 50%. The following graph, prepared by the US Energy Information Administration, shows smart meter penetration in the US by sector over the past three years.

Smart meters can also be integrated with home area networks or HANs. HANs are local area networks in the home that allow consumers to remotely control appliances and devices in the home. Based on price information communicated through smart meters, smart appliances’ energy consumption can be controlled for the purposes of demand response or simply avoiding higher peak electricity costs. Lighting in addition to high-load appliances such as washing machines, dish washers, refrigerators and pool pumps can all be optimized to use energy when it is cheapest or bid the option to reduce energy into demand response markets. Although many companies (e.g., Microsoft, Cisco, Motorola, etc.) are

---

9 McKinsey on Smart Grid, McKinsey & Company, Summer 2010
currently coming to market with HAN technologies, development of HAN technologies in general is in the earlier stages.\textsuperscript{10}

Both of these technologies aid adoption of the energy storage refrigerator, not only because they enable TOU pricing, but also because they embed communication technology at the customer site, and particularly in the home. Demand response using residential loads is widely believed to be unprofitable due to the small loads and high cost of communication technology. Interviews with EnerNOC revealed that they have not pursued the residential market for this exact reason.\textsuperscript{11} With communication technology established in the home via smart meters and home area networks, our solution can leverage the existing investment in communication technology and therefore reduce the cost to serve a residential customer. Akuacom, a technology and service provider for automated demand response, concurs with EnerNOC that the smart meter is the key to making residential demand response technologies, such as ours, financially viable.\textsuperscript{12}

**Potential Applications**

**Peak Cost Avoidance**

A device enabled with responsive thermal storage enables peak cost avoidance by allowing electricity customers on TOU rate structures to shift expensive peak electricity consumption to partial peak and off-peak hours and prices. Technologically, such an application of this technology would require relatively little sophistication as the complexity of device operation and communication requirements with the utility are both relatively low.

To estimate the value a device enabled with responsive thermal storage could provide, both to residential and commercial end users, we developed usage and cost models for an average residential and commercial user that leverage the relevant PG&E TOU rate structures. The following sections explain the assumptions used in those models and the potential cost savings the solution can provide per customer and for the entire California market.

---

\textsuperscript{10} McKinsey, Summer 2010
\textsuperscript{11} Interview with Aaron Breidenbaugh, EnerNOC, March 25 2011
\textsuperscript{12} Interview with Paul Lipkin, Akuacom, May 3 2011
Residential Case Study

The residential cost savings model is based on PG&E’s E-6 TOU rate structure, a variable rate structure available to residential customers except those with electric vehicles or on-site (e.g. solar or wind) generation. E-6 charges residential customers a different energy charge per kilowatt-hour of electricity consumed for different times of day (peak, partial peak and off peak) and different seasons (summer, winter). Below is a table of the E-6 TOU rate schedule for PG&E as of March 1st, 2011.

Table 1: E-6 TOU Rate Schedule as of May 2011, PG&E

<table>
<thead>
<tr>
<th>Total Energy Charge (per kWh)</th>
<th>TOU</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>Peak</td>
<td>$0.315</td>
</tr>
<tr>
<td></td>
<td>Partial Peak</td>
<td>$0.16</td>
</tr>
<tr>
<td></td>
<td>Off Peak</td>
<td>$0.095</td>
</tr>
<tr>
<td>Winter</td>
<td>Partial Peak</td>
<td>$0.115</td>
</tr>
<tr>
<td></td>
<td>Off Peak</td>
<td>$0.102</td>
</tr>
</tbody>
</table>

The “summer” period runs May through October and “winter” period November through April, each accounting for approximately 180 days out of the year. Weekends, holidays and winter weekdays are all off-peak time periods except for 5:00 PM to 8:00 PM, which is partial peak. Summer weekdays are divided into peak hours (1:00 PM to 7:00 PM), partial peak (10:00 AM to 1:00 PM and 7:00 PM to 9:00PM) and off-peak hours (9:00 PM to 10:00 AM).13

A typical residential refrigerator consumes 50 W of power on average throughout the day. Over the course of the day the 50 W average power consumption translates to 1.2 kWh of energy. While a residential refrigerator only has a 25% duty cycle (the amount of time per cycle that the compressor is running), there is an upper bound to the amount of time the compressor can safely run. In most cases, a compressor for a residential refrigerator could likely not withstand a duty cycle beyond 50%. This implies that one cannot shift all peak and partial peak consumption to off-peak hours.

Based on these constraints, the model uses the conservative estimate that a residential customer could shift summer weekday peak consumption, winter weekday partial peak consumption and year-round weekend partial peak consumption to off-peak hours. Currently a residential customer on PG&E’s E-6 TOU rate structure pays $54.60 per year for electricity consumption for his or her refrigerator. Under these conservative assumptions for peak cost avoidance, a residential customer could reduce electricity costs for refrigeration to $45.26, representing savings of $9.34 per year or 17.11% of current costs. The following graph illustrates how peak and partial peak costs would decrease as off-peak costs increase.

![Figure 6: Potential Cost Savings for a Residential Customer](chart)

The total potential savings for the state of California can be approximated by applying the 17.11% annual savings to the total California residential market’s spend on electricity for refrigeration. The EIA estimates that California residents pay on average $0.1474 per kWh for electricity in 2008 and consume approximately 13,848 GWh of electricity for refrigeration. This implies the total cost of residential refrigeration in California is $2.04B, with a savings potential of $349M (17.11%) per year.\(^\text{14}\)\(^\text{15}\) It is critical to note, however, that the current residential TOU rate penetration is only 1%. Therefore, even if this technology were fully deployed to the current base of TOU residential customers, the potential savings would only amount to $3.5M. Achieving the full $349M in potential savings relies on 100% TOU rate adoption, which is not realistic in the short or medium term.

\(^{14}\) State Energy Data System, EIA, 2008

Commercial Case Study

There are critical differences between the commercial and residential markets that result in higher annual savings per customer in the commercial markets. The following section highlights those key differences and explains how the potential cost savings were calculated both on a per customer and statewide basis for the California market.

