Cold Hard Facts About Metering Refrigerators That Aren't There

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ABSTRACT

For over a decade, program evaluators have considered how best to determine actual energy usage of refrigerators and freezers collected by utility turn-in programs to estimate program energy savings. While end-use metering is often regarded as a "gold standard" for such estimation, determining how to conduct this metering is challenging. Department of Energy (DOE) protocols for laboratory metering provide a standard basis for comparing units measured in different places and times using controlled settings. In situ metering measures individual units, reflecting the effects of varying in-home operating conditions. Both are intended to simulate "as operated" conditions.

We examine advantages and disadvantages of laboratory and in situ metering, drawing on prior studies. We report on the current state of the DOE protocols, which are the basis for appliances' labeled energy usage, and on the impact of changing standards. We then estimate the likely accuracy of population estimates based on different approaches, within budget and logistical constraints.

Based on this assessment, this study's approach is to leverage a large existing database of DOE-protocol measurements with a smaller sample of similarly metered units from the current program. The analysis develops a regression model to estimate what the laboratory measurement would have been for each unit collected by the current program. The sample of current units effectively gives an adjustment from the large pool of prior metering results to the current population.

The limitations of this approach are clearly identified. We describe the steps being undertaken by the California investor-owned utilities to address these limitations in future evaluations.

Background

For many providers of energy savings programs, refrigerator and freezer turn-in programs provide a significant share of energy savings and are a key part of their program portfolio. The energy savings from these programs derive from the consumption that is foregone when the unit is subsequently recycled or destroyed. Determining how much energy is saved from a unit that is no longer operating proved to be challenging and controversial in KEMA-XENERGY's recent evaluation of California's 2002 statewide Residential Appliance Recycling Program (RARP; KEMA-XENERGY 2004).

Approach Used in Evaluation of California's 2002 RARP

The evaluation of the 2002 RARP included an impact evaluation component. In this portion of the study, we collected new metering data from units picked up by the program, combined it with a large database of prior metering data from similar programs, and used the updated database to re-estimate annual Unit Energy Consumption (UEC) for those units collected through the 2002 program. A 1998 evaluation of the 1996 Southern California Edison program (Peterson 1998) took a similar approach.

Alternative Metering Approaches Considered

As noted, databases of metered refrigerator usage at the time of pickup for units collected by this or a similar program already existed at the start of the study. There were two reasons to conduct metering of a fresh sample of units recently collected by the program:

1. Because of changes over time in the efficiency of new units, the UEC of a unit that was of a certain age in 2003 was not the same as the UEC of a unit of the same characteristics that was that age in 1998. That is, a 20-year-old, 14-cubic-foot, single-door, manual-defrost unit observed in 2003 was not necessarily built the same as a similar unit that was 20 years old when observed in 1998.
2. Conversely, because of degradation of efficiency over time, the UEC of a unit of a given vintage is likely to be different in 2003 than it was in 1998, when the unit was 5 years younger.

At the same time, we wanted to use a sampling and analysis method that would allow us to take advantage of the existing metering database, rather than rely only on the current sample. In developing the study plan, considerable attention was given to the question of whether to devote the metering effort to laboratory or to in situ measurement or to a combination of both.

The laboratory measurements would be made according to a DOE test protocol (Code of Federal Regulations 10 CFR 430.27) that was designed to provide, in a few days of laboratory metering, results that could be extrapolated to a full year of typical usage. The lab metering protocols represent an attempt to have a simulation of conditions (such as door openings) that reflect typical usage effects. However, this protocol was first developed in 1967 and only minor changes have been made to it since then through revisions made in 1979, 1988, and most recently in October 2003. These changes are triggered by the expiration of the procedure approval at 10-year intervals. It is not clear whether it still provides realistic measures of actual annual use for new refrigerators or for the particular old refrigerators served by this program.

