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Impact of the EISA 2007 Energy Efficiency Standard on General Service Lamps

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Abstract. The Energy Policy and Conservation Act of 1975, as amended by the Energy Independence and Security Act of 2007 (EISA 2007), requires that, effective beginning January 1, 2020, the Secretary of Energy shall prohibit the sale of any general service lamp (GSL) that does not meet a minimum efficacy standard of 45 lumens per watt. This is referred to as the EISA 2007 backstop. The U.S. Department of Energy recently revised the definition of the term GSL to include certain lamps that were either previously excluded or not explicitly mentioned in the EISA 2007 definition. For this subset of GSLs, we assess the impacts of the EISA 2007 backstop on national energy consumption, carbon dioxide emissions, and consumer expenditures. To estimate these impacts, we projected the energy use, purchase price, and operating cost of representative lamps purchased during a 30-year analysis period, 2020-2049, for cases in which the EISA 2007 backstop does and does not take effect; the impacts of the backstop are then given by the difference between the two cases. In developing the projection model, we also performed the most comprehensive assessment to date of usage patterns and lifetime distributions for the analyzed lamp types in the United States. There is substantial uncertainty in the estimated impacts, which arises from uncertainty in the speed and extent of the market conversion to solid state lighting technology that would occur in the absence of the EISA 2007 backstop. In our central estimate we find that the EISA 2007 backstop results in significant energy savings of 27 quads and consumer net present value of $120 billion (at a seven percent discount rate) for lamps shipped between 2020 and 2049, and carbon dioxide emissions reduction of 540 million metric tons by 2030 for those GSLs not explicitly included in the EISA 2007 definition of a GSL.

1 Introduction

Beginning with the Energy Policy and Conservation Act of 1975 (EPCA), a series of congressional acts have directed the U.S. Department of Energy (DOE) to establish minimum energy conservation standards for a variety of consumer products and commercial and industrial equipment. These products include certain varieties of compact electric lamps, commonly referred to as light bulbs. In particular, the Energy Independence and Security Act of 2007 (EISA 2007) amended EPCA to expand coverage to include general service lamps (GSLs), defined by statute as including general service incandescent lamps (GSILs), compact fluorescent lamps (CFLs), general service light-emitting diode (LED) or organic LED (OLED) lamps, and any other lamps that the Secretary of Energy determines are used to satisfy lighting applications traditionally served by general service incandescent lamps, with certain exclusions. (EISA 2007, 2007; U.S. Code Title 42, 2010) In addition to expanding coverage, EISA 2007 set a series of energy efficiency standards for GSILs that took effect between 2012 and 2014. Driven in part by policy actions such as these, as well as federal funding of research and development into solid state lighting (SSL), energy utility incentive programs, and mandatory and voluntary energy efficiency labeling programs, the lighting market has been undergoing significant transformation in recent years, resulting in reduced energy consumption in the U.S. associated with lighting. (NEMA, 2016; EIA, 2014, 2015, 2016)

In addition to setting standards for GSILs, EISA 2007 directed DOE to undertake an energy conservation standards rulemaking for GSLs, to be completed by January 1, 2017. If the rulemaking was not completed in accordance with certain statutory provisions, or if the rulemaking did not produce savings greater than or equal to the savings from a minimum efficacy standard of 45 lumens per watt, a statutory provision (referred to as the backstop requirement) directed the Secretary of Energy to prohibit the sale of any GSL that does not meet a minimum efficacy of 45 lumens per watt, beginning January 1, 2020. In two final definition rules, DOE has clarified that the definition of a general service lamp is a lamp that (1) has an American National Standards Institute (ANSI) base, (2) is able to operate at a voltage of 12 volts or 24 volts, at or between 100 to 130 volts, at or between 220 to 240 volts, or at 277 volts, (3) has an initial lumen output greater than or equal to 310 lumens and less than or equal to 3300 lumens, (4) is not a light fixture, (5) is not an LED downlight retrofit kit, and (6) is used in general lighting applications[1]. (DOE, 2017a, 2017b) Certain exclusions exist, including the exclusion of high intensity discharge lamps and general service fluorescent lamps, the latter of which are covered by a separate set of standards[2]. DOE has also determined that exclusions from the GSL definition specified by EISA 2007 for certain incandescent lamp types should be discontinued, including reflector lamps, rough service lamps, shatter-resistant lamps, three-way

[1] The GSL definition differs slightly for modified spectrum GSILs and non-integrated lamps (i.e., GSLs that require an external ballast or driver). These lamp types are less common and not analyzed in this report.
[2] A full list of exclusions is included in a footnote in section 2.1.

incandescent lamps, vibration service lamps, and lamps of certain shapes[3]. Because an energy conservation standards rulemaking for GSLs was not completed in accordance with specified statutory provisions, the EISA 2007 backstop is required to take effect and any lamp sold after January 1, 2020 that meets this GSL definition must have an efficacy of at least 45 lumens per watt (lm/W).

DOE previously estimated considerable energy savings of 14 quadrillion British thermal units (quads) and carbon dioxide (CO_2) emission reductions of 817 million metric tons (Mt) (223 Mt of carbon equivalent) from 2008-2038 from the combined impact of the 2012-2014 GSIL standards and the impact of the EISA 2007 backstop on those lamps that meet the definition of GSL that is explicitly laid out in EISA 2007. (DOE, 2009) These lamps, which we refer to hereafter as "EISA-explicit" GSLs, include GSILs, CFLs, and general service LED or OLED lamps, as specified by Title 42, Section 6291(30)(BB)(i)(I)-(III) of the U.S. code, except for those exclusions specified by Title 42, Section 6291(30)(BB)(ii). These lamps typically have a medium screw base (MSB) and an A- or twist-type shape (the most common shape for household incandescent light bulbs and CFLs, respectively). In its 2017 definition rules, DOE revised the GSL definition to include additional lamp types, under its authority within the EISA 2007 definition to determine other lamp types that are used to satisfy lighting applications traditionally served by GSILs (Title 42, Section 6291(30)(BB)(i)(IV) of the U.S. code), as well as its authority to determine whether the exemptions for certain incandescent lamps should be maintained or discontinued based, in part, on exempted lamp sales collected by the Secretary from manufacturers pursuant to Title 42, Section 6295(i)(6)(A)(i)(II). These additional lamp types, which we will refer to hereafter as "non-EISA-explicit" GSLs, include MSB reflector lamps (commonly used in recessed ceiling fixtures), decorative lamps (such as candelabra-base lamps), multifaceted reflector (MR) lamps that commonly have a bi-pin or twist and lock base (and are often used in track lighting), MSB globe-shaped lamps (frequently found in bathroom vanities), and formerly-exempt MSB A-type lamps (hereafter referred to as miscellaneous A-type lamps).

EISA-explicit GSLs are the most common lamps in the installed stock of GSLs in the U.S. However, the stock also contains a significant proportion of non-EISA-explicit GSLs. Collectively the non-EISA-explicit lamp types have a nationwide installed stock at least 80% as large as the stock of EISA-explicit GSLs, and they offer a disproportionately large potential for energy savings since the vast majority are currently traditional or halogen incandescent lamps, as shown in Table 1. By contrast, the EISA-explicit lamps have a much stronger market presence of CFL and LED technologies already; since these technologies are more efficacious than 45 lm/W, there is proportionally less potential for future savings from the EISA 2007 backstop for the EISA-explicit lamps.

[3] Throughout this report we refer to lamps by their base type and/or shape. For illustrations of lamp shapes and base types, see http://www.lightopedia.com/bulb-shapes-sizes and http://www.lightopedia.com/bases-filament-types

Table 1: Estimates for 2015 of stock (in millions of units) and market share by technology for the most common general service lamp types. The source of the estimates for the EISA-explicit MSB lamps is DOE's GSL Notice of Proposed Rulemaking (NOPR) shipments analysis. The sources of the estimates for other lamp types are described in Section 2.4.

Lamp Type	Stock in 2015 (millions of units)	Stock Share by Technology in 2015		
		Incandescent	CFL	LED
EISA-explicit	3500	48%	47%	5%
MSB Reflector	960	82%	17%	1%
MR	170	99%	0%	1%
Decorative*	1400	96%	4%	0%
Globe-shaped**	330	100%	0%	0%
Misc. A-type***	--	--	--	--

*Decorative lamps were assumed to have the same stock share by technology as small-screw-base lamps (i.e., lamps with a screw base smaller than medium base, such as candelabra-base lamps), which are the most common type of decorative lamps. See Section 2.4 for details on stock share by technology for small-screw-base lamps.
**Total stock and technology share estimates for globe-shaped lamps can be derived using an analogous approach based on regional socket surveys to that described for MR and small-screw-base lamps in Section 2.4.
*** Data to estimate the total stock and stock share by technology in 2015 were not available. For several subcategories of miscellaneous A-type lamps (rough service lamps, vibration service lamps, and shatter resistant lamps), it can reasonably be assumed that the stock was entirely incandescent in 2015.

Just as is already underway in the market for EISA-explicit GSLs, some proportion of the non-EISA-explicit GSL market is expected to make a transition to LED technologies as more products become available and the prices of these products continue to drop. There is substantial uncertainty surrounding the rate at which this transition will occur and the fraction of the market that will ultimately convert to LEDs. Since incandescent technologies cannot meet the 45 lm/W minimum efficacy required by the EISA backstop provision, however, the backstop will result in a more rapid and complete transition to LED technology than would have occurred otherwise, yielding energy savings compared to a scenario in which the EISA backstop provision does not take effect. This paper details the methodology used to estimate the substantial energy, CO_2, and consumer savings associated with the application of the EISA 2007 backstop to all of the non-EISA-explicit GSLs and summarizes the results of that analysis.

2 Methods

Our goal is to estimate the U.S. national energy savings (NES), CO_2 emissions reductions (ΔCO_2), and consumer net present value (NPV), associated with improved energy efficiency for non-EISA-explicit GSLs, following the EISA backstop implementation in 2020, over a 30-year analysis period (2020-2049), which is the standard time horizon used for estimating the national impact of DOE energy conservation standards. In what follows, we often refer to these three quantities (NES, ΔCO_2, and NPV) collectively as the *impact of the backstop*. To calculate this impact, we compare the projected total national energy consumption, CO_2 emissions, and consumer costs in two cases: (1) a base case that assumes that the market for lamps under

examination will follow recent forecasts, and (2) a backstop case that assumes that no GSL with an efficacy less than 45 lumens per watt is sold in 2020 or thereafter.

