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### Publication Date

2018-08-28

Peer reviewed

# Estimating Residential Appliance Lifetime for Energy Efficient Policy Analysis

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**August 2018**

**This is a pre-print version of the proceedings of the 2018 ACEEE Summer Study on Building Energy Efficiency held in Pacific Grove, CA August 12-17, 2018**



This work was supported by the Office of Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

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## **ABSTRACT**

Accurate knowledge of appliance lifetimes helps policy makers set effective energy efficiency policy. The cost-effectiveness of an appliance efficiency measure depends on the length of time consumers will use an appliance. National shipments projections depend on the rate of replacement in the installed appliance stock. Furthermore, early retirement programs need an accurate understanding of the remaining useful life in order to calculate lifetime savings and cost-effectiveness of a program.

This paper uses a method for calculating lifetime of appliances based on the most recent data available on appliance shipments, total appliance stock, and the fraction of surviving appliances by age bins. An example of the calculation methodology is provided for residential gas boilers. This paper concludes by comparing the results to other available data on gas boiler lifetime.

## **Introduction**

Accurate product lifetime estimates are important for determining potential energy savings and economic benefits resulting from appliance efficiency programs and regulatory standards. While an average lifetime provides valuable information, a lifetime probability distribution reveals how impacts may vary among consumers.

An approach for deriving a lifetime probability distribution was described by Lutz (2011) and Welch (2010). Those studies determined the lifetimes of appliances based on data from public surveys on the presence of appliances in residential housing units combined with manufacturer data on historical shipments. This paper utilizes the basic methodology in Lutz (2011) and applies it to the case of residential gas boilers.<sup>1</sup> We used updated survey data, shipments data, and assumptions, and also provide a more comprehensive explanation of how the methodology is applied. One important feature of the approach presented in this paper is the use of data from several surveys across many years along with historical shipments data to develop the survival probability.

## **General Methodology and Assumptions**

The method described here consists of applying a survival function to the number of appliances shipped in a given year in order to estimate the number of appliances still in use in a future year. For example, suppose that manufacturers report having shipped 100,000 boilers between 1990 and 2000. If a 2010 survey indicates that 80,000 households have a boiler that is between 10 and 20 years old (corresponding to the 1990–2000 shipment period), then 80 percent of boilers aged 10–20 years are still in use, and 20 percent have been retired.

## **Primary Data Sources**

The method described in this paper relies on appliance shipments data, stock data, and data on the age of existing appliance. For residential gas boilers, shipments data were obtained from the Air-Conditioning, Heating and Refrigeration Institute (AHRI) and Appliance Magazine.

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<sup>1</sup> The lifetime methodology presented in this paper was used in the Department of Energy's energy efficiency standards final rule for residential boilers (DOE 2016).

Stock data for residential boilers were obtained from multiple years of the U.S. Census Bureau's American Housing Survey (AHS) (US Census 2015). Data on the age of existing residential boilers were obtained from multiple years of Energy Information Agency's (EIA) Residential Energy Consumption Survey (RECS) (EIA 2013).

## The Weibull Distribution

The Weibull distribution (Weibull 1951) is a probability distribution function of wide applicability. The Weibull distribution is capable of fitting a broad range of shapes of data. Many common distributions such as normal, exponential, or Rayleigh are exact or approximate matches of special forms of the Weibull distribution (Abernathy 2006). In addition, the Weibull distribution has been used to successfully model survival probabilities of appliances (Lutz 2011; Welch 2010; Young 2008; Fernandez 2001) and has been widely used in analyses of lifetime and reliability of mechanical and electronic equipment (Araneda 2008; Mahzar 2007).

In this paper, the Weibull distribution is used as the probability density function and survival function that describes residential gas boiler lifetimes.