We also found in situ metering to be problematic. Program participants are ready to have their appliances removed. However, we want to meter the unit as it would be operated if it stayed in place and in use. Participants who are recycling a refrigerator because they have just bought a new one wouldn't be expected to be using the old one the way they would have if they'd kept it as a spare. Even units that have been used as spares all along may be operated differently once the decision is made to discard them. Moreover, the subset of participants who are willing to wait an additional two weeks or more for metering before the unit is taken away may not be representative of the general participant population. Further, except in the case of very long-term metering, weather adjustments are required, appropriate to the location of the appliance within the dwelling/garage and the existence/level of AC use within the dwelling.

The laboratory conditions are designed to simulate the effect of typical food loadings, door opening frequency, interior temperature setting, and surrounding temperature and humidity over the course of a year. A unit that's been taken out of use and moved from a kitchen or spare room into a back porch or garage will not reflect typical conditions for any of these factors. It's not clear a priori which approach is likely to lead to worse biases.

With any of the metering approaches, we would leverage the existing database of laboratory metering results with the new data. A first step would be to fit a model to the laboratory metering data to estimate metered UEC as a function of unit characteristics, including age, size, defrost type, and door configuration. This model would then be applied to each unit collected by the 2002 program. The result is an estimate of the UEC that would have been obtained if we'd metered each of these units by the DOE lab protocol at the time of pickup.

The leveraging approaches considered were as follows:

- **In situ only:** Calculate the ratio of average annualized in situ UEC to average model estimate of laboratory UEC for the metering sample. Apply the ratio to adjust the population average model estimate of laboratory UEC.
- **Double metering (in situ plus laboratory for the same units):** Calculate the ratio of average annualized in situ UEC to average laboratory UEC for the metering sample. Apply the ratio to adjust the population average model estimate of laboratory UEC.
- **Laboratory only:** Update the model of laboratory UEC using the new metering data together with the prior metering data.

The capabilities of the different approaches, and the affordable sample sizes within the project budget, are indicated in Table 1. After considering the pros and cons of the different methods, the project advisory committee agreed that for this project we would conduct laboratory metering only, and would also conduct a review of the available literature comparing in situ with laboratory metering. The review would indicate whether and how it might be appropriate to adjust the laboratory results to be more representative of actual usage for the units if left in place.

Table 1. Comparison of Alternative Metering Approaches

Approach Capability	Laboratory Only	In Situ Only	Double Metering
Extending Lab Test Model & Database			
Add current year points	X		X
Refit UEC model, apply to all 2002 units	X	X	X
Translating Lab to As-Operated			
Secondary sources, other regions & populations	X		
Model annualized in situ vs. modeled lab UEC		X	
Model annualized in situ vs. actual lab UEC			X
Translating to Full Year			
Weather model based on unit location in home	O	X	X
Affordable Sample Size			
Attempted	100	216	57
Successful	102	194	46

Source: Measurement and Evaluation Study of 2002 Statewide Residential Appliance Recycling Program (KEMA-XENERGY 2004)

Findings from Prior Studies

The literature review compiled findings from studies that used different metering methodologies under varying situations. These studies were completed between February 1992 and March 2003 for refrigerators only. However, most of these compared in situ or field metering with the label UEC, rather than with results from the DOE protocol applied to the same specific units that were monitored in situ. The label UEC is the result of the DOE protocol applied to units of the same or a similar model at the time it was new.

Predominant themes that emerged from a review of these studies were as follows.

- There was no systematic relationship identified between the label rating and in situ results. Therefore, there was no definitive basis present at the time the evaluation was conducted for making an adjustment (either up or down) to the lab-metered estimates of UEC made for the evaluation.
- The results of these studies pointed in different directions. Some studies found that the label overpredicted actual energy consumption; others showed the opposite, and still others were inconclusive.
- None of the studies reviewed involved a combination of conditions similar to those of the statewide RARP; namely:
  - Predominantly southern California climate,
  - Old and secondary refrigerators, and
  - DOE protocol and in situ metering conducted at (approximately) the same point in time for the same particular units.