To estimate the impact of the backstop, we must model, in each case, the energy use, purchase price, and operating cost of all non-EISA-explicit GSLs purchased during the 30-year analysis period. To accomplish this, we first divide the lamps into product categories according to their typical applications. We then develop a small number of representative lamps for each product category, including lamp options that would and would not meet a 45 lm/W efficiency standard. These representative lamps are used as a proxy for the more diverse set of lamps available to consumers on the real-world market; simplifying the market in this way allows a tractable model to be constructed while still yielding a representative estimate of energy consumption and consumer costs. The representative lamps are defined by attributes including lumen output, wattage, rated lifetime, and purchase price, which are chosen to be typical for lamps within the category. To estimate the annual energy consumption associated with each representative lamp, we develop an estimate of the average daily operating hours for each lamp category, combine this with each lamp's wattage, and account for the average reduction in energy consumption expected from the use of lighting controls (e.g., dimmers).

Shipments (representing consumer purchases in each year) and national stock (total installed units) for each representative lamp are estimated for each year in the analysis period based on initial shipments and stock estimates and a stock turnover model which incorporates modeled survival probability distributions and time-dependent market-share projections for LED lamp penetration into each product category. By multiplying the installed stock of each representative lamp by its annual energy use, and summing over all representative lamps, we compute the total annual national energy consumption for each case. Together with projections of electricity prices, this also yields an estimate of annual consumer operating costs in each case. Similarly, the total consumer costs associated with lamp purchases are estimated based on the sum of the purchase price of each lamp shipped in each case, discounted to the present day, taking into account projected reductions in price for LED lamps. CO_2 savings are estimated by applying factors relating CO_2 emission to energy consumption to any estimated energy savings between cases.

In the following sections we discuss in more detail each step in the analysis. Section 2.1 describes how the analyzed lamp types were categorized; section 2.2 describes the representative lamps used in the analysis; section 2.3 describes the hours of use, lifetime, and energy use for each of our representative lamps; section 2.4 describes the initial estimates for shipments and installed stock for each lamp category, and the stock turnover model and projected efficiency distribution used to estimate shipments in each year; section 2.5 describes the calculation of the national energy savings and CO2 emissions reductions; and section 2.6 describes the calculation of the net present value to consumers.

2.1 Lamp Categorization

DOE's recently adopted GSL definition clarified the set of lamps for which the exemptions from the EISA 2007 GSL definition would be discontinued, after considering annual sales and the risk of substitution between exempt and non-exempt lamps. DOE discontinued exclusions from the EISA 2007 GSL definition for seven types of MSB lamps: reflector lamps, rough service lamps, shatter-resistant lamps, three-way lamps, vibration service lamps, T-shape lamps of 40 Watts or less or length of 10 inches or more, and B, BA, CA, F, G16-1/2, G25, G30, S, M-14 lamps of 40 Watts or less. In addition, any lamp that (1) has an ANSI base, (2) is able to operate at a voltage of 12 volts or 24 volts, at or between 100 to 130 volts, at or between 220 to 240 volts, or at 277 volts, (3) has an initial lumen output greater than or equal to 310 lumens and less than or equal to 3300 lumens, (4) is not a light fixture, (5) is not an LED downlight retrofit kit, and (6) is used in general lighting applications was determined to be used to satisfy lighting applications traditionally served by general service incandescent lamps, with certain exceptions[4,5]. Among the most common non-EISA-explicit lamps that fall into this broad definition are candelabra-base lamps and MR16 lamps.

For the analyses discussed in this report, we grouped the non-EISA-explicit GSLs into five categories: MSB reflector lamps, MR lamps, decorative lamps, miscellaneous A-type lamps, and globe-shaped lamps. These categories were chosen based on the similar applications for lamps in each category, as well as on the availability of data to support usage characterization and shipments estimates. The MSB reflector lamp category includes lamps that meet DOE's definition of an incandescent reflector lamp (IRL), including MSB lamps with ANSI shape classifications PAR, R, ER, BR, BPAR, or similar shape, as well as MSB reflector lamps that do not meet the statutory definition of an IRL because the lamp wattage or diameter is below the threshold specified in that definition. Such lamps are commonly used in recessed cylindrical ceiling fixtures (commonly known as "cans"). MR lamps that meet DOE's GSL definition are small reflector lamps used in track lighting and similar applications that typically have a bi-pin or twist and lock base. The decorative lamp category includes all lamps that meet DOE's GSL definition that have a screw-base smaller than MSB, including candelabra-base (E12),

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[4] General service lamps do not include: Appliance lamps; Black light lamps; Bug lamps; Colored lamps; G shape lamps with a diameter of 5 inches or more; General service fluorescent lamps; High intensity discharge lamps; Infrared lamps; J, JC, JCD, JCS, JCV, JCX, JD, JS, and JT shape lamps that do not have Edison screw bases; Lamps that have a wedge base or prefocus base; Left-hand thread lamps; Marine lamps; Marine signal service lamps; Mine service lamps; MR shape lamps that have a first number symbol equal to 16 (diameter equal to 2 inches), operate at 12 volts, and have a lumen output greater than or equal to 800; Other fluorescent lamps; Plant light lamps; R20 short lamps; Reflector lamps that have a first number symbol less than 16 (diameter less than 2 inches) and that do not have E26/E24, E26d, E26/50x39, E26/53x39, E29/28, E29/53x39, E39, E39d, EP39, or EX39 bases; S shape or G shape lamps that have a first number symbol less than or equal to 12.5 (diameter less than or equal to 1.5625 inches); Sign service lamps; Silver bowl lamps; Showcase lamps; Specialty MR lamps; T shape lamps that have a first number symbol less than or equal to 8 (diameter less than or equal to 1 inch), nominal overall length less than 12 inches, and that are not compact fluorescent lamps; Traffic signal lamps.

[5] As noted previously, the GSL definition differs slightly for modified spectrum GSILs and non-integrated lamps (i.e., GSLs that require an external ballast or driver). These lamp types are less common and not analyzed in this report.

intermediate-base (E17), and mini-candelabra-base (E11) lamps, with candelabra-base lamps being the most common. Also included in the decorative lamp category are MSB B, BA, CA, and F-shaped lamps of 40W or less, which are candle-shaped, MSB T-shape lamps of 40 Watts or less or length of 10 inches or more, commonly used in wall sconces, and MSB S lamps of 40W or less, the variety of which that fall within DOE's GSL lumen range are most commonly vintage style and used in pendants and chandeliers. The miscellaneous A-type lamp category includes MSB rough service lamps, vibration service lamps, shatter resistant lamps, three-way lamps, and high-lumen lamps with lumen output greater than 2600 lumens and less than or equal to 3300 lumens. The globe-shaped lamp category includes MSB lamps having shape G16-1/2, G25, and G30, operating at 40 W or less. Globe-shaped lamps are frequently used in bathroom vanity applications. See Table 2 for a summary of the analyzed lamp categories, including defining characteristics, typical applications, and example lamps.

Table 2: Lamp Categorization

Lamp Category	Defining Characteristics	Typical Application	Example Lamp	
MSB Reflector	MSB; reflector shape (PAR, R, ER, BR, BPAR, or similar)	Recessed ceiling fixture	BR30 shape, MSB	
MR	Bi-pin or twist and lock base; multi-faceted-reflector shape	Track lighting	MR16 shape, GU5.3 base	
Decorative	Small-screw base (e.g., candelabra [E12] base) lamp or MSB lamp with B, BA, CA, F, T or S shape	Chandelier, sconce, pendant	B11 shape, E12 base	
Globe	MSB; globe shape	Bathroom vanity	G25 shape, MSB	
Misc. A-type	MSB; rough-service, vibration-service, shatter-resistant, three-way, or high-lumen lamp	Various	Three-way lamp: A21 shape, MSB	

There are additional non-EISA-explicit lamps that meet DOE's GSL definition (e.g., lamps with mogul base) that have not been included in the analyses described in this report due to lack of available data. The lamp types with the largest volume of sales have been included, and these are the lamps that are expected to contribute most significantly to the energy, CO2, and consumer savings associated with the backstop. Any corrections to these savings arising from the lamps not explicitly modeled are expected to be negligible.

2.2 Representative Lamps

As mentioned earlier, for each lamp category, our analysis considers a simplified market made up of a limited set of representative lamp options, which span the range of relevant features (technologies and efficiency levels) that will be impacted by the backstop. Each modeled lamp

option is meant to serve as a proxy representing a number of similar lamp options available to consumers. For each category, we chose a set of typical lamp properties and then constructed representative lamp options having these properties for each of the most common lighting technologies (traditional incandescent, halogen incandescent, or LED) in use within each category. While there are CFL options available for several of these lamp categories, sales of CFLs, which meet the 45 lm/W minimum efficacy specified by the backstop, are not directly impacted by the backstop taking effect. Given trends in the lighting market, such as NEMA lamp indices for A-type lamps indicating that CFL market share has been declining since 2014, while LED market share has been increasing, and the announcement by General Electric that it would cease production of CFLs for the U.S. market and instead focus on LED lamps, it was assumed that CFL market share has already saturated. (NEMA, 2016; Mark Egan, 2016) As a result, it was assumed that by 2020, incandescent and halogen lamps sales displaced by the backstop will be met exclusively by LED lamps. It is likely that the present-day market for CFLs will also naturally transition to LED technologies during this period; however, this transition will not be driven by the backstop requirement, since both CFLs and LED GSLs have efficacy exceeding 45 lm/W. As a result, for simplicity, CFLs were not included among the representative lamps considered in our analysis of the impact of the backstop. Instead, our modeling considers only the market segment that was utilizing traditional or halogen incandescent technology as of 2015, since the portion of this market segment that still utilizes incandescent technology as of 2020 is the only segment that will be directly impacted by the EISA backstop.

In selecting representative lamp options for the analysis, we required that each of our options (1) be dimmable (with the exception of three-way lamps), (2) have a color-rendering index (CRI) of 80 or greater, and (3) have a correlated color temperature (CCT) of approximately 2700 K. We looked at lamp offerings from popular lamp retailers and selected lamp options meeting these criteria with typical values for efficacy, lifetime, and CRI within each available technology. Shipments data were used to identify the most popular lamp types in the miscellaneous A-type and globe lamp categories. (DOE, 2016a, 2016b) Lamp model counts and sales rankings of lamp models from popular lamp retailers were used to identify the most popular lamp types in the MSB reflector, MR and decorative lamp categories (because shipments data disaggregated by lamp type were not available), and to identify the most popular lumen output range for representative lamps in each category. Prices for each representative lamp option were chosen to approximate the lowest cost for commonly available lamps with similar characteristics. Prices listed for the representative lamp options in Table 3 are for the year 2016. Future price projections are discussed in section 2.5.1.1.