PG&E’s E-19 TOU rate structure – a rate structure that would be applied to a typical full-size supermarket – was used as a basis to model potential savings in the commercial refrigeration market. The same seasonal (winter, summer) and hourly (peak, partial peak, and off-peak) divisions for volumetric energy charges apply to the E-19 rate structure as they did to the E-6 rate schedule. A key difference, however, and one that substantially increases the potential cost savings of our solution, is the existence of demand charges on the E-19 rate structure. Demand charges are a per kW fee that a commercial customer incurs based on the peak power usage during a given billing cycle. A demand charge ideally should encourage a customer to use a smoother power profile over a long period as opposed to a high amount of power at any time. E-19 has temporal demand charges for the max-peak period, partial peak period and then also a demand charge for the maximum amount of power used at any point of the billing period. Below is PG&E’s E-19 TOU rate structure as of March 1st, 2011.

<table>
<thead>
<tr>
<th>Table 2: E-19 TOU Rate Schedule as of May 2011, PG&amp;E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demand Charges (per kW)</strong></td>
</tr>
<tr>
<td>TOU</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td><strong>Summer</strong></td>
</tr>
<tr>
<td>Max Peak</td>
</tr>
<tr>
<td>Partial Peak</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td><strong>Winter</strong></td>
</tr>
<tr>
<td>Partial Peak</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
</tbody>
</table>

The daily energy used by a commercial refrigeration customer and the maximum number of hours that could be potentially be shifted were used to determine the cost savings per customer. For the purpose of the model, we used a 15 square meter walk-in freezer for the typical commercial refrigeration
customer. The commercial walk-in freezer uses considerably more power than a residential refrigerator, approximately 2.4 kW of power on average. Over the course of a day this translates to 57.6 kWh. For commercial freezers, duty cycles can range from as low as 40% to up to 90%.\(^\text{16}\) This higher duty cycle, as compared to residential refrigerator units, decreases the potential to shift peak and partial peak hours to off-peak times. However, unlike residential refrigerators, the compressor in a commercial freezer can likely withstand a 100% duty cycle. The flexibility and robustness of commercial freezer compressors counteracts the decrease caused by higher duty cycle operation by increasing the number of peak and partial peak hours that can be shifted to off-peak hours.

Based on these constraints the same conservative assumptions for peak cost avoidance were used. Commercial customers can shift summer weekday peak consumption, winter weekday partial peak consumption and year-round weekend partial peak consumption to off-peak hours. Of critical note is that by shifting all summer peak consumption and winter partial-peak consumption to off-peak hours, commercial clients also avoid the summer peak and winter partial peak demand charges for the power required to run their freezer’s compressor. Currently, a commercial customer with a walk-in freezer on PG&E’s E-19 TOU rate structure would pay $887.81 in demand charges and $1940.68 in energy charges per year, totaling $2,828.48. Under these conservative estimates for potential peak cost avoidance, the potential annual savings is $341.25 in demand charges and $127.17 in energy charges, totaling $468.42 of annual savings or 16.56% of the total refrigeration energy costs. The following graph illustrates how the shift of peak consumption decreases overall electricity costs when accounting for both demand and energy charges. Even though partial peak and off-peak costs increase, they are offset by the large decrease in peak charges.

\(^{16}\) Interview with Don Fisher, Food Service Technology Center, April 21 2011
It is estimated that the total cost of California’s electricity for commercial freezers is $482M, which is based on California’s approximate total freezer electricity consumption of 3,595 GWh and the EIA’s estimate of the average commercial electricity price in California ($0.1342 per kWh). The 16.56% of cost savings associated with the avoidance of peak energy consumption implies the total potential savings for California commercial freezers is $80M. This estimate reflects the potential under a scenario in which all commercial users operated under TOU rate structures. Currently, the level of TOU rate structure penetration is approximately 30% among commercial customers. At this level of adoption, the estimated savings potential is closer to $24M. However, it should be noted that utilities are actively seeking to increase adoption of TOU rate structures within the commercial segment. Interviews with PG&E’s Rates group indicate that there is currently significant momentum to push commercial customers towards 100% adoption TOU rate structures in the near term.

Ancillary Services

Grid balancing authorities operate a series of ancillary services markets to compose the set of resources needed to balance supply and demand across the grid. Table 3 provides a general overview of ancillary services by category, though the collections of these markets differ according to the rules of each

\[17\] State Energy Data System, EIA, 2008
\[18\] Commercial End-Use Survey, California Energy Commission
system operator or administrative domain. In total they represent power that can be provided or removed from the electricity grid for specific durations when desired.

Table 3: Ancillary Services Overview

<table>
<thead>
<tr>
<th>Service</th>
<th>Service Description</th>
<th>Price Range* (average/max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regulating Reserve</td>
<td>Online resources, on automatic generation control, that can respond rapidly to system-operator requests for up and down movements; used to track the minute-to-minute fluctuations in system load and to correct for unintended fluctuations in generator output to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Electric Reliability Council (NERC 2006)</td>
<td>35-40/200-400</td>
</tr>
<tr>
<td>Load Following or Fast Energy Markets</td>
<td>Similar to regulation but slower. Bridges between the regulation service and the hourly energy markets.</td>
<td></td>
</tr>
<tr>
<td>Contingency Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>Online generation, synchronized to the grid, that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 min to comply with NERC’s Disturbance Control Standard (DCS)</td>
<td>6-17/100-300</td>
</tr>
<tr>
<td>Non-Spinning Reserve</td>
<td>Same as spinning reserve, but need not respond immediately; resources can be offline but still must be capable of reaching full output within the required 10 min</td>
<td>3-6/100-400</td>
</tr>
<tr>
<td>Replacement or Supplemental Reserve</td>
<td>Same as supplemental reserve, but with a 30-60 min response time; used to restore spinning and non-spinning reserves to their pre-contingency status</td>
<td>0.4-2/2-36</td>
</tr>
<tr>
<td>Other Services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Control</td>
<td>The injection or absorption of reactive power to maintain transmission-system voltages within required ranges</td>
<td>1-44/kvar-yr</td>
</tr>
<tr>
<td>Black Start</td>
<td>Generation, in the correct location, that is able to start itself without support from the grid and which has sufficient real and reactive capability and control to be useful in energizing pieces of the transmission system and starting additional generators.</td>
<td></td>
</tr>
</tbody>
</table>

---

In this section, we evaluate the set of ancillary services traded in California ISO markets by four criteria: market size, market growth potential, the “fit” with our technology, and the market and regulatory risk horizon.