The 3-parameter Weibull probability density function is given by:

$$f(x) = \frac{\beta}{\alpha} \left( \frac{x-\theta}{\alpha} \right)^{\beta-1} e^{-\left( \frac{x-\theta}{\alpha} \right)^\beta}, \quad (1)$$

and the survival function for the 3-parameter Weibull distribution takes the form:

$$P(x) = e^{-\left( \frac{x-\theta}{\alpha} \right)^\beta}, \quad (2)$$

where

$x$  = appliance age,  $x \geq 0$ ,

$f(x)$  = probability density at age  $x$ ,

$P(x)$  = probability that an appliance will survive (still be in use) beyond age  $x$ ,

$\alpha$  = scale parameter, which corresponds to the decay length in an exponential distribution,

$\beta$  = shape parameter, which determines the way the failure rate changes over time,<sup>2</sup> and,

$\theta$  = delay parameter, which provides for a delay before any failures occur.<sup>3</sup>

Based on Equation (2), the median lifetime  $\tilde{M}$  and mean lifetime  $\bar{M}$  can be written as:

$$\tilde{M} = \theta + \alpha (\ln 2)^{1/\beta}, \text{ and} \quad (3)$$

$$\bar{M} = \theta + \alpha \Gamma(1 + 1/\beta), \text{ where } \Gamma \text{ is the gamma function.} \quad (4)$$

Figure 1 shows probability density functions and survival functions with different Weibull distribution scale ( $\alpha$ ) and shape ( $\beta$ ) parameters.

<sup>2</sup> When  $\beta = 1$ , the failure rate is constant through time, producing a cumulative exponential distribution. In the case of appliances,  $\beta$  commonly is greater than 1, reflecting an increasing failure rate as appliances age.

<sup>3</sup> In this paper, we place the following constraint on the delay parameter:  $\theta \geq 1$ . This is equivalent to assuming that the appliance does not fail within the first year; indeed, most appliances come with a one year warranty

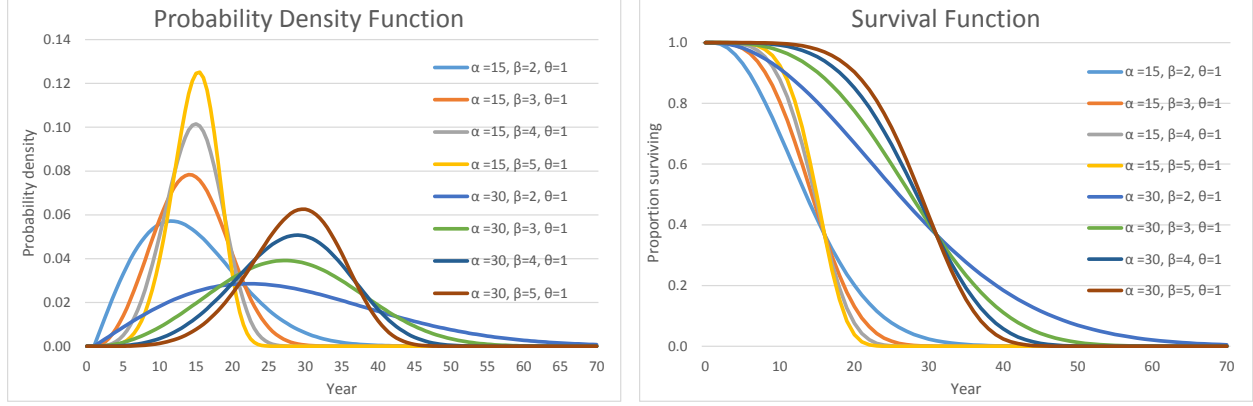


Figure 1 Probability density functions and survival functions with different Weibull distribution parameters