Of the MSB reflector lamps in DOE's GSL definition, we identified BR30 lamps with a lumen output equivalent to a 65W traditional incandescent lamp as the most common variety[6].

[6] DOE's 2010 LMC estimates that approximately 70% of the installed stock of incandescent reflector lamps is traditional incandescent lamps, of which BR30 lamps are the most common variety, whereas approximately 30% of the stock is halogen incandescent lamps, of which PAR 38 lamps are the most common variety. Additionally, the

Thus we have selected such lamps as the representative lamp options. BR30 lamps come most commonly in versions utilizing traditional incandescent and LED technologies.

MR lamps are available in low-voltage and line-voltage types with different lumen outputs. We chose the most common type, 12-volt lamps with a lumen output equivalent to a 50W halogen lamp, for our representative lamp options. These lamps exist in versions using halogen incandescent and LED technologies.

The most common type of decorative lamp is candelabra (E12) base lamps. We chose to analyze the two most common types: lamps having lumen outputs equivalent to 40W and 60W traditional incandescent lamps. These lamps come most commonly in versions utilizing traditional incandescent and LED technologies.

Of the miscellaneous A-type lamps in DOE's GSL definition, three-way lamps (that provide three options for light output level) are the most common variety, and therefore they were selected as the representative lamp options for this category. Three-way lamps are commonly offered in traditional incandescent and LED technologies and 50-100-150W-equivalent lamps were identified as the most popular variety and thus taken as the representative option. The distribution of time during operation spent at each of the three lumen levels is unknown, so in the absence of additional information we assumed that the average light output of miscellaneous A-type lamps is equivalent to the average lumen output for the A-type lamps that were analyzed as part of DOE's 2015 notice of proposed rulemaking for GSL energy conservation standards. (DOE, 2016c, Chap. 8) That average lumen package was approximately 1000 lumens, and so in this analysis we use that same average lumen output for miscellaneous A-type lamps. Estimates of average wattage and efficacy corresponding to the average lumen output were derived from a linear interpolation of the relationship between wattage and lumen output from manufacturer's specifications for each representative three-way lamp option.

The most common type of globe-shaped lamp is a G25 lamp with lumen output equivalent to a 40W traditional incandescent lamp. These lamps most commonly utilize either traditional incandescent or LED technology. Table 3 presents the properties of all the representative lamps used in our analyses.

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typical wattage consumption of the most common type of halogen PAR38 lamp is approximately 70W whereas the typical wattage consumption of an equivalent LED PAR38 lamp is 11W, which would yield similar energy savings to BR30 lamps.

Table 3: Representative Lamp Options and Properties

Lamp Option	Technology	Wattage	Initial Lumens	Rated Lifetime (Hours)	Efficacy (lm/W)	Price (2015$)
MSB Reflector Lamps						
1	Incandescent	65	635	2000	9.8	$2.33
2	LED	8.5	650	10000	76.5	$3.33
MR Lamps						
1	Halogen	50	430	3000	8.6	$3.49
2	LED	6.5	500	25000	76.9	$7.27
Decorative 40 W-equivalent Lamps						
1	Incandescent	40	360	3000	9.0	$1.24
2	LED	4	350	15000	87.5	$5.99
Decorative 60 W-equivalent Lamps						
1	Incandescent	60	475	3000	7.9	$1.24
2	LED	6	500	25000	83.3	$5.65
Miscellaneous A-Type Lamps						
1	Incandescent	72	1000	1200	13.9	$1.99
2	LED	11	1000	10950	90.9	$16.97
Globe-shaped Lamps						
1	Incandescent	40	320	3000	8.0	$2.32
2	LED	4.5	350	25000	77.8	$6.32

2.3 Hours of Use, Energy Consumption, and Lifetime

Two critical inputs for estimating the impact of the backstop are the representative lamps' annual energy consumption (in kWh) and service lifetime (in years). These depend on properties intrinsic to the lamp design, such as wattage and rated lifetime in hours, as well as on consumer usage patterns, such as the daily hours of use for each lamp and the frequency and degree to which the lamps are dimmed.

Studies examining daily operating hours for lighting in the residential sector have generally looked at lighting in aggregate, and do not provide information on operating hours disaggregated to the level of the lamp categories discussed in this analysis. It is, however, possible to assess average operating hours for lighting by room type. DOE's GSL NOPR analysis considered a distribution of operating hours by room type for GSLs that was developed by taking the hours of use for specific room types found by one study and scaling by a national-average hours of use value, determined from a number of field metering studies conducted across the U.S. (DOE, 2016c, Chap. 7)

A study in California performed for the public utilities commission (KEMA, Inc., 2010) (henceforth the CPUC study) looked at more than 60,000 residential sockets and estimated the distribution by room type for reflector lamps, small-screw-base lamps, MR lamps and globe-

shaped lamps. In this analysis we build on the analysis done in the DOE's GSL rulemaking and assume that, on average, representative lamps for each lamp category installed in a given room type have the same average hours of use as the overall average hours of use for that room type. The national-average hours of operation for the MSB reflector, decorative, MR, and globe-shaped lamp categories were estimated based on the room distributions from the CPUC study for reflector, small-screw-base, MR, and globe-shaped lamps, respectively. In an attempt to correct for any differences in the hours of operation based on utilizing regional room distributions compared to what would be expected from national room distributions, average hours of use for each product category were additionally scaled by the ratio of national-average hours of use for MSB A-type lamps found in the GSL NOPR analysis to the average hours of use for MSB A-type lamps that result from the room distribution of MSB A-type lamps from the CPUC report.

As an example of the estimates resulting from this methodology, consider the average hours of use for globe-shaped lamps. The CPUC study indicates that 74% of globe-shaped lamps are installed in bathrooms. Bathrooms are known to have lower average operating hours than most residential room types. As seen in Table 4, the methodology used results in an estimated average daily hours of use value for globe-shaped lamps (1.7 hours per day) that is significantly lower than for the other lamp categories.

For the miscellaneous A-type lamps, the CPUC study did not estimate a separate room distribution. For such lamps, the national-average hours of use in the residential sector were assumed to be the same as the national–average hours of use in the residential sector found for MSB A-type GSLs in DOE's GSL NOPR analysis.

For the commercial sector, distributions by room type or building type are not available to substantiate differences in hours of use among the lamp categories analyzed. Instead, the same hours of use were assumed for representative lamps in each lamp category as were estimated in the GSL NOPR for MSB A-type lamps in the commercial sector. (This assumption has limited impact on the results because, based on the stock analysis discussed in section 2.4.1, the commercial sector represents less than 20% of the stock for all lamp categories analyzed, and significantly less than 20% for some categories.) Table 4 lists the average daily hours of use used in this analysis for each product category.[7]

[7] Consistent with the analysis and discussion in the GSL NOPR, we have assumed no rebound effect due to increased hours of use when a less efficacious lamp is replaced by a more efficacious lamp. This is based on estimates of hours of use from lighting market characterization reports that suggest the average hours of use of all lamps is flat or slightly declining over time, even as the lighting stock has become more efficient.

Table 4: Average Daily Hours of Use by Lamp Type and Sector

	Residential	Commercial
MSB Reflector	2.9	10.7
MR	2.9	10.7
Decorative	2.6	10.7
Misc. A-type	2.3	10.7
Globe-shaped	1.7	10.7

A lamp's unit energy consumption (UEC) is determined by its operating wattage, hours of use, and the effects of lighting controls, if any. Lighting controls can affect energy use by reducing the operating wattage (e.g., dimmers) or the hours of use (e.g., occupancy sensors). For the residential sector, we assume any reduction in hours of use from lighting controls is already implicitly accounted for in field metering studies of hours of use, but take into account the reduction in energy consumption as a result of dimming. A meta-study of lighting controls in commercial applications found a 30% reduction in energy use for systems that utilize lighting controls, such as dimmers, compared to systems that do not (Williams et al., 2012). Similar data do not appear to exist, at present, for the effects of lighting controls in the residential sector and so we assumed the same 30% energy reduction for lamps operating with dimmers in the residential sector.

In the residential sector we also assumed that for each lamp category the fraction of lamps installed on dimmers will remain constant at its 2010 level, which we estimated as follows. For MSB reflector lamps, decorative lamps, MR lamps and globe-shaped lamps, we first summed the product of the fraction of the corresponding lamp type installed in each room type in the CPUC study and the fraction of dimming controls by room type reported in DOE's 2010 Lighting Market Characterization (LMC) (Navigant Consulting, Inc., 2012). To correct for any geographic differences in the results reported by the CPUC study and the LMC, we scaled the resulting fraction of lamps on dimmers by the ratio of the national-average fraction of lamps on dimmers from the 2010 LMC to the fraction of lamps on dimmers that would result from the room distribution of MSB A-type lamps in the CPUC study. The representative three-way lamps in the miscellaneous A-type lamp category were assumed not to be operated with dimmers, because of the inherent capability to control the lumen output of such lamps. As discussed in section 2.1, the average lumen output of three-way lamps was assumed to be lower than their maximum lumen capacity, since they will often be used at a lower setting.

To determine the fraction of lamps operated with lighting controls in the commercial sector in each year of the analysis period, we used the trend from the GSL NOPR, which assumes an increasing utilization of controls over time, arising from updated building codes that are increasingly specifying lighting controls in commercial construction and renovation. (DOE, 2016c, App. 10C) The 30% energy reduction from lighting controls mentioned previously was

assumed to be applicable to any increase in lighting controls penetration in the commercial sector compared to the current lighting controls penetration.

We calculated the average annual UEC for each lamp using the following equation which incorporates the rated wattage, W; the average daily hours of use, HOU; the fraction of lamps installed on controls, $f_{controls}$; and the fractional reduction in energy use from controls, $f_{reduction}$.

$$UEC = W * HOU * 365 * (1 - f_{controls} * f_{reduction})$$

The average UEC for each representative lamp is listed in Table 5. Note that, as discussed previously, only the fraction of lamps operated on dimmers was included in $f_{controls}$ for the residential sector, since the effects of other controls are assumed to already be accounted for in the HOU calculation.