**Capacity Curtailment**

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Curtailment</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Reserve capacity represents power resources that must be available at all times as “headroom” in case of sudden imbalances between supply and demand. For the California ISO, reserves represent 7% of total forecast system load.\(^{20}\) The total system energy load for California was 281 TWh in 2010 and is expected to grow by 1% annually to 316 TWh by 2020; thus, the reserve capacity will maintain the same growth rate.\(^{21}\) This market is typically serviced with interruptible loads that are aggregated by large incumbents such as EnerNOC and Converge. Despite the large potential size of the market (over $2B), the infrequency of the capacity utilization limits any competitive advantage this technology would have over the current model based on interruptible loads.\(^{22}\)

**Day Ahead Demand Response**

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day Ahead Demand Response</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

---

\(^{22}\) JP Morgan, 2009
Day ahead demand response is an agreement between utilities and customers to curtail electricity loads during periods of peak grid demand. In many RTO/ISO markets (e.g., NYISO, ISO-NE, etc.), customers can offer power reductions (for example, a minimum of 100 kW in ISO-NE) as bids into the day-ahead electricity market. If these bid prices are met, customers can decide whether to shed their load. Until recently in California, day-ahead demand response was handled through individual utilities; market size as of 2010 was 2,500 MW. The California ISO has recently introduced the Proxy Demand Resource product, which allows loads to act as generators by curtailing consumption, operating as a wholesale product in CAISO markets. For the same reasons as the capacity markets – established competitors/solutions and lack of technological advantage – responsive thermal storage is not appropriate for these markets.

**Load Following**

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Following</td>
<td><img src="https://via.placeholder.com/15" alt="Circle" /></td>
<td><img src="https://via.placeholder.com/15" alt="Circle" /></td>
<td><img src="https://via.placeholder.com/15" alt="Circle" /></td>
<td><img src="https://via.placeholder.com/15" alt="Circle" /></td>
</tr>
</tbody>
</table>

Load following is a service that provides flexibility for intra-hour volatility and hour-ahead forecast errors. Figure 8 shows that load following is essentially a low-frequency version of total electrical load – its magnitude follows the predictable daily patterns of consumption. In California, load following operates in the hour-ahead market. Though this market is large and attractive, the responsiveness of our technology is underutilized by its requirements.

---

24 [http://www.narucmeetings.org/Presentations/Demand_CPUC.pdf](http://www.narucmeetings.org/Presentations/Demand_CPUC.pdf)
25 Kirby, B. 'Frequency Regulation Basics and Trends.' December, 2004
Figure 8: Load Following and Regulation

Non-Spinning Reserve

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Spinning Reserve</td>
<td>![Icon]</td>
<td>![Icon]</td>
<td>![Icon]</td>
<td>![Icon]</td>
</tr>
</tbody>
</table>

Non-spinning reserve represents capacity that can come online and be synchronized to the grid in a relatively short period of time (i.e., 10 minutes), but does not need to respond immediately. Non-spinning reserve is usually actuated using the Automated Generation Control (AGC) protocol, whereby the system operator can call in capacity automatically.\(^{26}\) This is a small but growing market, fueled by the increase in intermittent generation on the grid. However, non-generation resources such as responsive thermal storage have not typically been used to provide non-spinning reserve.

### Spinning Reserve

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning Reserve</td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
</tr>
</tbody>
</table>

Spinning reserve is supplied by online resources that can respond immediately and therefore must be synchronized to the electricity grid. Spinning reserve is also actuated using the AGC protocol. Since our technology is a non-generation resource, it is already synchronized to the grid and provides an additional benefit over non-spinning reserve. The requirement for spinning reserve capacity is driven by the total capacity of intermittent generation on the electricity grid, so although this market is small, it is growing quickly.\(^\text{27}\) Spinning reserve is generally worth 3-4 times as much as non-spinning reserve. However, just as with non-spinning reserve, non-generation resources have not traditionally been used to provide spinning reserve.

### Frequency Regulation

<table>
<thead>
<tr>
<th>Potential Applications</th>
<th>Market Size</th>
<th>Market Growth</th>
<th>Technology Advantage</th>
<th>Regulatory/Market Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Regulation</td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
<td><img src="Image" alt="Circle" /></td>
</tr>
</tbody>
</table>

Of the potential ancillary services, frequency regulation aligns most closely with technological advantages of responsive thermal storage and could potential represent a meaningful market opportunity for this type of storage technology.

Frequency regulation consists of the rapid fluctuations in energy load around the underlying trends; see Figure 8. By nature, it operates in both directions – up when more load is needed and down when less load is needed. Approximately 1% of all electricity generated is required for frequency regulation. According to the U.S. Energy Information Administration (EIA), this implies a U.S. market of 4,557 MW in 2009 that is expected to grow to 5,109 MW by 2019\(^\text{28}\). In addition, renewable portfolio standards in many states are calling for significant increases in alternative or renewable generation within the next ten years. It is likely that the frequency regulation market will benefit from the growth in renewables, which require greater regulation reserves due to the intermittency of output.