### Estimating the Weibull Distribution Parameters

In order to estimate the Weibull distribution parameters ( $\alpha$ ,  $\beta$ , and  $\theta$ ), we define  $E$  to be the sum of weighted squared errors between *the historical stock* (based on AHS and RECS data) and the *modeled stock* (using historical shipments and the survival function which is described by equation 2). The Weibull distribution parameters can be then estimated by the following optimization problem:

$$\min_{\alpha, \beta, \theta} E = \sum_y W_y^{(t)} \cdot \left[ S_y^{(t)} - \hat{S}_y^{(t)}(\alpha, \beta, \theta) \right]^2 + \sum_{i,y} W_{i,y}^{(b)} \cdot \left[ S_{i,y}^{(b)} - \hat{S}_{i,y}^{(b)}(\alpha, \beta, \theta) \right]^2 \quad (5)$$

Where

$y$  = index of the year,

$i$  = index of the age bin,

$t$  = denotes total stock,

$b$  = denotes stock by age bin,

$S_y^{(t)}$  = historical total stock of appliances for year  $y$ , calculated based on AHS data,

$\hat{S}_y^{(t)}(\alpha, \beta, \theta)$  = modeled total stock in year  $y$ , from shipments model using Weibull distribution parameters  $\alpha$ ,  $\beta$ , and  $\theta$ ,

$S_{i,y}^{(b)}$  = historical stock in age bin  $i$  for year  $y$ , calculated based on RECS data,

$\hat{S}_{i,y}^{(b)}(\alpha, \beta, \theta)$  = modeled stock in age bin  $i$  for year  $y$ , from shipments model using Weibull distribution parameters  $\alpha$ ,  $\beta$ , and  $\theta$ ,

$W_y^{(t)} = 1/(\sigma_y^{(AHS)})^2$  is the weight of error of modeled total stock using shipments model for year  $y$ , where  $\sigma_y^{(AHS)}$  denotes the standard error due to sampling for AHS data, and

$W_{i,y}^{(b)} = 1/(\sigma_{i,y}^{(RECS)})^2$  is the weight of error of modeled total stock using shipments model in age bin  $i$  for year  $y$ , where  $\sigma_{i,y}^{(RECS)}$  denotes the standard error due to sampling for RECS data.

In this analysis, modeled total stock  $\hat{S}_y^{(t)}(\alpha, \beta, \theta)$  and stock in an age bin  $\hat{S}_{i,y}^{(b)}(\alpha, \beta, \theta)$  are calculated using historical shipments and the Weibull survival function:

$$\hat{S}_y^{(t)}(\alpha, \beta, \theta) = \sum_{x \in X} P(x) \cdot h(y - x) = \sum_{x \in X} e^{-\left(\frac{x-\theta}{\alpha}\right)^\beta} \cdot h(y - x), \quad \text{and} \quad (6)$$

$$\hat{S}_{i,y}^{(b)}(\alpha, \beta, \theta) = \sum_{x \in X_i} P(x) \cdot h(y - x) = \sum_{x \in X_i} e^{-\left(\frac{x-\theta}{\alpha}\right)^\beta} \cdot h(y - x). \quad (7)$$

Where

$h(y - x)$  = historical shipments in year  $(y - x)$ ,

$P(x)$  = survival function described by equation 2 with the Weibull distribution parameters  $\alpha$ ,  $\beta$ , and  $\theta$ ,

$X_i$  = the  $i$ th age bin  $[x_{i,1}, x_{i,2}]$ ,  $i = 1, 2, \dots, N$ , and  $X = \cup_{i=1}^N X_i$ .

## Data Inputs

### Historical Total Appliance Stock

Both AHS and RECS contain data to estimate historical stock for various appliances. AHS contains data of all housing units (i.e. occupied, unoccupied, and secondary homes), while RECS contains data of occupied housing units only. Also compared to RECS, AHS is conducted more often (every odd year) and samples more U.S. households. For these reasons, we used AHS as basis for estimating total appliance stock for residential gas boilers.

In addition, we also made several adjustments to the AHS data in order to address gaps, as outlined in Table 1.