The final attribute of the representative lamp options needed as an input to our analysis is the probability of lamp retirement (owing to lamp failure or other reasons) as a function of lamp age. For each lamp option we developed a survival probability in each year of a lamp's life following the same methodology used in DOE's GSL NOPR methodology, which is detailed in appendix 8E of the GSL NOPR technical support document (TSD). (DOE, 2016c, App. 8E) To determine the survival probability as a function of lamp year (i.e., lamp age), we used a Weibull distribution of the following form:

$$P_{surv,rated}(y) = e^{-\left(\frac{x(y)}{\lambda_{rated}}\right)^{k_{rated}}}$$

In this equation, $P_{surv,rated}(y)$ is the lamp's probability of survival at lamp year, y (i.e., the number of years the lamp has been in service), based only on the lamp's lifetime rating, in percent; λ_{rated} is the Weibull scale parameter; k_{rated} is the Weibull shape parameter; and $x(y)$ is the fraction of the lamp's rated lifetime consumed at lamp year, y, in percent. The values of the scale and shape parameters—155.2 and 1.718, respectively—were based on a least-squares cumulative Weibull distribution fit to 3-hour cycle length survival data of CFLs. (James J. Hirsch and Associates and Erik Page & Associates, Inc., 2015)

To estimate $x(y)$, we developed sector-specific hours of use distributions for each lamp category based on residential and commercial field metering data (Ecotope, Inc., 2012; Navigant Consulting, Inc., 2014a), scaled to match the average hours of use for each lamp category in each sector. Then $x(y)$ was calculated using the lamp's rated lifetime and the sector-specific hours-of-use distribution, as follows:

$$x(y) = \sum_{i=1}^{n} \left(\frac{y \times HOU_i \times 365}{L_{rated}} \times f_{HOU,i}\right)$$

In this equation, i is the sector-specific (i.e., residential or commercial) daily hours-of-use bin; n is the total number of sector-specific daily hours-of-use bins; y is the lamp year, in years; HOU_i is the sector-specific daily hours-of-use corresponding to bin, i, in hours per day; L_{rated} is the lamp's lifetime rating, in hours; and $f_{HOU,i}$ is the sector-specific frequency corresponding to bin, i. We also incorporated the effects of dimming on the lifetime of incandescent lamps by using equations from the Illuminating Engineering Society of North America (IESNA) to calculate a multiplier for L_{rated} based on the lumen reduction for incandescent lamps operated with dimming controls.[8] (IESNA, 2000) This was applied to the fraction of incandescent lamps in each category that are operated with dimmers.

Owing to their long rated lifetimes, the median lifetime of residential LED lamps when modeled based only on the lamp's lifetime rating (i.e., the lamp year at which $P_{surv,rated}(y)$ equals 50%) can be quite large (longer than 30 years in the case of a residential LED lamp with a rated lifetime of 25,000 hours). We therefore used another Weibull model with a median lifetime of 20 years to truncate $P_{surv,rated}(y)$, for all lamp types and sectors, as follows:

$$P_{surv}(y) = P_{surv,rated}(y) \times e^{-\left(\frac{y}{\lambda}\right)^k}$$

In this equation, $P_{surv}(y)$ is the lamp's survival probability after being truncated by the 20-year Weibull model, in percent, and the other variables are as defined previously. The second multiplicative term of this equation represents the Weibull model we used to truncate $P_{surv,rated}(y)$, which has scale (λ) and shape (k) parameters equal to 21.5 and 6.0, respectively. We truncated $P_{surv}(y)$ with a Weibull distribution having a 20-year median as a means to ensure the median lifetime of residential LED lamps did not exceed what is taken to be a reasonable renovation time-frame: 20 years. While we used the survival distribution based on $P_{surv}(y)$ to model the lifetime of all lamps in the analysis, we note that the difference between $P_{surv}(y)$ and $P_{surv,rated}(y)$ is minor for incandescent lamps as well as all lamps in the commercial sector. Furthermore, we assumed that the lamp survival function does not change form temporally.

The retirement probability in a given year is the difference between the survival probability in that year and in the previous year: $P_{surv}(y-1)$ - $P_{surv}(y)$. The median service lifetime, in years, is the lamp year that has a survival probability of 50%. The service lifetime for all lamp options is listed in Table 5 below.

[8] We assumed that any impact on lamp lifetime from reduced average lumen output was already incorporated into the rated lamp lifetime for three-way incandescent lamps.

Table 5: UEC and Service Lifetime for all lamp options

Lamp Option	Lamp Technology	Residential		Commercial	
		Median Service Lifetime (years)	UEC (kWh)	Median Service Lifetime (years)	UEC (kWh)*
MSB Reflector Lamps					
1	Incandescent	2.5	66.9	0.5	229
2	LED	13	8.62	4.4	26.6
MR Lamps					
1	Halogen	4.2	51.4	1.4	176
2	LED	19	5.63	8.5	18.5
Decorative 40 W-equivalent Lamps					
1	Incandescent	5.4	36.4	1.5	141
2	LED	17	3.12	5.1	11.6
Decorative 60 W-equivalent Lamps					
1	Incandescent	4.6	54.7	1.5	211
2	LED	19	4.46	8.5	16.6
Misc. A-type Lamps					
1	Incandescent	1.5	61.2	0.5	281
2	LED	16	9.53	3.7	43.7
Globe-shaped Lamps					
1	Incandescent	6.8	24.4	1.1	141
2	LED	19.6	2.73	8.6	14.9

*Commercial UEC indicates the energy that would be consumed by a lamp over the course of a full year, even if the median service lifetime is less than a year.

2.4 Stock and Shipments

We developed a shipments model to estimate the consumer purchases of each representative lamp in each year of the analysis period in the base case and the backstop case. The model starts from initial estimates of the historical shipments of lamps in each category, as well as the present-day stock, and it projects these estimates forward using a stock-turnover modeling methodology. In this section we summarize our methods for estimating the historical shipments and stock and for projecting these quantities over the analysis period.

2.4.1 Historical Shipments and Stock Estimates

For several lamp types, we were able to initialize the shipments model based on incandescent shipments estimates for 2015 provided by the National Electrical Manufacturers Association (NEMA, a trade association including lamp manufacturers) in the context of either DOE's most recent rulemaking for certain lamps or in comments on DOE's notice of proposed definition and data availability for GSLs. (DOE, 2016a, 2016b) These lamp types include rough service lamps, shatter-resistant lamps, three-way lamps, vibration service lamps, lamps with lumen output greater than 2600 lumens and less than or equal to 3300 lumens, T-shape lamps of

40 Watts or less or length of 10 inches or more, and B, BA, CA, F, G16-1/2, G25, G30, S, M-14 lamps of 40 Watts or less[9].

To initialize our shipments model for MSB reflector lamps, MR lamps, and the subset of decorative lamps that have small-screw bases, we began by developing an estimate of the stock of those lamp types. To estimate the stock of MSB reflector lamps, we were able to use national estimates of the stock and technology mix. We were unable to find national data explicitly on the stock of small-screw-base and MR lamps, so we estimated the stock of those lamps in the residential sector by scaling the national stock of MSB A-type lamps in the residential sector by regionally-determined ratios of installed small-screw-base or MR lamps to MSB A-type lamps (as detailed below). We refined our stock calculation by estimating the fraction of the stock of small-screw-base or MR lamps that are within the lumen range in the GSL definition, and then estimated the fraction of the stock that use traditional or halogen incandescent technology.

The following equation describes the calculation to estimate the stock of incandescent small-screw-base or MR GSLs in the residential sector:

$$\mathbb{S}_{i,GSL,Inc,Res} = \mathbb{S}_{A,Res} \times \frac{f_{All,i}}{f_{All,A}} \times f_{i,GSL} \times f_{i,Inc}$$

Where the subscript *i* represents either the small-screw-base or MR lamp type, $\mathbb{S}_{i,GSL,Inc,Res}$ is the stock of (traditional or halogen) incandescent GSLs of type *i* in the residential sector, $\mathbb{S}_{A,Res}$ is the stock of MSB A-type lamps in the residential sector, $f_{All,i}$ is the fraction of the stock of all lamps in the residential sector which are type *i*, $f_{All,A}$ is the fraction of the stock of all lamps in the residential sector which are MSB A-type lamps, $f_{i,GSL}$ is the fraction of the stock of lamps of type *i* that are within the GSL lumen range, and $f_{i,Inc}$ is the average stock share of incandescent technology among lamps of type *i*.

$\mathbb{S}_{A,Res}$ was estimated based on the sum of the stock in the residential sector for general service A-type incandescent lamps, general service halogen lamps, and general service screw-base CFLs in the residential sector from the 2010 LMC (a national study with lamp inventory estimates by light source technology and sector for a few lamp types)[10]. The ratio of $f_{All,i}$ to $f_{All,A}$ was estimated using both the aforementioned CPUC study and the Residential Building Stock Assessment performed by the Northwest Energy Efficiency Alliance (Ecotope Inc., 2014) (henceforth the NEEA study) which surveyed more than 70,000 residential sockets in Washington, Oregon, Idaho, and Montana. We compared the fraction of lamps identified as

[9] Shipments estimates from NEMA for T-shape lamps of 40 Watts or less or length of 10 inches or more, and B, BA, CA, F, G16-1/2, G25, G30, S, M-14 lamps of 40 Watts or less represent sales from four lamp manufacturers representing a significant part of the market, but do not include shipments from other NEMA manufacturers or non-NEMA manufacturers. Additionally, it is unclear if the shipments estimates are restricted to the lumen range in DOE's GSL definition, though lamps within the lumen range are expected to represent a significant majority of sales of such lamps. In the absence of more precise data, we take NEMA's shipments estimates to be representative.
[10] Decorative lamps, reflector lamps, and miscellaneous lamps are accounted for separately in the 2010 LMC.

small-screw-base/decorative or MR to the fraction of lamps identified as A-type/spiral in the two regional studies and took a simple average of the stock ratios from each study to determine the ratio of $f_{All,i}$ to $f_{All,A}$. We estimated $f_{i,GSL}$ using data from the NEEA survey on lamp type, lamp wattage, and technology-type for each lamp in the survey. We took a simple average of the fraction of small-screw-base or MR lamps that were identified as traditional or halogen incandescent in each regional survey to estimate $f_{i,Inc}$. We assumed that regionally-based stock fractions were nationally representative.

For the commercial sector, to estimate the stock of incandescent small-screw-base lamps, we assumed the fraction of the stock of general service small-screw-base lamps in the commercial sector was the same as the fraction of the stock in the commercial sector (~2%) for MSB A-type lamps from the 2010 LMC. (We additionally assumed that this 98%-2% residential-commercial sector stock split would also be applicable to non-small-screw-base decorative lamps, globe-shaped lamps, and miscellaneous A-types lamps.) To estimate the stock of MR lamps in the commercial sector, we first looked at lamps identified as low-voltage halogen lamps in the 2010 LMC, which we assumed were all MR lamps. We adjusted this number to account for the fraction of lamps that fall outside of the GSL lumen range and then assumed that this represented 80% of the total stock of commercial MRs, with the remaining 20% being line voltage lamps, based on an estimate of the ratio between low- and line-voltage MRs from the California Energy Commission (Singh and Rider, Ken, 2015).