For example, California has recently increased its renewables portfolio standard from 20% to a goal of 33% by 2020. To support the transition to a greater use of renewables, CAISO forecasts that it will need to double the amount of regulation capacity required. At current market rates, we expect the overall market size for frequency regulation in California to roughly double from approximately $60M in 2012 to $125M in 2020. This growth trend is likely to occur in other states as well. As PJM moves to 20% RPS, it expects its regulation requirement to double, from 1,000 MW today to 2,000 MW\(^\text{29}\).

| Table 4: Frequency Regulation Capacity Requirements and Estimated Market Size, CAISO 2009 |
|-----------------------------------|-----------------|-----------------|
| **Regulation Up** | **Maximum Reg Requirement (MW)** | 502 | 1,135 |
| | **Estimated market size ($7.51/MWhr)** | $33,025 | $74,668 |
| **Regulation Down** | **Maximum Reg Requirement (MW)** | -569 | -1,097 |
| | **Estimated market size ($6.01/MWhr)** | $29,956 | $57,754 |

*Source: CAISO 2009*

Participation in the frequency regulation market requires a high degree of responsiveness. Providers of frequency regulation typically have 4 seconds to acknowledge receipt of a regulation up/down signal and must initiate a response to the signal in less than 1 minute. Under California’s requirements, a participant has a maximum of 10 minutes to fulfill its load increase/decrease commitment. For example, in a regulation down scenario, a participant would have to begin turning off compressors within one

\(^{28}\) 2010 Annual Energy Outlook, EIA

\(^{29}\) Terry Boston, CEO of PJM
minute of receipt of the signal from CAISO and would have to turn off at least 500 kW worth of compressors (the minimum bid) within 10 minutes.

Table 5: Frequency Regulation (Up/Down) Requirements, CAISO 2009

<table>
<thead>
<tr>
<th>Response Time</th>
<th>Time to Reach Bid</th>
<th>Required Telemetry</th>
<th>Minimum Required Bid</th>
<th>Protocol</th>
<th>Duration</th>
<th>Market Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 min</td>
<td>&lt;10 min</td>
<td>4 sec</td>
<td>500 kW</td>
<td>Automatic Generation Control (AGC)</td>
<td>15 min (day-ahead) 60 min (real-time)</td>
<td>Day-ahead &amp; real-time</td>
</tr>
</tbody>
</table>

From a technical standpoint, it would be feasible to design this technology to meet the telemetry response, ramping (i.e. time to start/reach bid), and duration requirements. A potential benefit of frequency regulation over other ancillary services is the relatively short duration of the cycles. Given the user base of this technology contains refrigerator and freezer owners whose primary concern is food storage, short duration cycles will likely help to alleviate those customer concerns related to food quality and potential spoilage.

Aside from basic design challenges, there are a number of hurdles associated with participation in the frequency regulation markets. Operationally, the frequency regulation market requires a high level of sophistication. Aggregating control over a significant base of end-users and developing the ability to bid into day-ahead and real-time markets requires significant expertise, capital, and time. In addition, ISO/RTOs have little experience using demand response/demand side management to meet frequency regulation requirements. This lack of participation has been primarily due to lack of technological capability on the provider side. However, the growing sophistication of demand side management and aggregation technologies will continue to drive the participation of such services in frequency regulation markets. For example, ISO-NE, PJM, and IESO have partnered with Enbala, a small demand side management start-up, to test the ability of demand side management technology to meet their frequency regulation requirements. In the future, the participation of such services is likely to become more widely adopted.

---

30 www.enbala.com
Deployment Considerations

Thermal storage is applicable in refrigeration systems that are capable of maintaining temperatures near or below freezing. Such systems are typically employed both residentially and commercially. Broad adoption of this technology is essential for it to have a substantial impact since the relative fraction of energy consumption by any one user – residential or commercial – is small. However at a macro level, the amount of energy used for refrigeration/freezing by both residential and commercial end-user groups is large – suggesting that the deployment and thus market potential within each group is large.

Table 6: Residential and Commercial Refrigeration Market Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Residential Refrigeration</th>
<th>Commercial Refrigeration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of customers in US</td>
<td>145 M</td>
<td>2.5 M</td>
</tr>
<tr>
<td>Typical annual energy use per customer</td>
<td>438 kWh</td>
<td>21,400 kWh</td>
</tr>
<tr>
<td>Total annual energy consumption in US</td>
<td>151 TWh</td>
<td>118 TWh</td>
</tr>
</tbody>
</table>

In terms of actual technological deployment, existing units can either be retrofitted with this technology or the technology can be designed into new appliances. While both of the segments are attractive based on the potential impact on total refrigeration energy consumed, the actual incorporation of the technology into residential and commercial appliances requires different approaches.

Retrofit versus Replace

*Residential deployment favors a replacement approach*

The total number of refrigerator models for the residential market is estimated to be over 3,000, manufactured by over 50 different appliance manufacturers. There are approximately 1,394 residential refrigerator/freezers and freezer models that meet current ENERGY STAR® efficiency requirements. Despite the large number of models and manufactures, market share is fairly concentrated among four manufacturers – Whirlpool (41.5%), AB Electrolux (20.8%), GE (18.4%), and LG Electronics (8.7%). This large number of available models reflects the fact that manufacturers need to meet a wide variety of residential customer preferences such size, volume, design, and functionality.

31 ENERGY STAR, http://www.energystar.gov/
32 Major Household Appliance Manufacturing in the US, IBISWorld Industry Report, Dec 2010
In addition, residential refrigerators are typically covered by a manufacturer’s warranty. Importantly, a warranty is voided if any part of the refrigerator is modified from its original factory condition. In order to retrofit an existing refrigerator model with this technology, it would be necessary to modify the refrigerator in order to obtain a power source for the technology’s controller. This would likely void any existing warranty. Our research indicated that while warranties may be infrequently invoked, consumers would be extremely hesitant to risk voiding the warranty on their appliance.

The cost to retrofit is also a concern. There is the cost of the retrofit device along with the service installation. Based on our research, refrigeration repair services have a baseline cost that varies from $50 to $100 excluding labor charges, parts, etc. While it is difficult to estimate the potential duration of a residential retrofit, the variety of existing refrigeration models on the market and the complexity arising from that lack of standardization, makes the costs to retrofit likely prohibitive. It is also worth noting that such complexity may also impede the use of utility sponsored rebates for retrofitting.