Table 2 provides a summary of findings from these various studies. Based on these findings, no adjustment was made to the laboratory-based UEC estimates developed in the evaluation of the 2002 statewide program. While there is clearly broad variability between label and in situ results, there is no clear basis for adjusting laboratory results to be more representative of as-operated conditions. Efforts under the next round of statewide monitoring and evaluation activity may address this continuing uncertainty.

Literature reviews indicate that an unequivocal estimate of a gross, aggregate relationship between current DOE-based and in situ-based metering results for older, “recycling-prone” appliances is of course not available—supporting an argument for high-quality research into the relationship. While this need suggests a double metering approach, the resources of this study did not allow for a sufficiently large double metering sample to settle the question.

Table 2. Literature Review Summary

Source	Year	DOE Protocol vs. In Situ	Context	Use	# Units
Arthur D. Little, Inc.	1982	20% low	Florida	Primary	
Barakat & Chamberlin, Inc.	1996	15% – 22% high	Cite of E-source report		
Meier and Jansky	1993	10% – 14% high	Cold climates, relatively new	Primary	209
RLW Analytics, Inc., and The Fleming Group	1993	Inconclusive	Northeast, frost-free and manual	Secondary	58
Meier et al.	1993	13% high overall, low in summer	Rochester, NY, mostly frost-free	Secondary	20
Bos	1993	Low	SMUD turn-in program	Secondary	79
Quantum Consulting, Inc.	1994	Slightly high	SCE refrigerator rebate program	Primary	
Dutt et al.	1994	High	New	Primary	258
Goett	1995	Nearly the same	PG&E and SCE new	Primary	
Miller and Pratt	1998	28% low – 11% high	New York multi-family public housing	Primary	324
ICF Consulting	2003	90% high	CA Bay Area ("DOE" = model from previous evaluation)	Mix – some empty	22
Robert Mowris & Associates	2003	6% low but highly variable	6 cities in Northern CA	Primary	8

Meter Study Sample

Sample design. The metering sample was designed to represent the population of units collected by the 2002 program; that is, using 2002 program funds. However, since metering was conducted in 2003, only units collected in 2003 were available for metering. For this reason, the sample was designed according to the distribution of units collected using 2002 program funds as of February 26, 2003. Units were selected according to that design from units collected between May 19, 2003, and October 17, 2003. Many of these units were still collected using 2002 program funds and count toward that program year's accomplishments. While no major changes are anticipated between the 2002 and 2003 programs years, there could be some shifts in distributions.

The metering sample was stratified by

- Unit type (refrigerator or freezer),
- Size (cubic feet category),
- Defrost type (manual, automatic, partial),
- Configuration (single door, side by side, top freezer, bottom freezer, chest freezer, upright freezer), and
- Age.

The 100 units of the sample were allocated to the sampling cells using approximate modified Neyman allocation (Cochran, 1977, e.g.). Neyman allocation provides the best possible accuracy for the sample-based estimate of average UEC for the 2002 program year. This gives us the most accurate possible stand-alone estimate from the sample, without considering the potential gains from leveraging the already existing data.

Sample implementation. The targeted quotas by sampling cell had to be met by units as they were being taken from the field, since previously collected units had all been destroyed. In-field selection procedures were designed to randomize selection as much as possible within cells, and limit the potential for convenience sampling or tampering without extreme burden on recycling field operations. The procedure to fill the sample quotas was essentially to select a truck and day at random, then take units from the selected truck that belonged to unfilled sampling cells. Specific steps were as follows:

- The refrigerator recycler provided the evaluation team with a list of the units that were scheduled for the following one to two days' pickups. These lists contained detailed information on the units scheduled for pickup.
- Evaluation staff randomly selected trucks from which metered units were to be pulled.
- The recycling contractor notified its drivers of the truck selection and directed them not to go through the normal procedures for the units collected on that truck that day. Normal procedures include disabling each unit at the time of the pickup.
- These trucks were driven back to the recycler's facility, where unit information was confirmed. The detailed confirmed unit information was then emailed to the evaluation team. Units on the truck that fell into unfilled sampling cells were selected for metering. If there were more such units on the truck than were needed to fill the cell, evaluators randomly selected enough to fill the cell.
- The selected units were then taken to the metering laboratory.

