The California Residential Water Heating Project

David A. Springer and Richard C. Bourne, Davis Energy Group, Inc.

This paper reports on a two year project initiated by the CEC to evaluate potential improvements in residential water heating compliance methods and recommend appropriate revisions to the California Title 24 residential energy standards for water heating. The scope included technology status review, identification of research needs, detailed research and analysis, and development of a compliance method. Project research categorized and quantified sources of water heating energy use, and concentrated on water heater standby loss and piping distribution loss. Assessments were made of hot water use dependence on building size, and a "load dependent energy factor" concept was developed to modify standard water heater energy factor ratings for more accurate estimation of standby loss impacts on overall system efficiency.

As a result of this research, a typical relationship between water heating load and dwelling size was developed from monitoring data reported by others. Resulting project data indicated reduction of standby losses from center flue gas water heaters to be the most promising opportunity for water heating system improvement. Distribution losses were found to be highly dependent on plumbing system configuration and hot water use patterns. Improved distribution systems were identified, and corresponding Title 24 credits were developed. The proposed compliance methodology was adopted for the 1992 Building Energy Efficiency Standards.

Introduction

Changes in federal regulations, new information on water heating energy use, and availability of new water heating technologies prompted the CEC in 1989 to begin a two year project to review and revise the Title-24 residential water heating standards. Under California's 1988 Residential Building Energy Standards (CRBES), water heating energy budgets are fixed for each of sixteen climate zones and based on 35 gallon (multifamily) and 50 gallon (single family) per day usage. For compliance, projected water heating, and space heating and cooling energy use, in kBtu/ft^2 per year, are summed for comparison to a total energy budget.

Though water heating energy budgets under the 1988 CRBES exceed total space conditioning budgets in five of sixteen climate zones (for the 1384 ft^2 "base case" house on which standards are based), 1988 water heating standards are not as well founded as space conditioning standards, which are based on detailed building specifications and simulation models. With hot water use independent of house size, large houses have unrealistically low energy budgets, and vice versa.

The Water Heating Project was organized to evaluate potential improvements to residential water heating standards and compliance methods. Specific objectives included improving accuracy, simplifying calculations, and insuring compatibility with new U.S. standards. Accuracy improvements were desired in part to provide additional incentive for energy conservation. Simplification was desired because compliance for the most efficiency measures required lengthy computations.

Project scope included technology status review, identification of research needs, detailed research and analysis, and development of a compliance method. The Water Heating Project was divided into three phases. The first phase reviewed water heating technologies, existing compliance methods, and changes to federal standards. A literature search was conducted, key issues were defined, and a framework for subsequent analyses was presented. The second phase completed recommended research and developed the basic structure of a revised compliance method. A detailed compliance method was developed in the third phase.

Methodology

Preliminary Research

A preliminary report (Davis Energy Group, Inc. 1991) was prepared summarizing current water heating systems, performance data sources, current regulations, and water heating issues. This preliminary work included the development of a hot water system energy flow diagram, a review of standards and recommendations for a project research plan.

An energy flow diagram was constructed (Figure 1) to provide a framework for subsequent project activities. The flow diagram accommodates both combustion and electric (resistance and heat pump) heat sources. The CRBES are "source energy" based; for combustion heat sources, source and property line energy are considered equal, while for electrical systems, a fixed source energy conversion (1 kWh=10,239 Btu) is applied. Roles of the flow diagram components were discussed for major water heating technology alternatives. Auxiliary energy sources (wood, solar, heat recovery) and energy conservation technologies were identified and energy flow impacts were discussed.

The "fixture and appliance energy use" term accounts for total end use energy at fixtures and appliances, and depends upon the quantity of hot water drawn and the temperature difference between cold water entering the water heater and unmixed hot water at the use point. "Distribution losses" include heat lost from distribution piping and energy losses associated with hot water which cools in the lines and is subsequently wasted. "Recovery efficiency loss" is the burner input energy which is not converted to useful energy output. (For heat pump water heaters the recovery loss arrow in Fig. 1 can be treated as an energy gain.) "Standby loss" is a measure of water heater energy use while not heating water, and includes heat losses from insulated jacket, connecting fittings & piping, and flue (if any). Standby loss, by definition, includes additional recovery energy required to compensate for water heater efficiency losses. "Auxiliary system inputs" (solar, wood stove boilers, and heat recovery systems) decrease water heater fuel use by directly applying heat to the recovery load and sometimes standby losses as well. "Generation and transmission losses" occur in providing electricity to the building. California Title-24 standards assume a generation/transmission efficiency of 33% for electricity (gas is assumed to be 100%).