Designing the technology into future refrigerator models is likely the only realistic option to drive its adoption at a residential level. The concentrated nature of the market means that relatively few manufacturers would need to incorporate the technology to drive adoption. Furthermore, this approach would position the technology well to take advantage of the existing infrastructure and processes in place designed to support the incorporation and adoption of energy efficient technologies in residential appliances – namely ENERGY STAR certification standards and utility rebates for qualified appliance purchases.

*Commercial deployment is suited to a retrofit model*

The commercial market typically consists of food service, grocery stores, and refrigerated supply chain end-users. Unlike in the residential segment, freezers and refrigerators are typically decoupled due to greater storage requirements and greater diversity in end-user uses and needs. Because of this diversity, the market is much less concentrated with the top four manufacturers only accounting for approximately a 35% share of the market.

---

33 Rebates may also exist at the State and Federal levels but are less common
The high degree of customization and product diversity indicate that this market segment is not well suited to a replacement approach. Diversity lowers the potential for rebates to encourage adoption since they are likely to apply to a smaller proportion of the freezer systems on the market. It would also require partnership with a larger number of manufacturers to achieve a level of market penetration comparable to that of a smaller number of residential manufacturer partnerships.

However, a number of characteristics indicate that a retrofit approach would be feasible. Commercial freezers are much larger than residential models and often have excess capacity – the average walk-in commercial freezer is 15 square meters. Given the decreased importance of volume, a retrofit would be less likely to be perceived as an impediment to a commercial freezer’s functionality. Our research also indicated that due to the customized nature of commercial freezers, there is significantly less risk of a retrofit-triggered warranty violation.

**Maximizing Adoption**

Given recommended deployment approaches to both residential and commercial end-users, it is important to consider their respective implications on the expected “time-to-market” of this technology and the potential rate of adoption. In general, our research indicates that retrofitting commercial freezers would likely drive faster adoption of this technology.

**Residential Adoption Challenges**

A major advantage of residential deployment of this technology is that it would maximize the distribution of the technology throughout the grid. The distribution would yield substantial benefits to utilities when combined with energy storage as the value of storage increases the farther away it is located from generation sources. However, there are a number of hurdles associated with the residential deployment of this technology that make this user segment less attractive as a driver of rapid adoption.

According to a major US appliance manufacturer it typically takes eight to ten years to design a new refrigerator model. This base technology is on market for roughly the same amount of time and assumes

---

34 Ice Energy
the incorporation of marginal enhancements to the functionality and design. The length of the design period is a significant impediment to rapid residential adoption. Additionally, the technology must meet specific design criteria if manufacturers are to consider it for incorporation into a new model. After the price of the unit, the purchasing decision for a residential refrigerator is primarily influenced by four factors:

- Volume
- Design (i.e. look and feel)
- Size
- Energy consumption

Our research indicated that maximizing internal volume within a refrigerator is a primary goal of most manufacturers. Any design and/or functionality changes that reduce volume – as this technology would in its current incarnation – are not likely to be considered. While an alternative would be to incorporate such technology into the structure/insulation of the refrigerator, GE currently believes it is impossible to achieve this without compromising the structural integrity and insulation required for the appliance. This technical hurdle, coupled with the long design cycle of new refrigerators and the current stage of the technology, indicates that the potential time to market under this scenario is likely greater than ten years away.

It is also important to consider the potential rate of adoption assuming the technology is on the market. One benefit of the residential segment is the availability of rebate programs to encourage adoption. Under a typical program, customers who purchase a qualified appliance are eligible to apply for a rebate from the offering utility or government. Such programs, while partially supported (through certification) by federal programs like ENERGY STAR, are the primary financial and operational responsibility of utilities (or in some cases the government).

Given the grid-scale benefits associated with this technology, it is reasonable to assume that ENERGY STAR would incorporate Demand Response into its certification program. Recent conversations with ENERGY STAR indicated that the development of Demand Response criteria for ENERGY STAR qualification is currently underway for air conditioners and would likely be rolled-out over the next decade for various appliances.

However, the effect of rebate programs and certification as a driver of demand for refrigerators is somewhat ambiguous. For example, between 2006 and 2008, PG&E funded a rebate program to drive
adoption of energy efficient appliances (e.g. dishwashers, refrigerators, dryers etc.), windows, lighting, and insulation. Over this three year period, the program was oversubscribed, with 654,126 applications filed exceeding the $867M dollar budget. It is estimated that only a fraction of these rebates were for the purchase of refrigerators. Past rebate programs directed specifically at the purchase of energy efficient refrigerators generated approximately 30,000 qualified purchases. It is also important to note that program funding would likely be competing with other energy efficiency initiatives. Currently, PG&E views residential (and commercial) lighting as the source of largest economic potential - portion of achievable technical potential that meets a specific per-unit cost threshold. This suggests that not only is the effectiveness of rebates ambiguous, but the potential to obtain meaningful funding for such a program would by no means be a guarantee.

Figure 9: Economic Potential (GWh) by End Use and Segment, PG&E

![Economic Potential Graph](image)

Data from CPUC/Draft Potential Study April 2008

*Includes interior and exterior lighting
**Includes water and space heating
Commercial Retrofits Maximize Short-term Adoption

Retrofitting commercial units would likely bypass a number of the hurdles associated with the incorporation of this technology into a residential refrigerator. Most importantly, the design of a commercial product avoids the long design cycle of residential manufacturers and would not be subject to the stringent residential design requirements and challenges (i.e. no volume reduction). Furthermore, the large size of commercial freezers would allow for a relatively uniform retrofit design and greater degree of design flexibility.

There is also a clearer business case for commercial users – making them less reliant on rebate programs to drive adoption. Currently, 30% of commercial customers operate under TOU rate structures in CA and PG&E is actively driving towards 100% adoption\(^{35}\). Under such a rate structure, the potential savings generated from peak-shaving is proportionately much greater for a commercial user than a residential user, likely indicating their willingness to pay would also be greater. According to the Food Service Technology Center, the penetration of energy efficient technologies within the food service sector, which comprises a major component of commercial energy for refrigeration, is very low. This suggests that there is potential latent demand within this sector. While the commercial segment is subject to the same potential rebate program risks as the residential segment, the latent demand suggests that rebates may be better received by commercial customers. In addition, utilities have demonstrated a willingness to apply rebates to encourage both the purchase of new energy efficient refrigeration equipment and for the retrofitting of existing equipment\(^{36}\).