Table 1. Data gaps with AHS gas boiler stock data and adjustments applied in this paper

Data gap	Adjustment applied in this paper
Gas boilers serving multiple housing units: not reported	On average about a 30% decrease to the stock based on RECS data showing that about half of housing units have a gas boiler which serves multiple housing units, mostly multi-family, (EIA 2013)
Commercial gas boilers used in residential applications: cannot distinguish from residential gas boilers	On average a 12% decrease to the stock, based on sizing of the gas boiler (mostly applied to larger multi-family buildings)
Multiple gas boilers per housing unit: not reported	On average a 5% increase to the stock based on Decision Analyst (2009) data indicating that 5% of houses have more than one boiler
Gas boilers used as secondary heating equipment: not reported	On average a 1% increase to the stock based on RECS data (EIA 2013)
Time period of study: AHS typically conducted in middle of year while shipments data are provided for a calendar year	On average a 0.3% increase to the stock based on the number of boilers installed in homes constructed in the survey year.

Figure 2 shows the residential gas boiler stock based on both the unadjusted AHS data and after making the adjustments described in Table 1.<sup>4</sup>

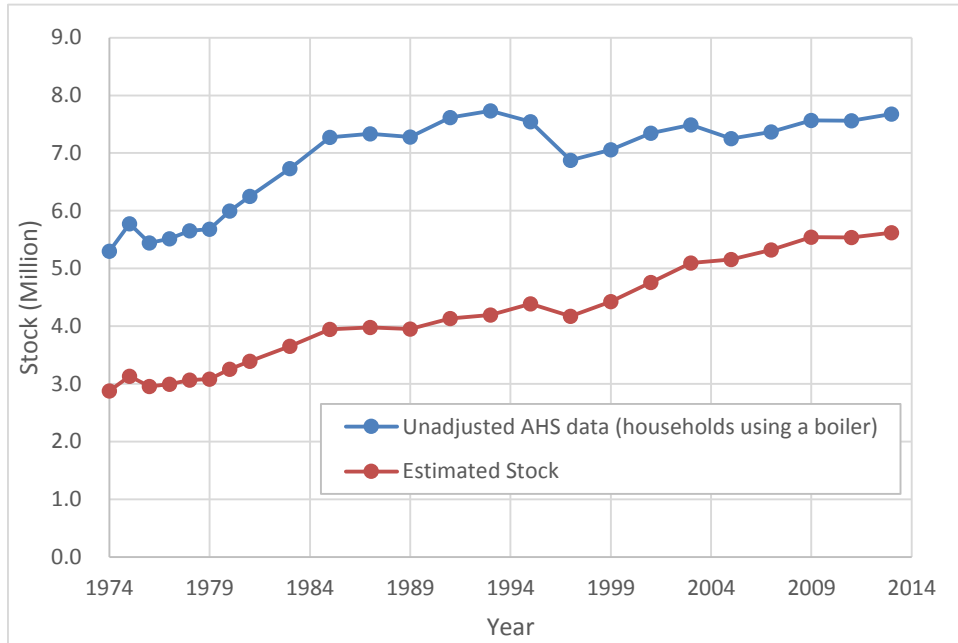


Figure 2 Unadjusted AHS Gas Boiler Stock and Estimated Total Stock Used in this Paper

We note that decreasing the stock values (e.g., by accounting for gas boilers serving multiple housing units and commercial gas boilers used in residential applications) will result in a lower lifetime estimate compared to using the original AHS data. In contrast, increasing the stock values (e.g., by accounting for multiple gas boilers per housing unit, gas boilers used as secondary heating equipment, and scaling AHS data to the end of the calendar year) will result in a higher lifetime estimate compared to using the original AHS data. However, as can be seen in Figure 2, the overall result is decreased stock, leading to a lower lifetime estimate.

### Historical Stock by Appliance Age Bins for Residential Applications

In order to calculate historical gas boiler stock by appliance age bins, we used RECS 1990 to 2009 (EIA 2013), which contain data regarding various appliances inside of occupied housing units, as well as the age of some of these appliances by age bins.