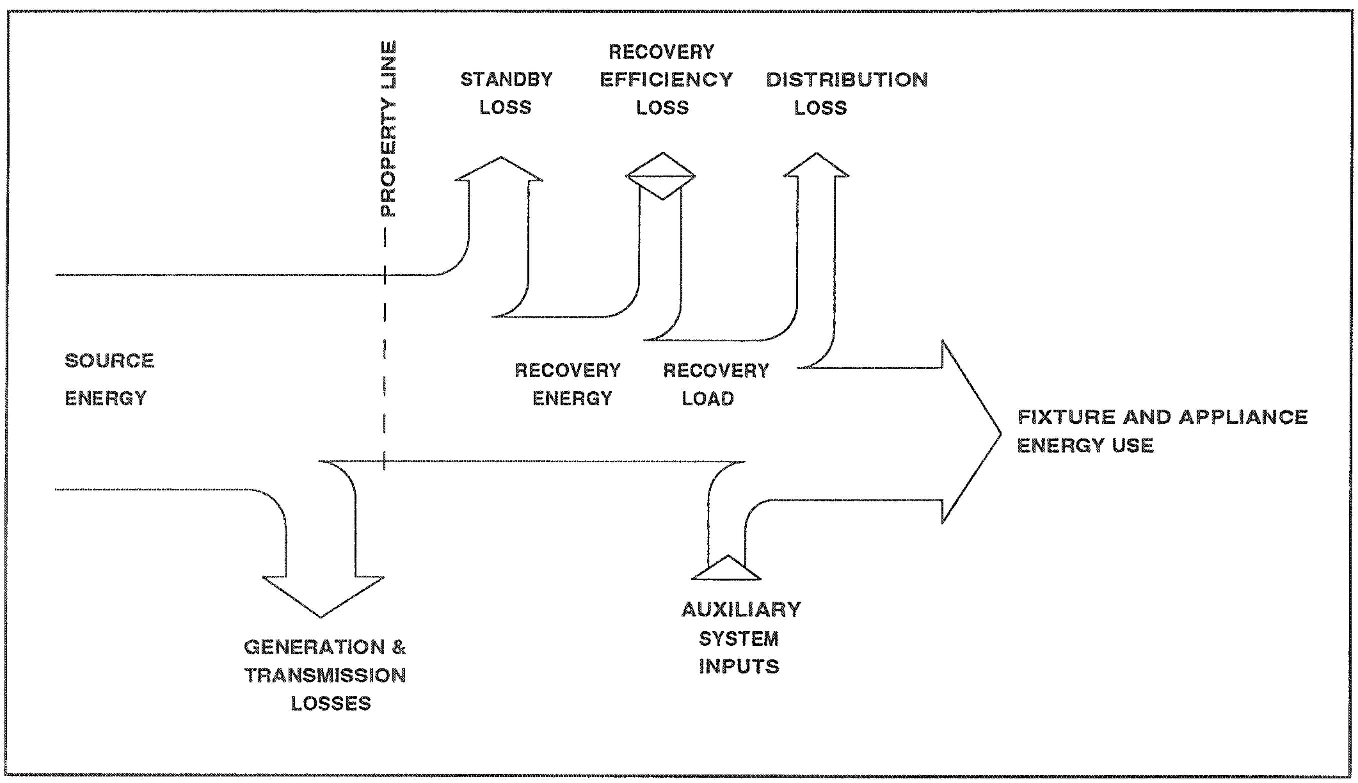

Figure 1. Basic Energy Flow Diagram

The preliminary report discussed major residential water heating energy issues categorized by the energy flow diagram components shown in Fig. 1. A research plan was proposed to generate required data related to key issues, with emphasis on assessing use variation with dwelling unit size, estimating distributing piping energy losses, and assessing whether water heater energy factors should be adjusted for water heating load. A technical literature search was conducted which concentrated on prior field monitoring of hot water use, hot water energy use, and system efficiencies. The research plan described how reference data would be used to meet research objectives.

Under the 1987 National Appliance Efficiency Conservation Act (NAECA), the CEC was required to adopt federal water heater appliance standards which prescribe minimum energy factors based on tank volume and water heater type. The 1988 CRBES are based on recovery efficiency and standby loss test parameters. The preliminary report also reviewed NAECA impacts on California water heating budgets and compliance methods, including non-uniformity of federal test parameters with values used in California compliance assumptions, such as hot water use quantity and supply temperature.