Units delivered to the laboratory were metered according to the DOE test protocol. In some cases, a unit could not be brought to a stable temperature. These units were excluded from the final metering database. In addition to the sampling cell identifiers, data provided for each metered unit included the UEC and model number.

UEC Model

The purpose of the UEC model is to provide a basis for estimating what the laboratory UEC would have been for each unit collected under the 2002 program. This model utilizes data from 1,143 units metered by the Appliance Recycling Centers of America (ARCA) between 1992 and 1995, together with 136 units metered by Southern California Edison in 1998 and the 100 units from the new metering sample. We refer to the new metering sample as the 2002 sample since it was drawn for the 2002 program, though the metering was conducted in 2003.

The model developed in this study builds on the prior model developed in the 1998 study. This prior model is described first. This model establishes the logic of leveraging a small sample from the current program with the large existing database. Similar logic applies to our use of the 2002 sample together with the two prior samples.

1998 UEC model. The model developed by Peterson (1998) for the 1998 metering study used the 1,143 ARCA units together with the 136 units from the 1998 sample. This model used the large database of prior metering to support an estimate of UEC as a function of unit type (refrigerator or freezer), door configuration, defrost type, age, and amperage. The model also included some interactions among these terms, determined to be important on theoretical and/or statistical bases.

A dummy variable indicating that the unit was in the 1998 sample was also included in the 1998 model. This variable accounts for ways that the prior metered units may be systematically different from the current population, after the other characteristics are accounted for. Reasons for differences between the prior data and the 1996 population could include the following:

1. Both vintage (characteristics of units built in a particular time period) and age (degradation or other changes over time) could affect UEC. Thus, an age variable can have a different meaning for units observed in 1998 than the same age would indicate for units observed between 1992 and 1996.
2. Units of particular characteristics in the Southern California Edison service territory may be different from corresponding units from other areas as a result of environmental or usage factors.
3. The original data were collected by ARCA, not by an independent third party. While there was no specific reason to suspect manipulation or bias in the sample, the inclusion of the 1998 sample dummy would account for any systematic differences related to sampling or other bias.

Developing the 2002 Model

Extending the 1998 model. The same types of factors that could make the 1998 SCE UECs different from those of the prior metering database could make the 2002 program UECs different from those that would be indicated by the 1998 model alone. We therefore developed a new model that used all the data from all three sources and included coefficients representing "adders" for 2002 units.

We explored a variety of forms for a model combining data from each of the three sets of metering data. The most direct extension of the 1998 model used all the same terms, plus an additional set of "new sample" terms for the 2002 sample. For each of the terms involving the 1998 sample dummy in the 1998 model, we added a corresponding term for the 2002 sample.

Alternative specifications. We examined alternative specifications with an objective of simplifying the UEC model. A consideration in attempting this simplification was that the goal of this analysis is to evaluate a particular program, not necessarily to develop a model that will be well suited to other applications. An additional reason to simplify the model was that we now have two sampling cohorts (the 1998 sample and the 2002 sample) for which effects must be estimated, both with a relatively small sample size. That is, we need one set of coefficients that will say how the UEC of a 1998 unit differs from that of the prior sample, all else being equal, and another set saying how the UEC of a 2002 unit differs from the earlier ones. In general, increasing the number of different terms in a model increases the standard error of the UEC calculated from the fitted model.

Inclusion of the age term required particular attention. There are three related effects of interest in the analysis:

1. The effect of age on UEC, controlling for other factors. That is, how much does UEC increase or decrease with age, all else being equal.
2. The effect of vintage (year of manufacture) on UEC.
3. The effect of sampling cohort (being drawn from the 1998 or 2002 population) on UEC.

Within any one sampling cohort, age and vintage are direct translations of one another; it is not possible to distinguish an age effect (a particular unit's UEC changes as it ages) from a vintage effect (units manufactured in different years have different UECs at the same age). With multiple sampling cohorts, we have units from each vintage observed at more than one age. We can therefore identify age and vintage effects separately, but only if we assume there is no sampling cohort effect. The sampling cohort effects are the ways the 1998 SCE population or the 2002 statewide population is different from the populations represented by the prior samples, apart from the characteristics controlled for in the model. Alternatively, if we wish to estimate the sampling cohort effects, we cannot distinguish age from vintage.