Similar to the AHS appliance stock data, RECS age bins have to be properly adjusted. For gas boilers, we adjusted for the following:

- Gas boilers serving multiple housing units. RECS reports if a boiler is serving multiple housing units, which mostly occurs in multi-family housing units. For gas boilers serving multiple single-family housing units, the RECS weight for the housing unit was divided by two (i.e. boiler serves two homes). For gas boilers serving multi-family housing units, the RECS weight for the housing unit is divided by the total number of housing units in the multi-family building (i.e. boiler serves all the units in the multi-family building).



- Commercial gas boilers used in residential applications. Based on the estimated size of the gas boiler for each housing unit, a fraction of the RECS housing units are assumed to be served by a commercial gas boiler (mostly occurs for gas boilers serving multiple housing units in a multi-family building).
- Multiple gas boilers per housing unit. RECS does not report the number of boilers in a housing unit. On average, 5% of housing units are assigned multiple boilers based on Decision Analyst (2009) data.
- Scaling RECS data to end of the calendar year. RECS is typically conducted in the middle of a year, so we accounted for new boilers installed in the latter half of the survey year.

For this paper, we assumed that gas boilers that don't have a reported age in RECS (such as secondary heating equipment,<sup>5</sup> housing units with multiple boilers, or respondents that did not know the age of their appliance<sup>6</sup>) have a similar distribution to the ones that are reported.

The resulting age distribution for existing gas boilers used in this paper is shown in Figure 3. Because the RECS data for the youngest age bins (less than 2 years old and 2 to 4 years) tend to have a large scatter relative to the shipments in those years, we combine the first two age bins reported in RECS. Note that combining those bins should not affect the shape of the distribution because it is unusual for gas boilers to fail during their first year. The resulting fraction of gas boilers by age bin are then weighted by total gas boiler stock calculated in the previous section to come up with historical stock by appliance age bins for gas boilers.

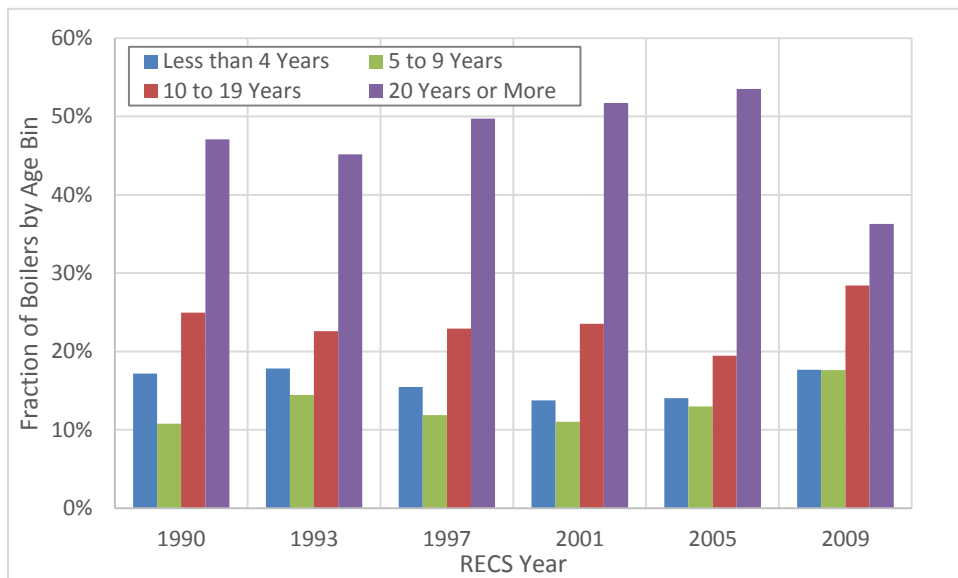


Figure 3 Resulting Residential Gas Boiler Age Distributions based on RECS 1990 to 2009 Data  
 Note that from RECS 1990 to 2005, age bin 10 to 19 years was a single bin, which was broken up into two bins for the RECS 2009 survey (10 to 14 years and 15 to 19 years).