The relative amount of energy used by a commercial customer is much greater than that of the typical residential refrigerator. In operational terms this is likely to result in a lower cost per acquired amount of capacity. The larger amount of energy consumed by commercial users may also support faster adoption.

\(^{35}\) PG&E

\(^{36}\) Southern California Edison
Achieving 25 MW of continuous controllable capacity would require adoption by approximately 11,700 commercial customers or 500,000 residential customers (when accounting for compressor duty cycles). Based on high level time-to-market estimates, end-user segment characteristics, and rate of adoption assumptions, commercial retrofits appear to be able to achieve a meaningful level of market adoption (measured in total controllable capacity) much faster than a deployment strategy reliant on replacing residential refrigerators.

**IP Strategy**

In the short-term, for any path involving licensing or patenting, it is required that an invention disclosure be filed with UC Berkeley. The invention disclosure is a legal document that will record what has been invented as well as the circumstances under which the invention was created. Berkeley’s Office of Technology Licensing (OTL) recommends that this disclosure be filed as soon as the invention has been conceived and initial data is available. Due to restrictions on patenting, public dissemination of the invention/technology may jeopardize potential patent rights outside of the United States.

---

37 Base Assumptions:
25MW represent .5% of peak demand
Commercial Customer Assumptions – 4.27KW in Avg Energy Savings, 30min duty cycle (*Office of Energy Efficiency, Canada*)
Typical Residential Customer Savings – 200W in Avg Energy Savings, 15min duty cycle (*Laboratory Estimates*)
Once disclosed to the OTL, the licensing staff conducts further research to engage in the following steps:

- Determining the invention’s ownership, third party rights and obligations
- Evaluating the invention’s commercial and patent/copyright potential
- Assessing licensing prospects
- Pursuing patents

The OTL may choose not to pursue patents for the invention if the above criteria are not satisfactory. A major driver of this is time and cost. It takes approximately 3 years to file a patent in the United States, with costs ranging from $10,000-$20,000 to prepare and file a patent application. The cost to file in the big three geographies (US, UK, Japan) is estimated to be approximately $50,000. Other countries, such as China are likely to have lower application preparation and filing costs, due to a weaker (but strengthening) enforcement structure. In these geographies, patent filing is usually regarded as a defensive measure. Ultimately, where patents are filed should depend on where the market is for the product, where potential competitors operate, and where potential competitors manufacture.

**Licensing**

Licenses can be exclusive, nonexclusive, or co-exclusive, and can also be limited in duration, geographical jurisdiction, or particular purpose. The general method pursued will depend greatly on the goals of the patent holder. In the case of this technology, there are four potential options.

1. **Start a Business**
   UC Berkeley grants an exclusive license to the inventors to commercialize the technology. It should be noted that the University maintains an obligation to grant licenses to “the best qualified company”. In most cases, the University regards the inventors as being best qualified on account of their expertise. However there is a potential risk should a large sophisticated appliance manufacturer choose to pursue the license.

2. **Co-Develop**
   UC Berkeley grants an exclusive or co-exclusive license with one or more manufacturers to commercialize the technology. In this case, some level of partnership is assumed with the manufacturer, but is likely to be restricted primarily to R&D. The University/inventors would likely receive licensing fees and potentially royalties from any eventual product sales. A potential
risk is that once the technology is licensed, the patent holder has no control over whether the manufacturer commercializes the technology. This can be potentially mitigated through the structure of the license agreement, such as minimum payments.

3. **Targeted Proliferation**

UC Berkeley grants non-exclusive licenses with multiple manufacturers to commercialize the technology. Unlike in the case of an exclusive or co-exclusive license, a limited to nonexistent partnership is assumed. Generally, this option is ideal when the patent holder can play a direct role in establishing demand (i.e. advertising, State/Federal regulation, etc) for the particular invention, thereby creating incentive for manufacturers to license and produce.

4. **Broad Proliferation**

In this case, the technology would be published in public domain without any patents. It should be noted that this approach does carry risks – particularly that appliance manufacturers with potentially competing technologies, may set up patents “around” this technology to hinder or outright block commercial development as a defensive strategy to protect their investments.

The licensing strategy ultimately chosen will require further development of the technology and a deeper understanding of its potential. However, in the interest of maximizing adoption, options one and two appear to provide the clearest path to widespread use of the technology. Their primary advantages are that they maximize control over the development and proliferation of the technology and limit the risk of defensive patent walls or shelving in favor of competing technologies already in process.

**Application Rollout**

Developing the technology with a focus on peak energy cost reduction within the commercial segment is likely the most attractive path to maximize technological adoption from an end-user standpoint. Initial focus on this application and end-user segment, as opposed to frequency regulation within ancillary service markets, carries the following benefits:

- Lower technical requirements
- Simpler operational requirements
- Clearer support of markets
- No scale requirements
Frequency regulation and broader ancillary service markets are attractive but require much more technical (i.e., telemetry) and operational (i.e., aggregation and bidding capabilities) sophistication. At a basic level, both of these require time and significant capital. Participation in ancillary service markets also requires significant scale. Based on our estimates of rate of adoption, it would take a prohibitive amount of time to build a large enough user base to allow for meaningful participation in the frequency regulation market in the near-term.

Furthermore, ancillary service markets are still evolving. Recent regulatory developments have been largely supportive of the participation and fair compensation of non-generation resources, and our research indicates that broad participation is likely, but by no means guaranteed. A near-term focus on peak energy cost reduction would provide time (and potentially finance) to develop solutions to technical and operational hurdles posed by the frequency regulation market. Most importantly, it would provide a means to develop the scale necessary to participate in the frequency regulation market and allow the markets to mature from a regulatory standpoint.