Detailed Research

Issues identified in the preliminary report formed the basis for detailed research. Research included development of a relationship between dwelling unit size and water heating load, development and application (for three typical residences and various load patterns) of a hot water system computer model; and development of a process to derive load dependent energy factors (LDEF's) for major water heater types applied to a range of water heating loads.

From more than fifteen "residential water heating loads" data sources, two California sources were selected as most relevant for standards development. CEC annual end use data from 30 gas water heater homes from the 1990 Residential Building Monitoring Project (Berkeley Solar Group and Xenergy 1990) became the primary data source. The secondary source was Pacific Gas & Electric Appliance Monitoring Project data for 53 homes with electric water heaters, all located in five coastal climate zones (Brodsky and McNicholl 1987). The CEC data were preferred for their statewide distribution and gas heat source, the predominant water heating fuel in California population centers.

While water heating loads typically correlate better with number of occupants than with floor area, number of occupants is neither fixed nor determinable by building officials performing plan checks. Therefore, regression analyses were completed on the data sets to derive load/floor area relationships.

Other research (Schultz and Goldschmidt 1983) indicated use pattern is also a determinant of water heating energy use. Seven weekly patterns with varying load magnitude, number of draws, and time of use pattern (either with or without daytime use) were developed to generate a broad range in both pattern and use magnitude. Table 1 summarizes the characteristics of six of the profiles which were analyzed in detail.

Piping distribution loss varies with pipe length, diameter, pipe wall conductivity, surrounding conditions, water temperature, and flow rate. Distribution losses may be sorted into "surface" and "waste" categories. Surface losses occur through pipe walls. Waste losses occur when previously heated water has cooled below the desired use temperature and is wasted at fixtures.

A computer model (in Basic code) was developed to analyze piping heat losses for any specified plumbing "tree," with fully variable main/branch specifications. Each branch terminates at a plumbing fixture; one of three draw "types" is specified for each fixture. Type 1 draws (shower) require a user-specified use temperature; water below the use temperature is wasted. Type 2 draws (bathtub) are mixed to a desired use temperature and imply no waste losses. Type 3 draws (washing machines) use all water flow, regardless of temperature. For a specified daily or weekly hot water use pattern, the model tabulates both surface and waste losses. To develop heat loss decay constants used in the model, water temperature measurements were taken on two existing homes with piping in concrete slab and raised wood floor locations.

The six alternate hot water load patterns were modelled for three sample dwelling units (1384 & 2545 ft^2 one story, and 1997 ft^2 two story). The 1384 ft^2 and 1997 ft^2 plans have been used for standards development and "approved compliance method" certification by the CEC. The 2545 ft^2 plan was selected to represent a house with widely distributed fixtures and long piping runs. The one story units were modelled with both slab and raised floors.

Hot water loads lower than the 64.3 gal. per day basis of DOE energy factors (Department of Energy 1990) result in lower net water heater efficiencies because standby losses consume a larger portion of water heater input energy. Accordingly, the term "load dependent energy

Table 1. Hot Water Use Patterns

Use Pattern	Ave gpd	Average draws/day	Daytime Loads	Other
I	29	12.0	no	
II	43	17.7	yes	
III	52	21.0	yes	
V	67	25.1	yes	
VI	100	34.9	yes	stndrd tub
VII	101	33.9	yes	large tub

Table 2. Monitored Hot Water Use Quantities

Reference	Sample Size	Average Use (gpd)
Usibelli 1984	---	59-63
Perlman & Milligan 1988	5 multifamily bldgs	64
Merrigan 1988	98 houses	57-61
Gilbert Assoc. 1985	110 houses	66
Kempton 1984	7 houses	68
Perlman et al. 1984	58 houses	63
Diamond & Szdlowski 1987	4 multifamily bldgs	61
Decicco 1986	60 multifamily units	22
Barvir et al. 1981	15 houses	61

factor" (LDEF) was coined to describe an adjusted energy factor at recovery loads other than the DOE test value (64.3 gal. at 77°F rise).

To quantify the relationship between LDEF and recovery load, LDEF's were calculated for representative sets of gas, electric resistance, and heat pump water heaters. From these data, equations were developed which yielded the best fit of the LDEF's calculated for the individual water heaters as a function of recovery load and DOE energy factor.

Compliance Method

A compliance method, developed using data developed from the detailed research, was presented in a project technical report (Davis Energy Group, Inc. 1990). The method included floor area-dependent water heating source energy budget and recovery load, based on DOE-minimum efficiency gas water heaters with R12 external blankets. Modifiers were proposed to provide credits for energy-conserving hot water distribution systems. The proposal served as a basis for public discussions prior to design of a detailed compliance method.