<sup>5</sup> RECS data from 1997 to 2009 reports secondary, but not the age for this equipment.

<sup>6</sup> RECS data from 1990 to 2005 included this option. In RECS 2009, this bin was removed and the age bin for all gas boilers used as primary equipment was reported.

## Historical Shipments Data to Calculate Stock

Historical residential gas boiler shipments from 1954 to 2012 were derived using data from AHRI (AHRI 2005; AHRI 2013) and Appliance Magazine (2014). The 2013 shipments value was estimated using the shipments model developed in DOE (2016). The AHRI and Appliance Magazine shipment data are adjusted to account for companies that are not AHRI members,<sup>7</sup> by comparing data from residential gas boiler model directories (AHRI 2015b; CEC 2015; NRCAN 2015; EPA 2015).<sup>8</sup> On average these adjustments increased the annual shipments from 1980 to 2013 by about 7 percent. Figure 4 shows the resulting national total shipments for residential gas boilers.

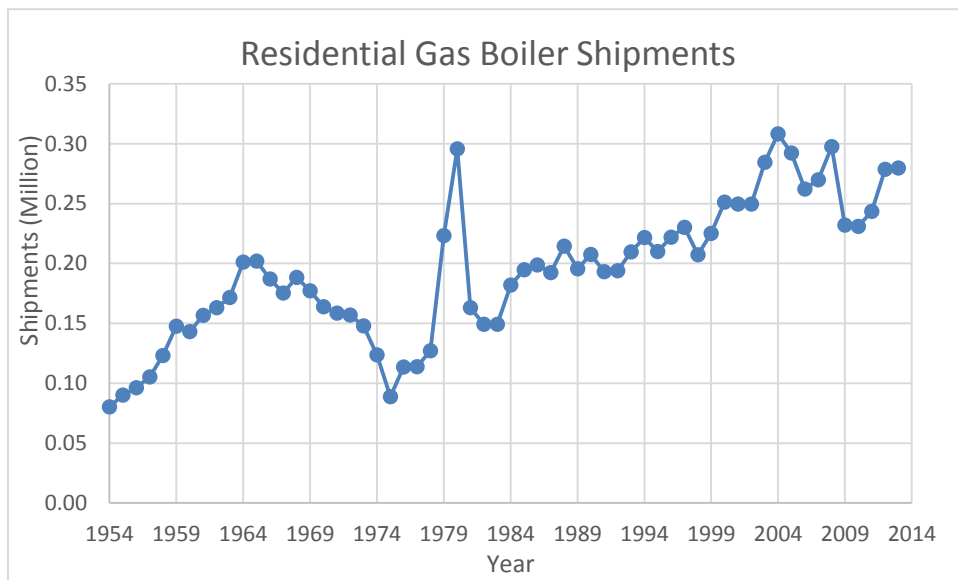


Figure 4 Residential Gas Boiler Shipments Estimate (1954-2013)

Note large increase in gas boiler shipments for 1979 and 1980 is likely due to the 1979 oil crisis. Shipments of oil boilers in these two years significantly decreases as well.

Modeling the residential gas boiler stock requires using historical shipments that were adjusted to account for residential gas boilers used in commercial applications. As the historical shipments data was not disaggregated into residential or commercial applications, we adjusted the shipments based on the percentage of existing stock in commercial buildings. Using EIA's 2003 Commercial Building Energy Consumption Survey (CBECS) (EIA 2008) and RECS 2009, we determined that 7 percent of residential gas boilers were used in commercial applications.<sup>9,10</sup>

<sup>7</sup> Appliance Magazine's shipments data comes from AHRI.

<sup>8</sup> The total of all models in the four directories was compared to the models that were only listed in the AHRI directory to account for manufacturers that are not a part of AHRI. Shipments were scaled to reflect the percentage increase between the models in the AHRI directory and the models all four directories.