To estimate the installed stock of MSB reflector lamps in each sector, we took a similar, but simplified, version of the approach for small-screw-base or MR lamps. We were able to use the 2010 LMC to estimate the total stock of incandescent and halogen reflector lamps (identified separately from low-voltage halogen lamps) in each sector.[11] As with small-screw-base and MR lamps, we refined our incandescent reflector lamp stock estimates by estimating the fraction of all non-MR reflector lamps that fall within the GSL lumen range using data from the NEEA study. We further refined our estimate of non-MR reflector GSLs by estimating the fraction of non-MR reflector lamps that have a MSB based on model counts of reflector lamps from lamp retailers. We found that the vast majority (more than 95%) of non-MR reflector lamps have a MSB.

For the decorative lamp category, an additional step was needed to split the stock between the two types of representative lamps identified in section 0. We subdivided the subset of decorative lamp stock which is small-screw-base lamps into lamps with lumen output between 310 and 450 lumens (corresponding to a 40W equivalent lamp) and lamps with lumen output greater than 450 lumens (corresponding to a 60W equivalent lamp). Using data from the NEEA

[11] A stock estimate could also be derived following the approach for small-screw-base and MR lamps based on the fraction of lamps lamp identified in the CPUC study as "reflector" and in the NEEA study as "reflector" or "PAR". ("MR" lamps were separately identified in both studies.) An analogous procedure to the one described for small-screw-base and MR lamps would yield an installed stock estimate for MSB reflector lamps 18% higher than the estimate from LMC. The national study was assumed to be more representative.

study, we estimated the breakdown of the installed small-screw-base stock to be 70% 40W-equivalent lamps and 30% 60W-equivalent lamps. (All of the shipments of non-small-screw-base decorative lamps from NEMA were of the 40W-equivalent variety.) We assumed that the lumen-range breakdown for decorative lamps is identical in the residential and commercial sectors and does not depend on technology.

Finally, we developed 2010 shipments estimates for (traditional or halogen) incandescent small-screw-base, MR and MSB reflector lamps based on the installed stock estimates. To estimate the shipments in 2010, we divided the sector-specific incandescent stock in 2010 for each product type by the sector-specific average service lifetime, in years, for the representative (traditional or halogen) incandescent lamp option for that product type.[12] Similarly, the 2015 shipments of incandescent non-small-screw-base decorative, globe shaped, and miscellaneous A-type lamps from NEMA were subdivided by sector based on the ratio of the estimated share of the stock in each sector to the sector-specific average lifetime of the representative incandescent lamp option for that product type.

2.4.2 Stock Turnover Model

To project the stock of lamps into the future we used a stock turnover model similar to that used DOE's GSL NOPR analysis. This model calculates shipments in each year of the analysis based on demand for replacements of retired lamps (i.e., lamps that failed or were replaced in renovation) and for lamps to be installed in new construction. Chapter 9 of the GSL NOPR TSD describes the governing equations of the stock turnover model in detail. Broadly speaking, the shipments model projects future shipments by estimating the demand for new lamps in each year, for use in new construction and in replacement of retired lamps. The total (sector-specific) shipments of each lamp type in each year are then required to fulfill the total demand for that lamp type:

$$s_i(y) = D_{tot,i}(y) = D_{ret,i}(y) + D_{NC,i}(y),$$

Where $s_i(y)$ represents the shipments of lamp type i in year y, and $D_{tot,i}(y)$ is the total demand for type i in that year, which is made up of the demand for replacements of retired lamps, $D_{ret,i}(y)$ and the demand for lamps to be used in new construction, $D_{NC,i}(y)$.

The demand for retirement replacements is given by computing the number of shipments in past vintages v that are retired in year y, summed over all representative lamp options k within lamp type i:

[12] Estimated shipments of MR lamps were additionally reduced by 10 percent to account for those MR lamps that do not meet DOE's definition of a GSL, such as MR lamps smaller than 2 inches in diameter and MR16 lamps that operate at 12 volts and have a lumen output greater than or equal to 800 lumens. The 10 percent reduction was based on the fraction of MR lamp model counts that do not meet DOE's definition.

$$D_{ret,i}(y) = \sum_{k} \sum_{v<y} s(v) \times [P_{surv}(y - v - 1) - P_{surv}(y - v)],$$

where $P_{surv}(a)$ is the probability that a lamp survives to age a. The demand for new construction comes from assumed steady growth in the total stock of lamps, owing to growth in total floor space:

$$D_{NC,i}(y) = S_i(y - 1) * \gamma,$$

where $S_i(y - 1)$ is the total stock of lamp type i in year $y - 1$ and γ is the assumed fractional annual growth, taken to be 1.0% and 1.2% in the commercial and residential sectors, respectively, based on the floor space and housing stock forecasts in DOE's Annual Energy Outlook. (EIA, 2015) The total stock is given by summing up the number of surviving shipments from all past vintages, and summing across the representative lamp options k:

$$S_i(y) = \sum_{k} \sum_{v<y} s(v) \times P_{surv}(y - v).$$

The most naïve impact estimate would compare a backstop case that transitions all demand to LED technology in 2020 to a base case in which the market share by lighting technology would stay constant at its present value. This would suggest very large energy savings arising from the backstop. While this would yield an estimate of the total energy savings that accrue from the market for non-EISA-explicit GSLs transitioning to LED technology, this savings is not attributable solely to the EISA 2007 backstop but to a combination of the backstop, natural market forces, and policies already in place. So some portion of the savings would already be expected occur without the backstop.

In this analysis, as in the GSL NOPR analysis, we project an evolution in the market share of LED and incandescent lighting technology among non-EISA-explicit GSLs over time. The key difference between the present analysis and the GSL NOPR analysis is the method for allocating each year's shipments among the available lamp options. The GSL NOPR assigned market share using an econometric discrete-choice model (specifically a nested logit model), calibrated to consumer preferences for certain MSB A-type GSL properties, including first costs, energy use, lifetime, and mercury content. For the lamps included in this analysis, we were unable to find appropriate data to develop the parameters for a discrete-choice model, so we used a simplified method. In the base (no backstop) case, for each lamp type we developed a time series of projected market shares for each lamp option based on existing forecasts of market share by technology in the lighting market.

We started by considering the market shares of the LED lamp options. A recent report on SSL adoption from DOE's SSL program (Navigant Consulting, Inc., 2014b) projects SSL market

shares for 2015 through 2030[13]. The projections are based on an econometric model that incorporates a Bass adoption curve to predict the market shares of these products. A Bass adoption curve is a 2-paramter curve widely used to describe how new products diffuse into a market (Bass, 1969). If the fraction of the market is zero in an initial year, y_0, the market penetration, MP, in any later year y can be presented as:

$$MP(y) = \frac{1 - e^{-(p+q)(y-y_0)}}{1 + \left(\frac{q}{p}\right) e^{-(p+q)(y-y_0)}} \times MP_{max}$$

Where p is the coefficient of external influence (a parameter representing the influence of 'innovators' or early adopters on the market), q is the coefficient of internal influence (a parameter representing the influence of 'imitators' or late adopters on the market), and MP_{max} is a parameter controlling the maximum market penetration that is achievable by the new technology.

We fit a Bass adoption curve to the LED market-penetration forecasts presented in the DOE SSL report to project the LED market shares for each lamp type. For decorative, globe-shaped, and miscellaneous A-type lamps we used the DOE projections for the decorative lamp submarket[14]. For MSB reflector lamps and MR lamps we used the projections for the directional lamp submarket. For each lamp category the remaining (non-LED) market share in each year was fully allocated to the traditional incandescent or halogen lamp option.

In projecting shipments and stock over a thirty-year period, there can be significant uncertainty in long term trends. One particularly significant source of uncertainty in this analysis is the fraction of consumers that will continue to purchase traditional incandescent or halogen lamps even as LED options become more cost effective. This 'holdout' fraction specifies a fraction of the stock that is achievable for LED lamps in the absence of the EISA 2007 backstop by assuming that a certain fraction of consumers (representing a certain fraction of the stock) will consider only traditional incandescent or halogen lamps unless those lamp options are not available to them due to the backstop. A given holdout fraction corresponds to a maximum market penetration MP_{max} for LED lamps in the absence of the backstop. The forecasts from the SSL program that we used to derive our Bass adoption curve effectively assume a holdout fraction of zero. The present-day LED penetration for the lamps modeled here is quite low, however, so it is difficult to have certainty in a complete market transformation. Moreover, we

[13] SSL adoption projections from a more recent SSL report were not used because the report did not include market share projections and based faster adoption projections on NEMA sales indices for MSB A-type lamps, which are subject to different market pressures (and have historically been subject to different regulatory pressures) than decorative and directional lamps.

[14] DOE's projections for the decorative lamp market were used for miscellaneous A-type lamps because those lamps were not subject to the 2012-2014 GSIL standards and have only recently been added to the GSL definition, based on lamp sales and substitution risk from EISA-explicit A-type lamps. This suggests, in the absence of the EISA 2007 backstop, a slower adoption of LED lamps into this product category than for EISA-explicit A-type lamps.

note that in the case of CFL adoption in the MSB GSL market, which is the most direct analog available, CFLs achieved a maximum stock penetration of approximately 50% and a maximum market penetration of approximately 30% of shipments (at least prior to the compliance date for the EISA GSIL standards), despite the cost-effectiveness of the technology[15]. (NEMA, 2016) Given the substantial uncertainty in the holdout fraction we therefore explored several possible holdout-fraction scenarios in this analysis.

At the low end of plausible range of holdout fractions is a holdout fraction of zero. In this scenario, 100% of the installed stock for each of the lamp types considered in this analysis will eventually transition to LED technology, even in the absence of the EISA backstop's taking effect. At the high end of the plausible range is a holdout fraction of 50%, i.e., that 50% of the installed stock for each of the lamp types considered will be LED lamps by the end of the analysis period. This high-holdout fraction is consistent with the maximum fraction of the stock accounted for by CFLs in the MSB GSL market. Initial indications, such as LED lamp sales exceeding CFL sales for A-type lamps in the most recent quarters in the NEMA lamp indices, suggest that LED lamps may be more widely accepted by consumers than CFLs. (NEMA, 2016) So an estimate consistent with a holdout fraction midway between the holdout fraction for CFLs and a zero holdout fraction is also plausible. All three scenarios are presented in the results section.

To allocate market share among lamps in the backstop case, we assumed that after January 1, 2020 only LED lamp options are purchased, since they are the only option remaining that meets the minimum efficacy requirement for each lamp category. Thus, all lamps are LEDs starting in 2020 in the backstop case.