**Recommended Next Steps**

Based on our analysis, we believe that there are several key next steps to be performed to further the technology and better understand the characteristics of potential markets.

As the commercial sector has been identified as a better short term target market, it is important to gain a clearer understanding of the needs of the market. Analysis should be performed to determine the relative size of the subsections of the commercial market (e.g., supermarkets, refrigerated warehouses, etc.), as well as critical end-user needs and characteristics (e.g. the proportion of walk-in freezers as opposed to reach-in freezers). Determining the needs of these subsectors such as willingness to pay and willingness to sacrifice freezer capacity will better inform the design of the solution as well as the optimal path to market.

In terms of design, next steps include developing prototypes for commercial freezers and determining the communication requirements for the device for various applications – focusing on the minimum viable solution. The communication capabilities must also be designed and tested to ensure that it meets the telemetry and protocol requirements for ISOs’ for peak shaving and potentially ancillary
service markets in the locations where it will be used. It will also be important to determine whether the same solution can be used for both walk-in and reach-in freezers. Once specifications for the communication are set, the phase change solution has been chosen, and a commercial prototype is built, it will be crucial to assess whether the scaled manufacturing cost per unit aligns with the estimated thresholds for the minimum viable product.

Lastly, decisions on where and whether to develop a business will inform the patenting and licensing next steps for the product. Once an invention disclosure has been filed to start the UC Berkeley patenting process, there will be approximately a year to determine in which geographical markets patents should be filed. Further analysis of potential markets (domestic and international), applications (i.e. peak shaving), potential cost, and supporting ecosystem will inform the decision to start a business, develop the technology with a single manufacturer, or proliferate the technology (i.e. through non-exclusive licenses or publicly publishing the technology). If the last option is pursued, it may not be necessary to complete the UC Berkeley patent process.
Appendix
### Adoption Model Assumptions

#### Residential Adoption of New Refrigerators

- Estimated Number of Residential Refrigerators in CA: 11,500,000
- Average Refrigerator Lifespan: 12 yrs
- Estimated Annual Refrigerator Sales in CA: 958,333
- Estimated Annual Sales of Top Two US Manufacturers: 578,833
- Percent of Models that Incorporate Technology: 1%
- Annual Growth of Technology Incorporation: 1%
- Residential Refrigerator Duty Cycle: 15 min
- Power Consumption Per Refrigerator: 200W
- Estimated Time to Market: 9 yrs

#### Commercial Retrofit Adoption

- Estimated Number of Commercial Freezers in CA: 132,000
- Average Refrigerator Lifespan: 12 yrs
- Estimated Share of Top Two US Manufacturers: 66,000
- Percent of Models that Incorporate Technology: 1%
- Annual Growth of Technology Incorporation: 1%
- Commercial Freezer Duty Cycle: 30 min
- Power Consumption Per Freezer: 4.27 KW
- Estimated Time to Market: 4 yrs

### Calculation of Estimated Controllable Power (per hour basis):

\[
\frac{([\text{Total Installed Base}] \times \text{(Power Consumption Per Refrigerator/Freezer)})}{(60 \text{min} \div \text{Duty Cycle})}
\]
Time of Use Model Assumptions

Residential Market

<table>
<thead>
<tr>
<th></th>
<th>Rate</th>
<th>Hours/Day # of Days</th>
<th>Total Cost - Status Quo</th>
<th>Hours/Day # of Days</th>
<th>Total Cost - With Us</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>0.315</td>
<td>6</td>
<td>130</td>
<td>$12.29</td>
<td>0</td>
</tr>
<tr>
<td>Partial-Peak</td>
<td>0.16</td>
<td>5</td>
<td>130</td>
<td>$5.20</td>
<td>5</td>
</tr>
<tr>
<td>Partial-Peak (Weekend)</td>
<td>0.16</td>
<td>3</td>
<td>52</td>
<td>$1.25</td>
<td>0</td>
</tr>
<tr>
<td>Off-Peak (Weekdays)</td>
<td>0.095</td>
<td>13</td>
<td>130</td>
<td>$8.03</td>
<td>19</td>
</tr>
<tr>
<td>Off-Peak (Weekends)</td>
<td>0.095</td>
<td>21</td>
<td>52</td>
<td>$5.19</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$31.95</td>
<td></td>
</tr>
<tr>
<td><strong>Winter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial-Peak</td>
<td>0.115</td>
<td>9</td>
<td>131</td>
<td>$2.26</td>
<td>0</td>
</tr>
<tr>
<td>Off-Peak (Weekdays)</td>
<td>0.102</td>
<td>21</td>
<td>131</td>
<td>$14.03</td>
<td>24</td>
</tr>
<tr>
<td>Off-Peak (Weekends)</td>
<td>0.102</td>
<td>24</td>
<td>52</td>
<td>$6.36</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$22.65</td>
<td></td>
</tr>
<tr>
<td><strong>Status Quo</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Total</td>
<td></td>
<td></td>
<td></td>
<td>$54.60</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>$54.60</td>
<td></td>
</tr>
<tr>
<td><strong>With Us</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Total</td>
<td></td>
<td></td>
<td></td>
<td>$45.26</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>$45.26</td>
<td>Savings</td>
</tr>
</tbody>
</table>

91431 GWh in CA residential blgs.
13848 Refrigeration (from CA end-use data)
$2,041,195,200.00 Total Cost ($0.1474/kWh for CA residential)
17.11% Savings (%)
$349,249,326.19 Total Savings in CA (Value Created)
### Commercial Market