<sup>9</sup> For this paper, commercial market does not include boilers serving multiple units in a multi-family buildings.

<sup>10</sup> We assumed that boilers in residential buildings and commercial buildings that are smaller than 10,000 sq. ft. are residential boilers and that half of buildings between 10,000 and 20,000 sq. ft. use a residential boiler. In addition, we adjusted the weights of residential buildings with a gas boilers serving multiple housing units and it assumed that commercial buildings over 5,000 sq. ft. use two or more boilers. In order to match the RECS 2009 and CBECS 2003 weights year, the CBECS 2003 weights were increased by 1.09 using the total historical commercial square footage data from 2003 compared to 2009.

The shipments used to model the residential gas boiler stock were reduced by 7 percent so the modeled stock would only represent residential applications

We note that increasing the shipments values (e.g., by accounting for companies that are not AHRI members) will result in a lower lifetime estimate compared to using the unadjusted shipments data. In contrast, decreasing the shipments values (e.g., by accounting for residential gas boilers used in commercial applications) will result in a higher lifetime estimate compared to using the unadjusted shipments data. As both adjustments discussed above were 7 percent and one increased shipments while the other decreased shipments, the total overall shipments value are similar to the unadjusted data.

### **Further Considerations**

The following assumptions are adopted to evaluate the survival characteristics of an appliance:

- RECS and AHS utilize a complex survey method and their errors are well controlled, therefore any additional sources of error do not lead to bias in our estimation method and those errors do not scale with sample size.
- Structural changes such as impact of efficiency standards, early replacements, incentives, impacts of different technologies/customer preferences, equipment switching, etc. do not have long term impacts on equipment lifetime.<sup>11</sup>
- We are able to accurately represent the stock of residential appliances in commercial applications using CBECS data and that the lifetime of residential appliances in commercial applications is similar enough that it does not significantly impact overall lifetime estimates.
- We assume the lifetime derived for a specific type of appliance does not change significantly over a given time period. This assumption was checked by deriving lifetime values over different time periods. It is important to note that the derived appliance lifetime is an aggregate of multiple technologies<sup>12</sup> and is independent of other factors (such as household size, appliance use, or region).

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<sup>11</sup> Several market drivers have impacted the boilers market: incentives, especially between 2005 and 2011, which led to early replacements and equipment switching; and large increases in energy prices from late 1990's to early 2000's, leading to equipment and fuel switching. The data used in this paper indicates that the incentives and increases in gas and oil prices have had the most significant impact on early replacements and equipment switching. This is most clearly shown by the significant decrease in 20 or more years old boilers in the RECS 2009 data compared to previous RECS data. The long term impact of these changes on gas boiler lifetime is still unclear. In addition, in 2012 a new efficiency standard for boilers became effective, but the data used in this paper is not recent enough to assess any impact from this standard on gas boiler lifetime.

<sup>12</sup> The residential gas boiler technology has changed significantly over the past 20 years. During that time, the market share of high-efficiency boilers has increased dramatically. High-efficiency condensing boilers now account for close to half of boilers shipments, compared to about 2 percent in 2000 (DOE 2016). However, there still is not enough data on high-efficiency boilers to assess whether their lifetime varies significantly compared to lower-efficiency boilers.

## Results: Appliance Lifetime

Table 2 shows the lifetime results for residential gas boilers: the Weibull parameters that provide the best fit to the data and the resulting mean and median lifetimes. The table compares the results using different sets of data: 1) using only data before 2000; 2) using only data after 2000; 3) using only data after 2005 (most recent data); 4) using only the total stock data; 5) using only the stock by age bin data; 6) using all the available data. The average lifetime varies by three years from 25.6 to 28.6 years. Using the stock by age bin results in the highest average value (28.6 years) mainly due to the higher number of 20 or more year old gas boilers. Figure 5 shows the Weibull lifetime distribution and survival function using all the available data (DOE 2016).