Results

Water Heating Loads

Table 2 lists average gallons per day hot water use conclusions from 9 sources. The "gallons per day" measure ignores inlet and outlet temperature impact and is therefore less precise than "Btu/year recovery load," but is used here because of its familiarity, and because many studies did not provide temperature data.

Table 2 emphasizes the general trend in the literature toward typical single family home hot water use in the 55-70 gallon per day range. Multifamily results have ranged more widely, probably due to the greater variance of washing appliances, water heating system types, hot water distribution systems, and utility payment responsibilities in multifamily buildings.

Fig. 2 compares "source" energy use in MMBtu/yr (MMBtu = Btu x 10^6) vs. floor area for CEC and PG&E data. Approximate equivalent total recovery volume in gallons is shown on the right scale.

The CEC and PG&E (AMP) data sets show similar hot water energy use dependence on floor area (i.e. regression line slopes are similar). This conclusion was reassuring and supported development of a revised compliance method reflecting use quantity dependence on floor area. The CEC data however, shows lower hot water energy use than the PG&E data. This result may be due to full penetration of low flow fixtures in the newer homes of the CEC sample.

There are several possible explanations for relatively low hot water energy consumption in new California homes. The mild climate results in higher inlet water temperatures and in lower distribution and standby losses. Mandated features (low flow fixtures, tank jackets, and "near-tank" pipe insulation) reduce use quantities and standby losses. California appliance efficiency standards, which until NAECA implementation have been more stringent than federal standards, may have resulted in improved water heater efficiency and reduced end use.

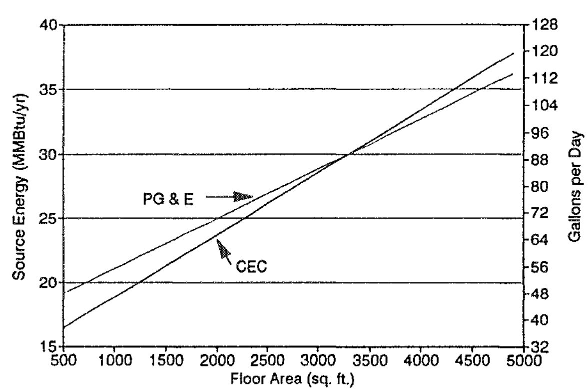

Figure 2. CEC & PG&E Energy Use Data

The paradox of establishing low hot water energy budgets is that low budgets reduce the potential savings margin and the apparent cost-effectiveness of hot water system energy conservation measures. Therefore, logic supported selection of water heating energy budgets consistent with the CEC data levels. The CEC line in Figure 2 was recommended for use in the compliance method.

Multifamily dwelling unit hot water use trends should not differ significantly from single family units. As for single family units, apartment hot water use should be proportionate to the number of occupants, and therefore floor area. This project did not develop separate multifamily water heating energy use vs. building size relationships since the PG&E and CEC data sets did not include multifamily units. A key difference between single family and apartment units is that individual apartment units seldom have clothes washing machines. However, apartment buildings usually include central on-site laundry facilities, such that project hot water use per unit floor area may be comparable to that for single family units.

Distribution Systems

Table 3 summarizes load magnitude and use pattern impacts for the just the one story 1384 ft² house and the 1997 ft² house (both slab on grade). Results are shown as both "percent of property line source energy" and "annual MMBtu's" of recovery load (as defined in Figure 1, MMBtu = Btu x 10^6) for a nominally complying storage gas water heater.

For the full range of cases analyzed, projected distribution loss (DL) ranged from 3.7% to 11.4% (9.4% for the base case) of property line energy, and from 0.58 to 3.75 MMBtu's per year (2.55 MMBtu for the base case). In 80% of the cases, DL was between 7.1% and 10.0% of property line energy. Projected DL ranged from 7.8% to 26% of recovery load (18% for the base case). DL was found to be the smallest energy use component on the flow diagram in every storage gas water heater case evaluated. Apportioned over building floor area, projected DL ranged from 0.29 to 2.21 KBtu/year-ft².