#### Summer

<table>
<thead>
<tr>
<th>Electricity</th>
<th>Rate</th>
<th>Hours/Day</th>
<th># of Days</th>
<th>Total Cost - Status Quo</th>
<th>Hours/Day</th>
<th># of Days</th>
<th>Total Cost - With Us</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>0.146</td>
<td>6</td>
<td>130</td>
<td>$273.31</td>
<td>0</td>
<td>130</td>
<td>$0.00</td>
</tr>
<tr>
<td>Partial-Peak</td>
<td>0.103</td>
<td>5</td>
<td>130</td>
<td>$160.68</td>
<td>5</td>
<td>130</td>
<td>$160.68</td>
</tr>
<tr>
<td>Partial-Peak (Weekend)</td>
<td>0.103</td>
<td>3</td>
<td>52</td>
<td>$98.56</td>
<td>0</td>
<td>52</td>
<td>$0.00</td>
</tr>
<tr>
<td>Off-Peak (Weekdays)</td>
<td>0.086</td>
<td>13</td>
<td>130</td>
<td>$348.82</td>
<td>19</td>
<td>130</td>
<td>$509.81</td>
</tr>
<tr>
<td>Off-Peak (Weekends)</td>
<td>0.086</td>
<td>21</td>
<td>52</td>
<td>$225.39</td>
<td>24</td>
<td>52</td>
<td>$257.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$1,046.76</strong></td>
<td></td>
<td></td>
<td><strong>$928.08</strong></td>
</tr>
</tbody>
</table>

#### Demand Charge

<table>
<thead>
<tr>
<th>Rate</th>
<th>Max Usage Months</th>
<th>Total Cost - Status Quo</th>
<th>Max Usage Months</th>
<th>Total Cost - With Us</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>12.11</td>
<td>4.266666</td>
<td>6</td>
<td>$310.02</td>
</tr>
<tr>
<td>Partial Peak</td>
<td>2.81</td>
<td>4.266666</td>
<td>6</td>
<td>$71.94</td>
</tr>
<tr>
<td>Max</td>
<td>9.27</td>
<td>4.266666</td>
<td>6</td>
<td>$237.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>$619.26</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Winter

<table>
<thead>
<tr>
<th>Electricity</th>
<th>Rate</th>
<th>Hours/Day</th>
<th># of Days</th>
<th>Total Cost - Status Quo</th>
<th>Hours/Day</th>
<th># of Days</th>
<th>Total Cost - With Us</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial-Peak</td>
<td>0.093</td>
<td>3</td>
<td>131</td>
<td>$87.72</td>
<td>0</td>
<td>131</td>
<td>$0.00</td>
</tr>
<tr>
<td>Off-Peak (Weekdays)</td>
<td>0.084</td>
<td>21</td>
<td>131</td>
<td>$554.60</td>
<td>24</td>
<td>131</td>
<td>$633.83</td>
</tr>
<tr>
<td>Off-Peak (Weekends)</td>
<td>0.084</td>
<td>24</td>
<td>52</td>
<td>$251.60</td>
<td>24</td>
<td>52</td>
<td>$251.60</td>
</tr>
<tr>
<td></td>
<td>1.22</td>
<td>4.266666</td>
<td>6</td>
<td><strong>$803.92</strong></td>
<td>1.22</td>
<td>4.266666</td>
<td><strong>$882.43</strong></td>
</tr>
</tbody>
</table>

#### Demand Charge

<table>
<thead>
<tr>
<th>Rate</th>
<th>Max Usage Months</th>
<th>Total Cost - Status Quo</th>
<th>Max Usage Months</th>
<th>Total Cost - With Us</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Peak</td>
<td>1.22</td>
<td>4.266666</td>
<td>6</td>
<td><strong>$31.23</strong></td>
</tr>
<tr>
<td>Max</td>
<td>9.27</td>
<td>4.266666</td>
<td>6</td>
<td><strong>$237.31</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>$268.54</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Status Quo

- **Electricity Total**: $1,940.68
- **Demand Total**: $887.81
- **Total**: $2,828.48

#### With Us

- **Electricity Total**: $1,813.50
- **Demand Total**: $546.56
- **Total**: $2,360.06
- **Savings**: 16.56%

- 676.2 GWh in CA commercial blgs.
- 8986.318 Refrigeration (13.4%)
- 3552.292 Freezers (40%)
- $482,492,910.24 Total Cost ($0.1342/kWh for CA commercial)
- 16.56% Savings (%)
- **$79,905,023.80** Total Savings in CA (Value Created)
## Interviews

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Group, Organization</th>
<th>Topics Discussed</th>
</tr>
</thead>
</table>
| Andrew Bell          | Analysis & Rates Department, PG&E                                                   | ▪ TOU rate schedules  
▪ TOU rate penetration                                           |
| Aaron Breidenbaugh  | Regulatory Affairs, EnerNOC                                                           | ▪ Residential demand response  
▪ Ancillary service markets                                         |
| Rich Brown           | Environmental Energy Technologies Division, Lawrence Berkeley Labs                   | ▪ Potential partners/advisors  
▪ Existing work                                                        |
| Duncan Callaway      | Energy & Resources Group, UC Berkeley                                                | ▪ Ancillary services markets  
▪ Existing work                                                        |
▪ Licensing options                                                   |
| Len Conapinksi       | Former Patent Lawyer                                                                 | ▪ Patent process, costs and timeline                         |
| Jim Detmers          | Operations, CAISO                                                                    | ▪ Grid implications of renewable resource adoption           |
| Doug Frazee          | Energy, Environment & Transportation Consultant, ICF International                   | ▪ ENERGY STAR certification of demand response technologies |
| Don Fisher           | Food Service Technology Center                                                       | ▪ Applicability of technology to commercial segment  
▪ Commercial end-user requirements                                    |
| Ilan Gur             | Commercialization, ARPA-E                                                            | ▪ Technology partners                                       |
| Sila Kiliccote       | Demand Response Research Center, Lawrence Berkeley Labs                              | ▪ Communication requirements  
▪ DR pilot programs                                                   |
<p>| Paul Lipkin          | Akuacom                                                                              | ▪ Grid telemetry requirements                                |
| Amanda Stevens       | ENERGY STAR Appliance Program, EPA                                                   | ▪ ENERGY STAR certification process                         |</p>
<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Group, Organization</th>
<th>Topics Discussed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scott Welham</td>
<td>Advanced Technology, GE</td>
<td>• Refrigerator development cycle and pipeline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Consumer preferences</td>
</tr>
</tbody>
</table>