Table 2. Results for Lifetime Weibull Parameters and Statistics

Sets of Data	Weibull Parameters			Statistics	
	Scale ( $\alpha$ )	Shape ( $\beta$ )	Delay ( $\theta$ )	Mean	Median
Pre 2000 Survey Data	30.0	2.14	1.0	27.6	26.3
Post 2000 Survey Data	29.1	1.84	1.0	26.8	24.8
Post 2005 Survey Data	28.5	2.06	1.0	26.3	24.9
Total Stock only	25.4	3.19	1.0	25.6	25.4
Stock by Age Bin Only	24.6	1.45	1.0	28.6	24.6
<b>All Data</b>	<b>28.5</b>	<b>2.39</b>	<b>1.0</b>	<b>26.3</b>	<b>25.5</b>

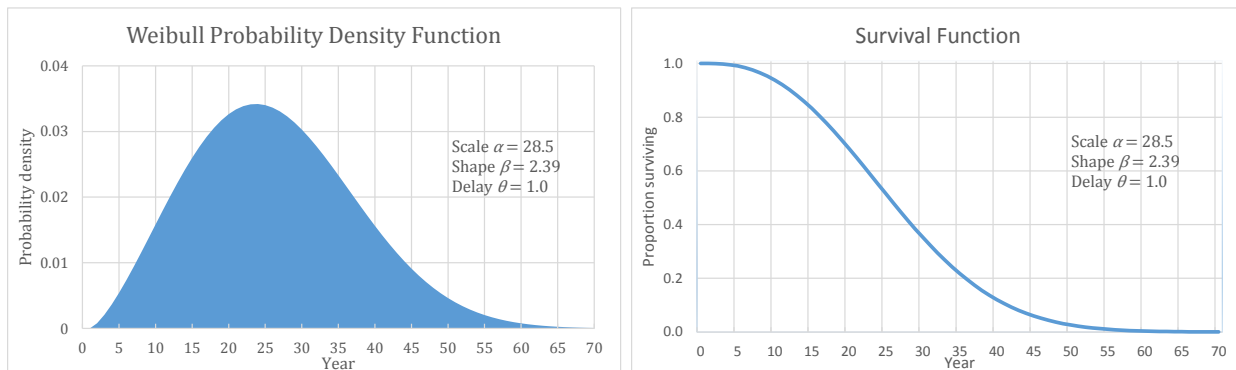


Figure 5 Weibull Lifetime Distribution and Survival Function for Residential Gas Boilers

For residential gas boilers, the calculated lifetime values in this paper lie in the middle of the 20-30 years estimated from other sources shown in Table 3.

Table 3. Comparison of Estimated Appliance Lifetimes

Source	Mean or Typical Lifetime	Notes
Appliance Magazine (2009)	20	Survey of appliance manufacturers, including engineers, designers, and product managers
ASHRAE (2015)	24 to 35	Depends on boiler type
AHRI (2015a) Contractor Survey	25	Based on a contractor survey
Lutz (2011)	25	Weibull distribution based on shipments and survey data
This Paper (DOE 2016)	26	Weibull distribution based on updated shipments, survey data, and assumptions compared to Lutz (2011)
RS Means (2018)	30	Based on surveys of contractors, engineers, building managers

## Summary and Conclusions

This paper describes a methodology to determine a distribution of lifetimes, as illustrated with residential boilers. Refinements applied in this paper to calculate an accurate representation of the key factors include: 1) scaling data for total number of households; 2) accounting for multiple gas boilers per housing unit, gas boilers serving multiple housing units, and gas boilers used as secondary heating; 3) scaling survey data to complete calendar year; 4) accounting for shipments by non-AHRI member companies; and 5) accounting for commercial gas boilers used in the residential market and residential gas boilers used in the commercial market. Based on the current shipments and survey data, average residential boiler lifetime was estimated to be approximately 26 years.

## Acknowledgements

This work was supported by the Office of Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

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