Table 3. Distribution Loss Results Summary

Floor Area	Avg gpd	Daytime Loads	DL% of Source	Annual DLMMBtu
1384	29	No	7.9%	1.32
	43	Yes	10.3%	2.13
	52	Yes	10.6%	2.44
	65	No	8.6%	2.30
	67	Yes	9.4%	2.55
	100	No	8.3%	2.98
1997	29	No	3.7%	0.58
	65	No	4.0%	1.00
	67	Yes	4.1%	1.04
	101	Yes	4.5%	1.52

Modelling of different distribution system energy efficiency measures using the 1384 ft² house were used to develop annual energy credits for compliance purposes. Table 4 lists the measure types evaluated and corresponding energy savings percentages for the 1384 ft² CEC plan, and are relative to a total distribution loss of 2.56 MMBtu/year (23% of recovery load and 12% of source energy use). "Hot water recovery devices" which draw hot water from piping back into the hot water storage tank were not evaluated due to complexity, but were assigned the same credit value as point-of-use water heaters. Except for "demand" systems, recirculation system "savings" assume application of R-4 pipe insulation to recirculation piping.

Table 4. Distribution Loss Energy Efficiency Measures and Savings

Measure	Definition	Percent Savings
Point of Use	Fixtures less than 8' from water heater	80
Parallel Piping	Direct small diameter piping runs from water heater to each fixture	63
Pipe Insulation	R-4 insulation applied to all mains 3/4" and larger	33
Recirculation Systems	Timer controlled pump	-120
	Temperature controlled pump	-22
	Timer & temperature controlled pump	16
	Pump controlled "on demand"	7

In summary, studies conducted using the distribution loss (DL) model suggest:

(1) DL, as a percentage of source energy, is not strongly affected by load magnitude.

(2) DL, both as a percentage of source energy and in absolute energy terms, typically increases as recovery load increases, since distribution piping contains hot water more frequently with higher loads.

(3) DL is higher if loads are distributed throughout the day than if they are concentrated in the mornings and evenings.

(4) DL is can be lower for two story than for one story houses due to more compact piping layouts.

A key conclusion drawn from these results is that differences in piping system design, chiefly associated with the number, length, and orientation of mains, can have a major impact on distribution loss.

Heat Sources and Energy Flows

Standby loss as a percentage of property line energy varies substantially with recovery load since absolute standby loss is relatively fixed (as recovery load falls, standby loss percent increases). "Load dependent energy factors" (LDEF's), computed by dividing recovery load (end use plus distribution loss) by property line energy can cause considerable EF degradation at low recovery volumes.

Figure 3 plots typical LDEF's vs. recovery load for both storage gas and electric water heaters. Storage electric LDEF's are much higher than storage gas values due to lower standby losses. However, the 3.0 source energy multiplier for electrical energy use, reduces LDEF's to 1/3 of their value in Fig. 3.

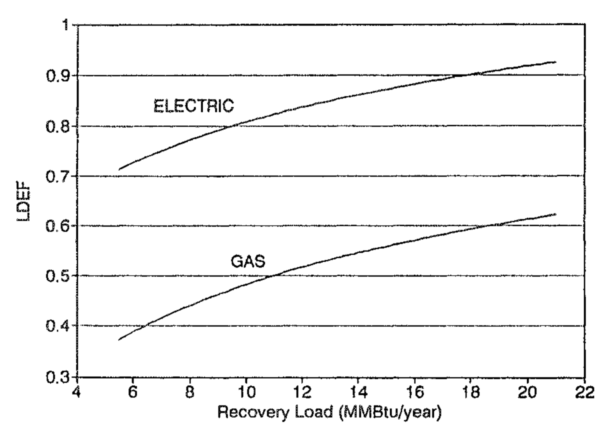

Figure 3. LDEF vs. Annual Recovery Load

Energy flow diagrams are shown in Figs. 4 and 5 for storage gas water heaters with 29 and 67 gallon per day recovery volumes. Labels indicate absolute and percentage source energy flows in MMBtu's per year.