2.5 National Energy Savings and CO_2 Emissions Reduction

The national energy savings (NES) is the difference in the energy used by non-EISA-explicit GSLs in the base case and the backstop case. To calculate the national annual energy consumption (*AEC*) in each year, *y*, for each case, we multiplied the stock of lamps in that year by the average annual unit energy consumption (*UEC*) of each lamp type, *i*, to yield energy savings at the site of consumption in TWh (i.e., the reduction in energy consumption in homes and buildings, as would be reflected in a utility bill):

$$AEC(y) = \sum_i STOCK_i(y) \times UEC_i(y)$$

[15] The maximum CFL stock fraction of 50% is higher than the maximum shipments fraction of 30% that was mentioned previously. This difference is explained by the fact that CFLs have a longer service lifetime than the incandescent products they replaced; thus, their penetration in the installed stock will be higher than their overall share of shipments, since they persist in the stock for a longer period. Note, however, that cycle-time (on/off switching) effects reduce the lifetime of CFLs relative to incandescent products compared to what a simple comparison of rated lifetimes would suggest.

Site energy savings were then converted to a reduction in primary energy consumption at the source of generation (i.e., reduction in energy consumption at the power plant), measured in quads, by applying a site-to-power-plant conversion factor in each year of the analysis period, as developed by DOE in chapter 10 of the GSL NOPR TSD. (DOE, 2016c, Chap. 10) We also accounted for the full-fuel-cycle (FFC) energy use of lamps—which includes the energy required to extract, refine, and deliver primary fuel sources—following the methodology described in appendix 10B of the GSL NOPR TSD. (DOE, 2016c, App. 10B) Our analysis accounted for the energy used over the full lifetime of all lamps shipped during the 30-year analysis period. For long-lived lamps and lamps shipped late in the analysis period, this meant tracking energy consumption through 2088, the year in which the last lamp shipped during the analysis period is assumed to be retired. Following the methodology presented in chapter 10 of the GSL NOPR TSD, we also accounted for the ingrowth of lighting controls in the commercial sector (except for three-way lamps).

The estimated reduction in CO_2 emissions is computed from the energy savings in each year of the analysis by applying a multiplier representing the projected average carbon intensity per unit of electricity delivered. These multipliers are developed by DOE for its energy efficiency rulemakings, and are based on the projected mix of electricity generators on the grid; details can be found in appendix 10 B of the GSL NOPR TSD. We calculated the cumulative emissions reductions for the full lifetime of all lamps shipped during the analysis period. For comparison to other policy actions, we also computed the cumulative emissions reductions achieved through 2030, which is commonly used as a reference year for emissions reduction targets.

2.6 National Net Present Value

The national net present value (NPV) is the difference between the total costs to consumers (including first costs and operating costs) in the base case and the backstop case, discounted to a common reference year and summed over the years of operation for lamps shipped during 30-year analysis period. For consistency with the GSL NOPR we discounted all consumer costs to year 2015, and we computed results using discount rates of 3% and 7%. Following the methodology presented in chapter 10 of the GSL NOPR TSD, we also accounted for price trends over time.

The total first costs in a given year, $FC(y)$, are the installed price of a lamp option times the shipments of that option, s_i, summed over all lamp options. The installed price of a lamp is the purchase price of the lamp in that year, $PP_i(y)$,—taking into account price trends, as discussed below—including sales tax, t, and installation cost, IC_{sector}, if any. Mathematically, this can be expressed as:

$$FC(y) = \sum_i (PP_i(y) \times t + IC_{sector}) \times s_i(y)$$

We assumed that lamps installed in the residential sector had zero installation costs and lamps in the commercial sector had a per lamp installation cost of $1.45, consistent with the GSL NOPR analysis described in chapter 8 of the associated TSD.

The total operating cost in each year is the sector-specific average annual energy consumption, *AEC(y)*, for all lamp options, *i,* in the installed stock, multiplied by the sector-specific cost of electricity, *ep(y)*, summed over sectors:

$$OC(y) = \sum_{sector} \left[ep_{sector}(y) \times \sum_{i} AEC_{i,sector}(y) \right]$$

We used the same sector-specific electricity prices as the GSL NOPR which are discussed in chapter 8 and presented in chapter 10 of the associated TSD.

2.6.1 Price Trends

Prices for LEDs have been decreasing rapidly in recent years in a manner that is consistent with a so-called learning curve. (Gerke et al., 2014) Learning curves reflect systematic decreases in manufacturing costs resulting from cumulative production experience. (Wright, 1936; Yelle, 1979) Typically this manifests as a decline in consumer price as a power-law function of the cumulative shipments to market of a particular technology. Several recent studies have addressed the importance of considering price trends and learning effects when performing cost-benefit analyses for energy-efficient technologies. (Dale et al., 2009; Desroches et al., 2013; Van Buskirk et al., 2014; Weiss et al., 2010) To develop a consumer price trend for LED products this study, we developed an estimate of the cumulative LED shipments to date in each year of the analysis, and we applied the learning curve parameters measured for LED lighting products in a recent study to yield a price index for LED products in each year, relative to their 2016 prices. (Gerke et al., 2015, 2014) To estimate the cumulative LED shipments in each year, we compiled the cumulative LED shipments in each year of DOE's GSL NOPR analysis (no-new-standards case) and combined this with the cumulative LED shipments for LED products in the revised GSL definition that we project in the no-backstop case for this study. (DOE, 2016c, Chap. 9) The resulting learning curve is shown in Figure 1. Because the backstop will increase the cumulative shipments of LEDs for the product categories considered here, the actual LED learning curve will be marginally steeper than this in the backstop case. This effect is small, however, and it will only serve to increase the consumer benefits of the backstop, so we neglect it to be conservative. In contrast to LED products, we assume that incandescent (including halogen) technology is mature and that price learning will be negligible for incandescent lamps in the future, leading to flat real prices for these technologies.

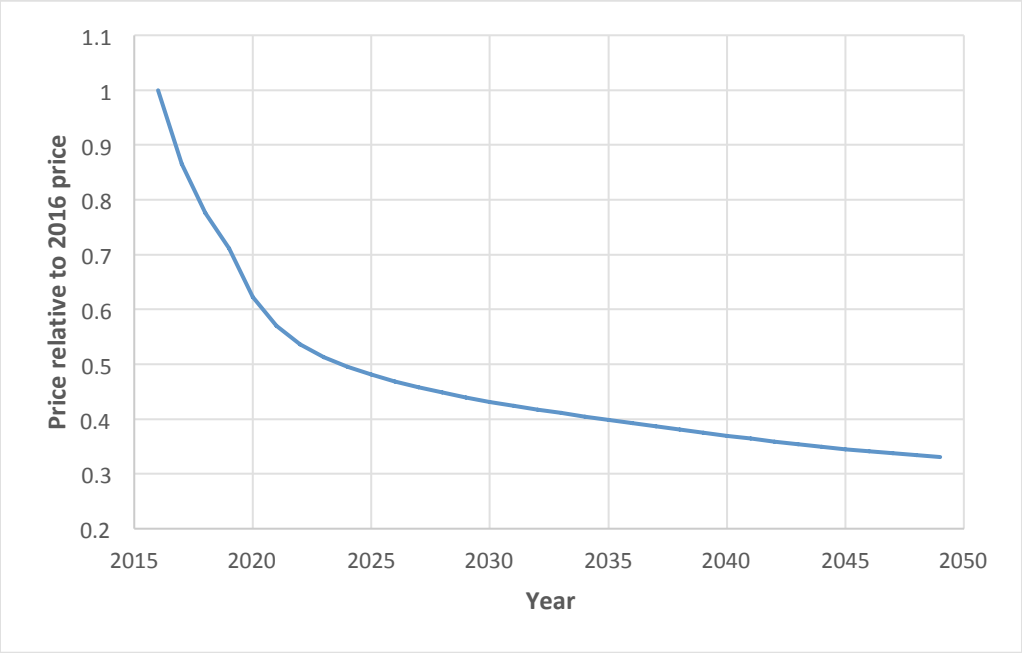

Figure 1: Price index for LED lamp options.

3 Results and Discussion

In this section we present the energy savings and consumer financial value estimated to result from the EISA 2007 backstop provision, as it applies the non-EISA-explicit lamps, based on the impact-assessment model outlined in section 2. In particular, we present the NES and consumer NPV arising from all lamps shipped to market over a 30-year analysis period, for an analytical case in which the backstop takes effect in 2020, as compared to a base case in which the backstop does not take effect. For ease of comparison to the NPV values that are commonly estimated for the adoption of DOE energy conservation standards as part of the federal rulemaking process, we report NPV values using assumed consumer discount rates of 3% and 7%.

As discussed in section 2.4.2, there is substantial uncertainty surrounding the ultimate level of LED market penetration that would occur for the non-EISA-explicit lamps in the absence of the backstop. We therefore present results for three different scenarios in this section, labeled by the assumed "holdout fraction," or fraction of sockets that would continue to have traditional or halogen incandescent lamps installed after LEDs reach their maximum market penetration. Specifically, we consider scenarios with a holdout fraction of 0%, 25%, and 50%. For our primary results, we use the 25% holdout fraction, as a central estimate of the eventual LED penetration.

3.1 Base Case

This section summarizes the model outputs for the base case, in which the EISA 2007 backstop does not take effect and the market follows current trends for the non-EISA-explicit lamps in DOE's GSL definition.