Because we have a definite interest in estimating sampling cohort effects, we can estimate age or vintage effects, but not both. We chose to work with age, in part because the age data are somewhat more natural. At any time units are collected, their ages tend to be reported in five-year increments.

We found that the logarithm of age had slightly better explanatory power than did the square root of age, which was used in the 1998 model. A further improvement was obtained by truncating the age at 20 years. That is, units that survive more than 20 years do not show continuing increase in UEC with age beyond that.

The strongest alternative model to the expanded 1998 model was developed by a combination of statistical diagnostics and a desire to have certain effects explicitly estimated, even if with low precision. We also examined the effect of alternative specifications on the estimated UECs by subgroups of potential interest.

In the final model, the age term is included only for frost-free units. We attempted to estimate separate age terms for frost-free and manual-defrost units. These units were expected to age differently because the frost-free have different mechanics. However, the non-frost-free age term was small, negative, and not at all statistically significant. We therefore dropped the non-frost-free age term. This decision does not mean that we believe there is no effect of age on UEC for non-frost-free units. It simply means that, with the available data, we are not able to estimate this effect.

The final model included two terms that were not statistically significant, but were conceptually important:

- **1998 sample dummy:** The model estimates by subgroup were essentially unchanged whether or not this term was included. This stability is consistent with the lack of statistical significance of the term. We retained the dummy in the final model so that this model would show explicitly that there was no statistical evidence of a difference between the 1998 sample and the prior samples.
- **Freezer dummy:** The model estimates by subgroup, including refrigerators as a group and freezers as a group, were essentially unchanged whether or not this term was

included. The term also was small in magnitude. We retained the term in the model because a separate estimate of freezer UEC was an explicit objective of the analysis. Thus, even if the effect was small, we wanted to include it.

The final model specification is shown in Table 3.

Table 3. Model Coefficients for the Reduced Model

Variable	Coefficient	Standard Error	T-Value
Intercept *	456	192	2.37
Frost-Free Defrost Binary *	-49	221	-0.22
Top-Freezer Binary *	-416	107	-3.89
Frost-Free/Side-by-Side Binary *	1,196	388	3.08
Manual Defrost/Single-Door Binary *	-601	128	-4.68
Partial Defrost/Top Freezer *	348	126	2.77
Label Amperage *	116	22	5.21
Volume in Cubic Feet *	43	11	4.09
Amperage/Side-by-Side Interaction *	-163	55	-2.99
Freezer Binary *	24	122	0.2
Natural Log Truncated Age/Frost-Free Interaction +	294	68	4.35
1998 Metering Sample Binary	-41	73	-0.57
2003 Metering Sample Binary +	-432	83	-5.23

n = 1,378 Adjusted R2 =0.4534
* – In 1998 and 2003 Final Model
+ – Added/Changed from 1998 Model

The final model results indicate the following:

- The coefficients of the 1998 dummy and its interactions are not statistically significant. This result indicates that there is no systematic difference between the 1998 sample and the earlier ARCA samples once the other characteristics are controlled for.
- The 2002 sampling cohort dummy is statistically significant. Thus, there is a difference between the units being turned in for the 2002 program compared with those turned in for earlier programs, even after the other characteristics are accounted for.
- For frost-free units, UEC increases with age.

Population UECs from alternative models. As noted, a consideration in selecting the final model was not only the statistical precision of the coefficients, but also the effect of alternative specifications on UEC estimates for the program and for subgroups of interest. This model provides similar UEC estimates by subgroup to those from the primary competing specifications, with standard errors as approximately as good or better for the subgroups of interest. Subgroups considered were unit type crossed with each of defrost type, door configuration, size category, and age group. Estimates for these subgroups were generally quite stable across the alternative specifications considered. The final model selected provided certain distinctions that were important, as described above. The statistical accuracy of the subgroup UECs from the final model was approximately as good or better (standard errors approximately as small or smaller) as the accuracy for the other model forms tried.