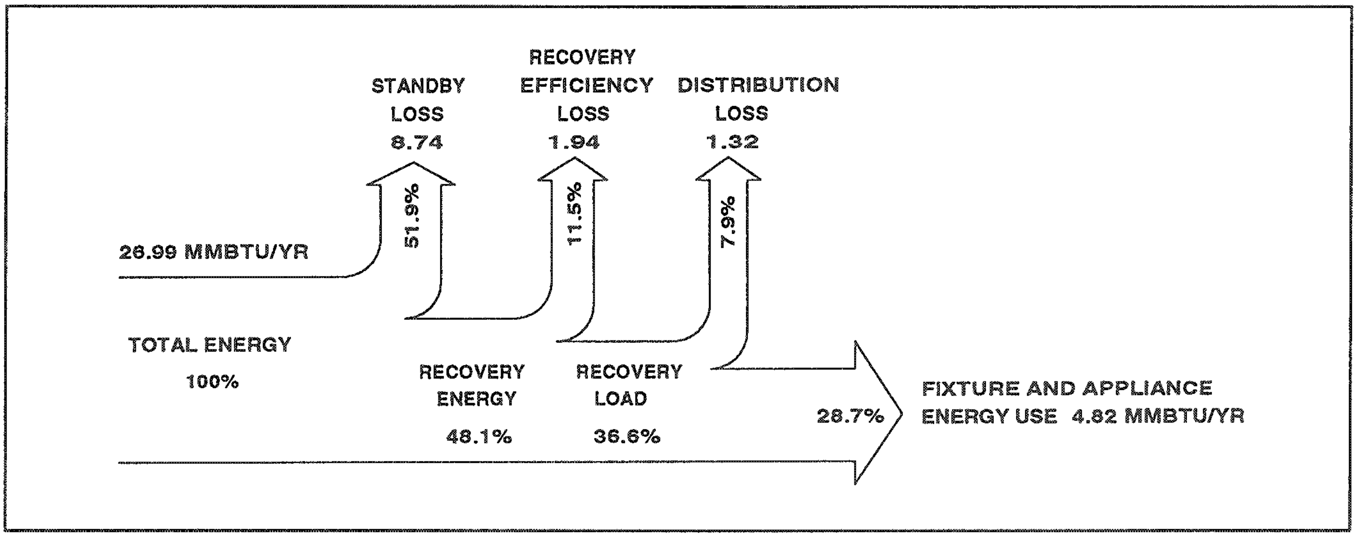

Figure 4. Energy Flow Diagram, Gas Water Heater, 29 gpd Recovery Volume

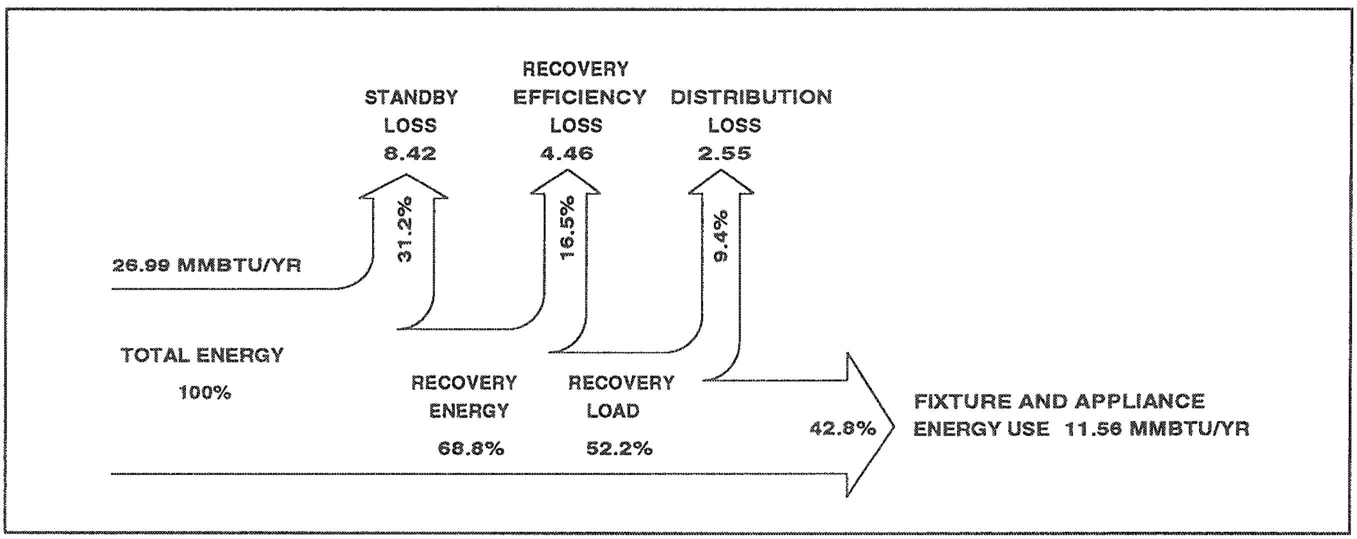

Figure 5. Energy Flow Diagram, Gas Water Heater, 67 gpd Recovery Volume

Figs. 4 and 5 show graphically the inefficiencies of current storage gas designs applied to small loads. At the 29 gallon per day recovery volume, only 28.7% of input energy becomes end use energy, compared to 42.8% at 67 gallons per day. While distribution loss percentage increases slightly over the range, recovery loss increases more noticeably and standby loss percentage falls dramatically. At 29 gallon per day recovery volume with a standard storage gas water heater, projected standby loss is almost twice end use and more than four times both recovery efficiency loss and distribution loss.