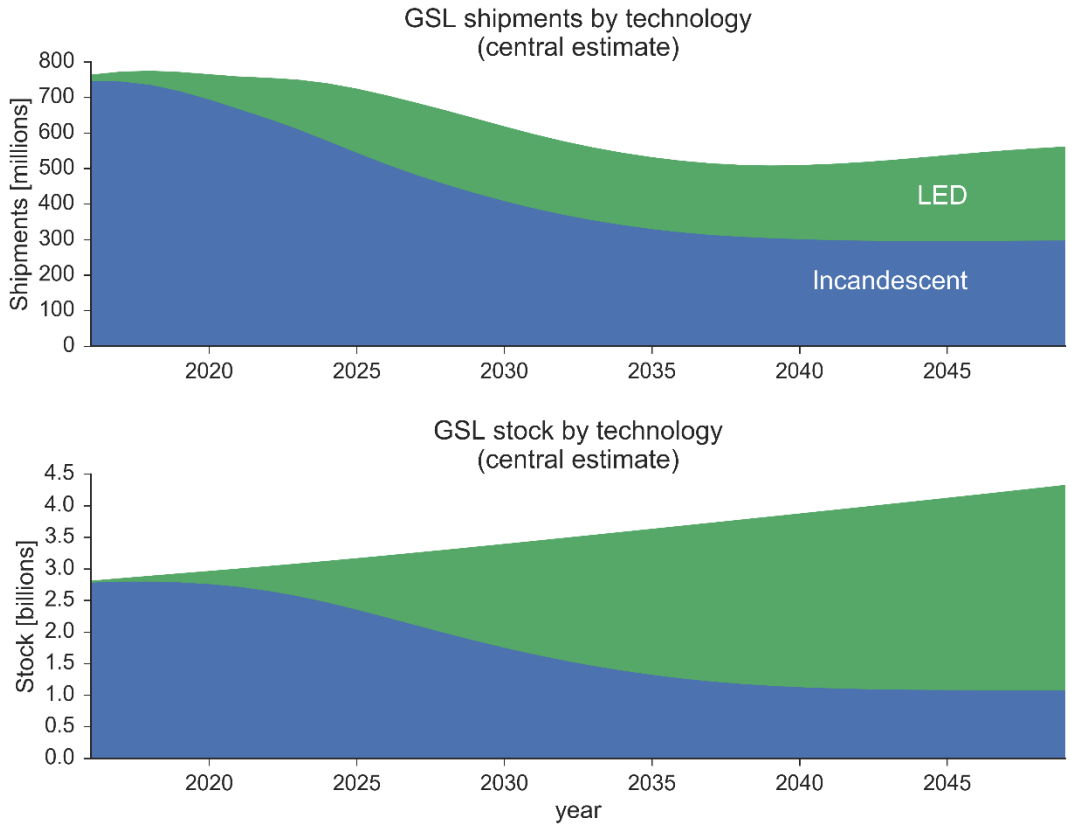

Figure 2: Shipments (top) and stock (bottom) volume by lamp technology, aggregated across lamp type and sector, in the base case for the central estimate scenario. Note the different scales of the vertical axes.

Figure 2 presents the annual shipments and stock volume by lamp technology, aggregated over lamp type and sector, for the central estimate (25% holdout) scenario, from the present day through the end of the analysis period in 2049. In the early years of the period, the shipments and the stock are mostly incandescent lamps, with a fraction of LED lamps that increases over time. The total stock (lower panel) grows steadily over the analysis period, driven by the overall growth that is projected for the US building stock over this period due to new construction. The assumption of a 25% holdout fraction means that 25% of all lighting sockets will continue to have incandescent (or halogen) lamps installed by the end of the analysis period; this is reflected in the LED fraction of the stock, which grows to 75% at the end of the analysis period. By contrast to the stock, there is a reduction in overall shipment volume over most of the analysis period as longer-lived LED lamps replace shorter-lived incandescent lamps, which reduces the

rate of lamp replacements, suppressing demand for new shipments. Toward the end of the analysis period, when the LED and incandescent market shares (and hence lamp replacement rates) have stabilized, overall shipments begin to grow again owing to demand from new construction. Incandescent lamps represent a larger proportion of shipments than they do of the stock throughout the analysis period, because their shorter lifetimes result in a higher demand for replacements compared to LED lamps.

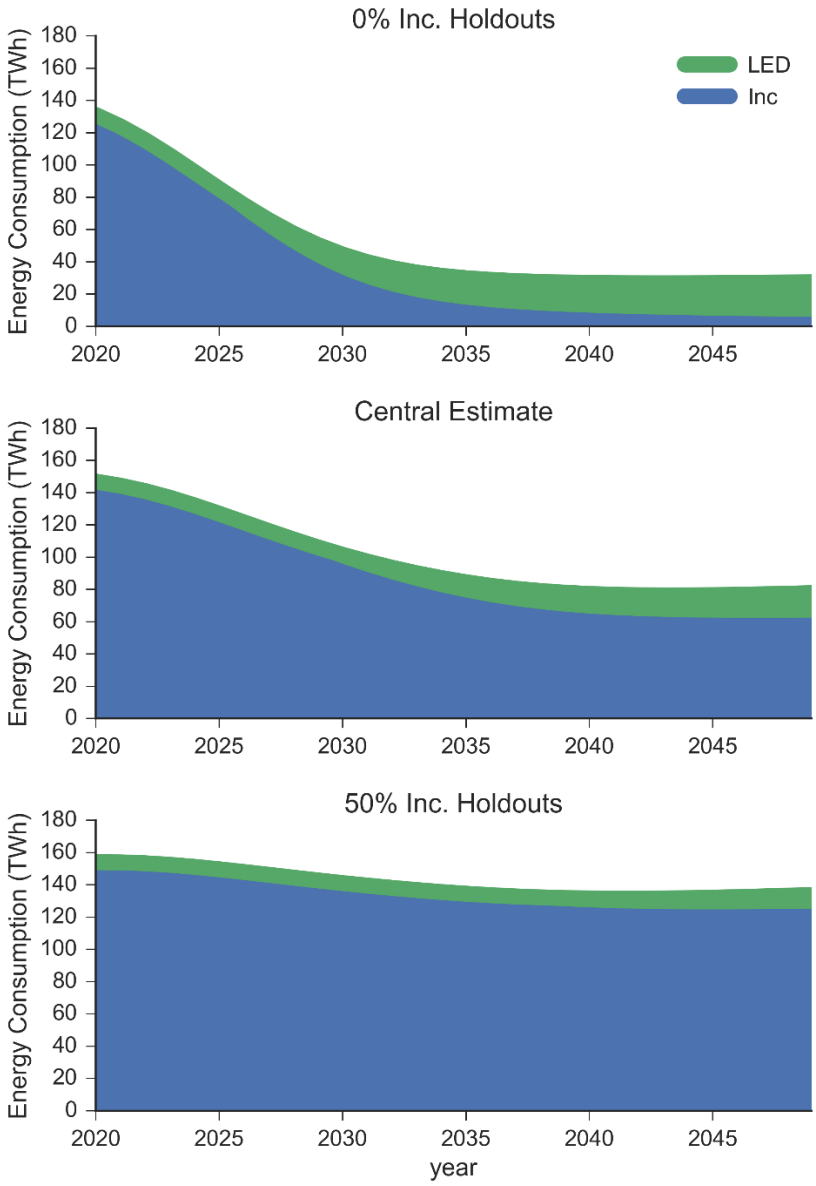

Figure 3: Site annual energy consumption by technology, aggregated across lamp type and sector, in the base case over the analysis period (2020-2049) for the three scenarios discussed in Section 2.4.2.

Figure 3 shows the site energy consumption by lamp technology, aggregated over lamp type and sector, for the three scenarios described in Section 2.4.2, over the 30-year analysis period from 2020 through 2049. From a comparison of Figure 2 and the central-estimate plot in Figure 3, one can see that incandescent lamps represent a much larger fraction of the AEC than they do of the stock. This is because of the large difference in energy use between incandescent lamps and LED lamps. In Figure 3, the blue wedge of energy used by incandescent lamps represents the energy-savings potential from the backstop in each scenario. For all scenarios considered, the annual energy-savings potential falls over time as existing policies and market forces increase the LED market share even in the absence of the backstop.

3.2 Impact of the EISA 2007 Backstop

As discussed in section 2, the impact of the backstop is estimated based on the difference in projected total national energy consumption, CO_2 emissions, and consumer costs in the base case and the backstop case. In the backstop case, all lamp demand for new construction and replacements is assumed to be fulfilled by LED lamps, yielding a substantial reduction in energy consumption and an attendant savings in energy costs. Since the LED lamps have significantly longer lifetime than the incandescent lamps they replace, there is also a significant reduction in overall lamp shipments, which is more than sufficient to offset any higher prices for LED lamps, so that the backstop case also results in a significant reduction in consumer expenditures for lamp purchases.

Figure 4 shows the annual site energy savings, in TWh, arising from the backstop in the central-estimate scenario, broken down by lamp category. For all lamp types, the energy savings peak relatively early in the analysis period due to the larger energy-savings potential at that time in the base case, as shown by the blue wedge in the central estimate panel of Figure 3. MSB reflector lamps and decorative lamps represent the largest contributions to the national energy savings among all analyzed lamp categories, reflecting the relatively large installed stock of such lamps in the U.S.

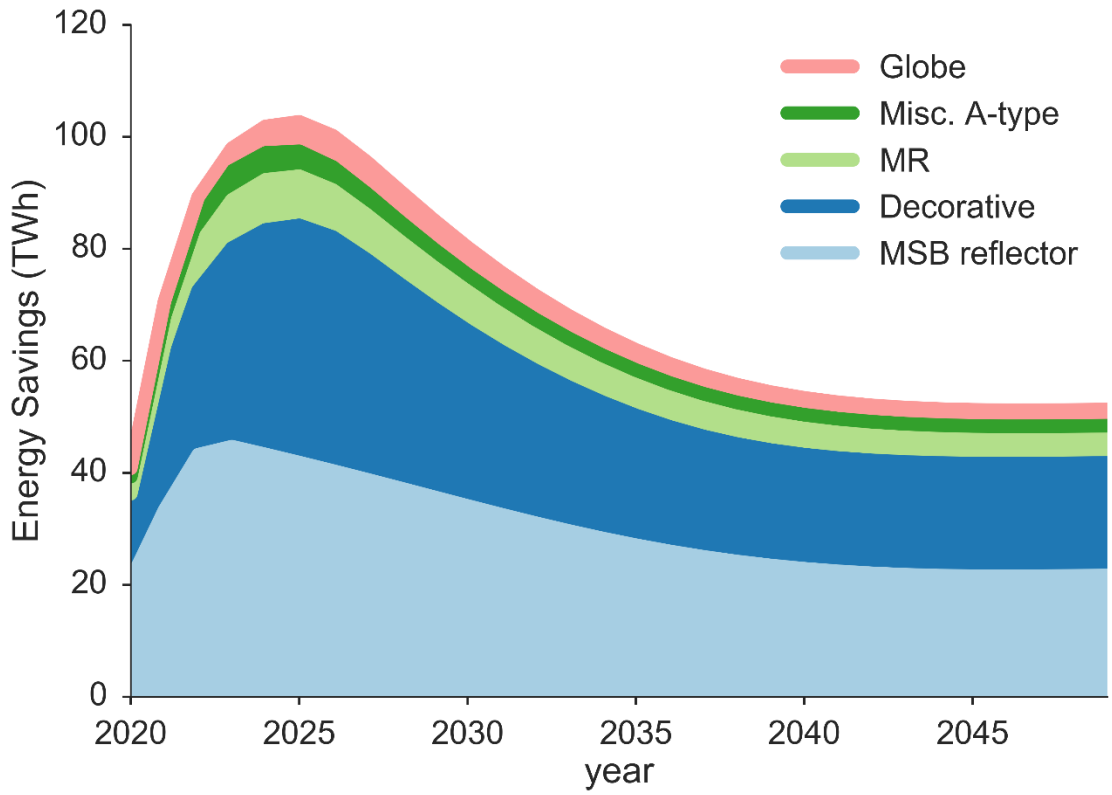

Figure 4: Annual Site Energy Savings by lamp type for the central estimate scenario. MSB reflector lamps and decorative lamps offer the largest share of energy savings.