Of particular interest as a competing model was the weighted average of the 2002 metering sample alone. This weighted average is an unbiased estimate for the current population. The 2002 sample was designed to provide as good accuracy as possible for this stand-alone estimate. However this estimate does not leverage the larger data set. Ideally, the leveraging should provide estimates that are both more meaningful and better estimated (smaller standard errors).

The leveraged estimates, that is, those from the final model based on all three data sets, are more meaningful in the sense that they take into account the specific characteristics of all the units in the 2002 program, rather than relying only on the random sample of 100 to represent these units. The leveraged estimates also have smaller standard errors for the key subgroups of interest, as shown in Table 4.

Table 4. Leveraged UEC Estimates from Final Model (kWh/year)

	Number		2002 Weighted Average		Final Model Estimate	
Subgroup	**2002 Population**	**2002 Sample**	**UEC**	**Standard Error**	**UEC**	**Standard Error**
All Units	42,945	1,379	1,980	82	1,915	77
Refrigerators	4,735	137	1,817	207	1,662	101
Freezers	38,210	1,242	2,000	88	1,946	77

The improvement in accuracy is modest for refrigerators, and for the overall program, which is about 90 percent refrigerators. The improvement for freezers is much more substantial: the standard error for freezers as a group was twice as high using the weighted sample alone, compared to that for the leveraged model. There are only 10 freezers in the 2002 sample. Hence, this stand-alone sample is not a very sound basis for estimating typical freezer UECs.

Similarly, the leveraged model provides estimates with good accuracy for smaller subgroups, such as refrigerators or a particular age, size, or configuration, that have few or no cases in the 2002 sample. These subgroups would have a poor estimate or none relying solely on the 2002 data.

Changes from previous program. The average UEC of units in the 2002 program based on the final model estimate is 215 kWh lower than the average for the 1996 program. Part of this difference is due to the different mix of size, age, defrost type, and configuration. However, the 2002 model results also show that the units being collected in the current program tend to have lower UEC than units of similar characteristics collected in earlier programs. Alternative ways of calculating the magnitude of this difference are presented in Table 5. The table shows that the current program UEC is on the order of 300 kWh lower than would have been predicted for these units based on the earlier sample data alone, regardless of the modeling approach used.

Table 5. Alternative Estimates of the UEC Reduction

Measure of Difference	Measure of Difference	Standard Error
Weighted 2002 Sample Mean vs. 1998 UEC Estimate	-268	106
Final 2002 Model UEC Estimate vs. 1998 Model	-333	
1998 Model with vs. without 2002 Cohort Term	-341	
1998 Model Incremental 2002 Cohort Term	-421	82
Final Model 2002 Cohort Term Minus 1998 Cohort Term	-390	110

Conclusions

The key substantive finding from the analysis of metering data is that the average UEC of units being collected by the 2002 program has dropped by about 215 kWh compared to that determined previously for the 1996 program. This finding is consistent with an observed reduction in the average age of units being collected by the program. In addition, the average UEC determined for the 2002 program is about 300 kWh lower than would have been estimated for these units using the 1998 model. This finding illustrates the importance of continuing to collect new metering data from current programs.

At the same time, the analysis shows that leveraging the existing large database of lab metering can provide better UEC estimates both for the program overall and for subgroups of interest, compared to relying on the small stand-alone metering sample from the current program. On the other hand, the relationship between the laboratory-based UEC and usage of these units as they would have been operated if left in place merits further study.

As we write this paper, there is new data collection activity planned for this program. This data collection will use a dual metering approach to address questions about the most effective approach to estimate gross savings for the program that satisfies conditions of validity as well as reliability of estimates. A sample of refrigerators will be metered both in situ and in a DOE test protocol laboratory setting such that in situ-metered data can be used to make any needed adjustment to gross savings estimated through laboratory-metered data.

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