Fig. 6 shows the 29 gallon per day electric water heater energy flow diagram. All loss values are lower percentages of source energy for electric water heaters than for gas because of the source energy conversion factor. Relative to property line energy use, standby loss and recovery efficiency are lower and distribution loss is higher for electric than for gas storage water heaters.

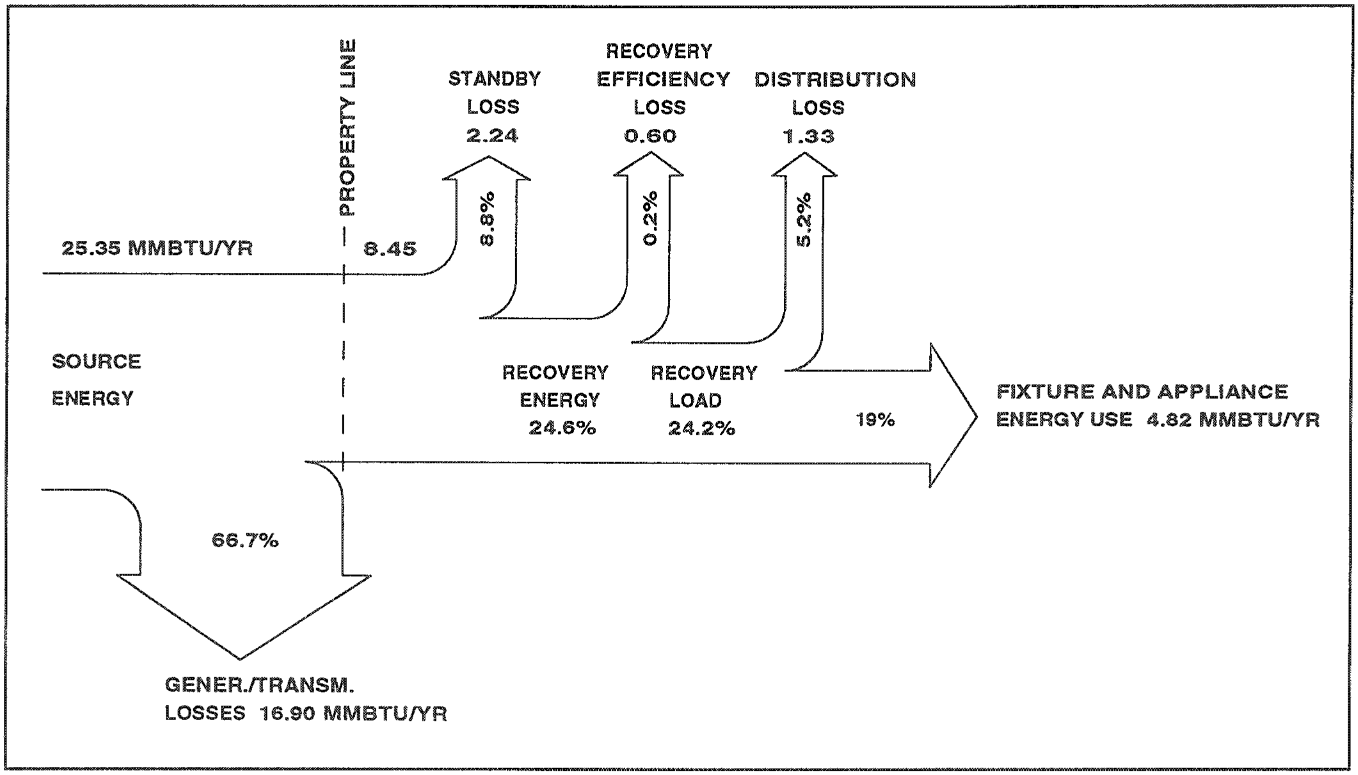

Figure 6. Energy Flow Diagram, Electric Water Heater, 29 gpd Recovery Volume

Conclusions and Compliance Method

Key research conclusions were incorporated into the 1992 CRBES compliance methodology. Major conclusions and resulting compliance method development approaches are listed below:

(1) Water heating budgets and recovery loads vary with floor area.

A "standard energy use" equation was developed, based on regression analysis of CEC gas water heater monitoring data. Recovery load-floor area relationships were developed based on the efficiency of a 50 gallon federal minimum EF water heater with an external R-12 insulating blanket, from standard energy use.

Equation 1 defines the floor area (FA) dependent relationship for water heating source energy budget. Equation 2 for calculating recovery load is based on the LDEF concept presented in Section 4.2.3.

Equation 1: Source MMBtu/year = $14.0 + 0.00485 \times FA$

Equation 2: Recovery MMBtu/year = $6.04 + 0.00361 \times FA + 8.54\times10^{-8} \times FA^2$

(2) Distribution system design affects recovery loads.

Using the distribution loss model, a table of credits and penalties was developed which modify recovery load. Distribution system design features considered included: "point-of-use" water heaters, hot water recovery systems, "parallel" pipe layouts, pipe insulation, and controlled hot water recirculation systems.

(3) Water heater efficiency varies with load.

Look-up tables were prepared for determining "basic energy use" (source Btu's) from water heater DOE energy factor and recovery load. The tables were constructed using "load dependent energy factor" equations and were developed for gas storage, electric storage, heat pump, and instantaneous water heater types.

(4) Standard energy use is independent of climate zone.

The proposed new water heating compliance methodology will not be climate-zone specific. Under the current assumption that water heater inlet temperature equals average annual outdoor temperature, average water heating recovery load only varies +/-5.5%, except for climate zones 15 and 16, which are not highly populated. Given that actual inlet temperatures may vary widely within each zone (depending on water source) the modest load variations caused by varying inlet temperature and ambient water heater temperature do not justify complicating the compliance process.

Acknowledgments

Work described by this paper was supported by a California Energy Commission contract, managed by David Ware. Substantial project contributors included Marc Hoeschele and Ken Nittler. The California chapter of the Plumbing, Heating, and Cooling Council's assistance with validation of plumbing layouts and contractor questionnaires was highly valued.

References

Davis Energy Group, Inc. 1991. *Residential Water Heating Study*. Final report for California Energy Commission Contract No. 400-88-003 (2 vols.).

Berkeley Solar Group and Xenergy. 1990. *Occupancy Patterns & Energy Consumption in New California Houses (1984-1988)*. California Energy Commission Publication No. P400-90-009.

Brodsky, J.B., McNicholl, S.E. 1987. *Residential Appliance Load Study, 1985-1986*. Pacific Gas & Electric Regulatory Cost of Service Department.

Schultz, W.W., Goldschmidt, V.W. 1983. "Distribution Efficiency and Characteristics of Start-up and Shutdown of Flow in Hot Water Distribution Lines." *ASHRAE Transactions*, Volume 4. American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia.

Department of Energy. 1990. "Energy Conservation Program for Consumer Products; Final Rule Regarding Test Procedures and Energy Conservation Standards for Water Heaters." Federal Register Vol. 55 No. 201 p. 42174.

Usibelli, A. 1984. "Monitored Energy Use of Residential Water Heaters." *Proceedings from the ACEEE 1984 Summer Study on Energy Efficiency in Buildings*. American Council for an Energy-Efficient Economy, Washington, D.C.

Perlman, M., Milligan, N.H. 1988. "Hot Water and Energy Use in Apartment Buildings." *ASHRAE Transactions*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia.

Merrigan, T.J. 1988. "Residential Hot Water Use in Florida and North Carolina." *ASHRAE Transactions*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia.

Gilbert Associates Inc. 1985. *Electric Water Heating for Single-Family Residences: Group Load Research and Analysis*. EPRI Report No. EA-4006. Electric Power Research Institute, Palo Alto, California.

Kempton, W. 1984. "Residential Hot Water: A Behaviorally Driven System." *Proceedings from the ACEEE 1984 Summer Study on Energy Efficiency in Buildings*. American Council for an Energy-Efficient Economy, Washington, D.C.

Perlman, M. Mills, B.E. 1985. *Development of Hot Water Use Patterns. ASHRAE Transactions*, Vol. 91. American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, Georgia.

Vine, W., Diamond, R., Szdlowski, R. 1987. "Domestic Hot Water Consumption in Four Low Income Apartment Buildings". *Energy*, Vol. 12, No. 6.

Decicco, J.M. 1986. "Domestic Hot Water Service in Lumley Homes: A Comparison of Energy Audit Diagnosis with Instrumented Analysis." *Proceedings from the ACEEE 1986 Summer Study on Energy Efficiency in Buildings*, Vol. 2. American Council for an Energy-Efficient Economy, Washington, D.C.

Barvir, E.J., Doak, L.G., Waterman, R.E., Gervasio, C. 1981. "Hourly Use Profiles for Solar Domestic Hot Water Heaters in the National Solar Data Network." *Solar Engineering*, pp. 319-324.