As discussed in section 2.5, we convert the cumulative site energy savings in TWh to FFC energy savings at the generation source, in quads, by accounting for energy savings from generation, transmission and distribution, and primary fuel extraction, refinement, and delivery. In addition, we compute the associated reductions in CO_2 that accrue from these energy savings. We also compute the NPV of consumer savings arising from energy savings and altered lamp purchases, using the methods presented in section 2.6. Table 6: National Energy Savings, CO_2 Emissions Reduction, and Net Present Value at 3% and 7%, by Lamp Type and Sector, for the Central Estimate ScenarioTable 6 presents the cumulative FFC energy savings and NPV at 3% and 7% discount rates for lamps shipped between 2020 and 2049 resulting from the EISA 2007 backstop, for each analyzed lamp category and sector, in the central estimate scenario. Table 6 also includes CO_2 emissions reduction for each lamp category through 2030 and the total CO_2 emissions reduction for lamps shipped between 2020 and 2049. Table 7 presents total values for all three scenarios, summed across all lamp categories and sectors, for NES, NPV, and avoided CO_2 emissions. The fractional contributions from each lamp category and sector for the non-central-estimate scenarios are similar to those for the central estimate scenario presented in Table 6.

Table 6: National Energy Savings, CO_2 Emissions Reduction, and Net Present Value at 3% and 7%, by Lamp Type and Sector, for the Central Estimate Scenario

		Residential Sector	Commercial Sector	Total*
NES (FFC quads)	**MSB Reflector**	9.7	1.6	11
	MR	1.5	0.92	2.4
	Decorative	9.4	1.1	11
	Globe-shaped	1.4	0.14	1.6
	Misc. A-type	1.2	0.073	1.2
	Total*	23	3.8	**27**
CO_2 Savings Through 2030 (million metric tons)	**MSB Reflector**	200	35	240
	MR	28	20	48
	Decorative	180	28	200
	Globe-shaped	24	3.5	27
	Misc. A-type	24	1.9	26
	Total*	450	89	**540**
Total CO_2 Savings (million metric tons)	**All**	1200	200	**1400**
NPV 3% (Billion 2015$)	**MSB Reflector**	84	13	97
	MR	12	6.3	19
	Decorative	73	7.6	80
	Globe-shaped	11	1	12
	Misc. A-type	9.4	0.56	9.9
	Total*	190	29	**220**
NPV 7% (Billion 2015$)	**MSB Reflector**	47	7.6	55
	MR	6.6	3.6	10
	Decorative	38	4.5	43
	Globe-shaped	5.6	0.61	6.2
	Misc. A-type	5.1	0.34	5.4
	Total*	100	17	**120**

*Totals presented here may differ from the sum of the residential and commercial columns. The difference is due to rounding.

Table 7: National Energy Savings, CO_2 Emissions Reduction, and Net Present Value at 3% and 7% for Three Scenarios Considered

	No Holdouts	Central Estimate (25% Holdouts)	50% Holdouts
NES (FFC quads)	6.6	27	46
CO_2 Savings through 2030 (million metric tons)	300	540	680
Total CO_2 Savings (million metric tons)	360	1400	2300
NPV 3% (Billion 2015$)	72	220	350
NPV 7% (Billion 2015$)	51	120	170

Despite the expected widespread adoption of LEDs in the base case, the EISA backstop provision nevertheless yields large impacts, albeit with substantial sensitivity to the assumed incandescent holdout fraction. The NES is estimated to range from 6.6 to 46 quads over 30 years, in the three scenarios considered, with the central estimate corresponding to 27 quads. This is equivalent to the total energy consumption of all US households for a period of 7 months to 3 years. The net present value to consumers (discounted at 7%) ranges from $51 to $170 billion in the plausible scenarios, with the central estimate corresponding to $120 billion. As can be seen in Figure 4, the energy savings are somewhat weighted toward the earlier years of the analysis period. This results in more CO_2 savings per quad of energy saved than if the savings were shifted to later years, since the carbon intensity of the grid is projected to decrease over time as adoption of renewable energy sources grows. We estimate that the range of CO_2 savings associated with the backstop is 300 to 680 million metric tons through 2030, with a central estimate of 540 million metric tons, and 360 million to 2.3 billion metric tons, with a central estimate of 1.4 billion metric tons, when accounting for emissions over the full lifetime of lamps shipped from 2030 through 2049.

A flat-LED market share scenario, in which the market share by technology remains fixed at the 2015 value for each lamp type and sector in the base case, was also analyzed to estimate of the total energy, financial, and emissions savings that are available from the adoption of LED technology for the non-EISA-explicit GSLs. This total savings is quite substantial: transitioning fully to LEDs by 2020 would be expected to reduce US energy consumption by 67 quads and save 3.3 billion metric tons of CO_2 for lamps shipped through 2049, with a consumer NPV of $223 billion (discounted at 7%). These NES and NPV levels are more than double the central-estimate values, indicating that a substantial amount of the available energy savings from LED adoption in this market is expected to occur even in the absence of the EISA 2007 backstop, owing to existing policies and market forces.

3.3 Discussion

The large gap between the savings presented in the flat-LED scenario and the central-estimate scenario demonstrates the importance of projecting future market trends when estimating the impact of efficiency policies and programs: the estimated energy and financial savings from the EISA 2007 backstop is highly sensitive to the base-case adoption of LED lamps that is expected to occur in the absence of the backstop. An analysis that naively projected a pure business-as-usual scenario for the base case would greatly overestimate the impact of the backstop, as can be seen by comparing the flat-LED scenario to the more realistic scenarios presented here. Thorough consideration of potential future market trends also allows for an assessment of the range of uncertainty in the estimated policy impacts, as reflected in the range of results for the different holdout-fraction scenarios presented here.

It is worth noting, however, that the difference between the flat-LED scenario and the other scenarios should not be entirely attributed to natural evolution in an unregulated market. The EISA-explicit MSB A-type lamps have been the subject of previous efficiency policies, most notably the EISA standards that effectively phased out traditional incandescent technologies in favor of halogen, CFL, or LED technologies. It is likely that the increased market adoption of LED lamps among the non-EISA-explicit lamp types in the base case is driven in part by price declines and technological advances induced by technological spillover effects from EISA-explicit market segment. Thus, some fraction of the difference between the flat-LED and central-estimate scenarios could reasonably be attributed to follow-on effects previous efficiency regulation for GSLs. Any savings resulting from such effects have not been quantified to date in any analyses of policy impacts. The nature and extent of such secondary impacts of efficiency policies on broader technological trends are a ripe area for future study.

As Table 7 highlights, a significant source of uncertainty in estimating the impact of the backstop comes from the holdout fraction of consumers who would continue to purchase incandescent or halogen lamps as long as they are an available option[16]. For this analysis, we have taken the view that the holdout fraction could range from 0% to as high as 50%, which yields a very broad range in estimates of NES, NPV and avoided emissions. We also assumed, for simplicity, that this fraction of consumers would be the same in the residential and commercial sectors. In reality the fraction of commercial holdouts may be lower than in the residential sector, since commercial consumers may have greater sensitivity to operating-cost savings. The impact of a reduced holdout fraction in the commercial sector would be modest, however. We analyzed an alternative to the central-estimate scenario, in which the commercial

[16] An additional uncertainty in the NPV calculation is the portion of consumer savings that are off-set by consumer welfare losses that may be present because underinvestment in energy efficiency absent the backstop may result from rational consumer decision-making, and the portion of the benefits that reflect true welfare gains resulting from the correction of true demand side market failures such as consumer biases in projecting benefits or costs of energy efficiency improvements, imperfect information, bounded rationality, and split-incentive/principal-agent problems. This analysis also does not attempt to fully capture any benefits from the correction of potential supply side market failures such as underinvestment in innovation relative to the social optimum and imperfect competition.

holdout fraction was assumed to half as large as in the residential sector. Total savings were reduced by approximately 10% in this scenario.

Other sources of uncertainty exist as well. For example, the typical rated lifetime of LED lamps shipped to market may decline over time from the 25,000 hour lifetime we assumed in this analysis. This is potentially foreshadowed by a number of newer less-expensive LED lamp models that have been introduced to the market recently with rated lifetimes of approximately 15,000 hours. Recall, however, that our calculation of the lamp retirement probability (see section 2.3) assumed that lamps are retired when a space is renovated, regardless of whether they are still functional. In the residential sector, this means that a large proportion of LED GSLs are retired before reaching 25,000 hours of use. For this reason, reducing the rated lifetime of LED lamps from 25,000 hours to 15,000 hours has minimal impact on the results discussed here.

There is also uncertainty arising from the existence of lamps that fall just below the minimum lumen output of 310-lumens for GSLs. For example, some incandescent candelabra-base lamp models have a lumen output of approximately 300 lumens. Such lamps could potentially be used as a substitute for slightly higher-lumen output lamps that are eliminated by the backstop, instead of more efficacious LED lamps, thus reducing the energy savings achieved for these lamps. In this report we assume that such lamps will have a negligible impact on the estimated impact of the backstop as a result of market pressures arising from the market transformation to LED technology for lamps with lumen output of 310 greater and the reduced utility of lower-lumen lamps for consumers.

LED lamp efficacy trends are another source of uncertainty: DOE's SSL reports project average LED lamp efficacy to increase over time, whereas we have assumed constant efficacy for LEDs in this analysis. But an increase in the average efficacy of LED lamps would have minimal impact on energy savings estimates compared to the difference in energy consumption between incandescent and LED lamps. Moreover, this trend would tend to increase our estimated NES and NPV, so our present analysis is conservative in this regard.

Finally, additional uncertainty arises when one considers the future market adoption of so-called "smart" lamps (e.g., wirelessly-controllable or internet-connected lamps) which can allow for additional features and means of control and also include a standby load. We assume that the market adoption of such high-end lamps is driven by early adopters and thus would not be substantially impacted by the backstop. Overall, our results are much less sensitive to the open questions discussed here than they are to the uncertainty in the base-case holdout fraction.

4 Conclusion

In this report we estimate the impact of the EISA 2007 backstop on those lamps that meet DOE's definition of a GSL, but were not explicitly included in the GSL definition laid out in EISA 2007. We do so by projecting the total shipments of such lamps to the US market during a 30 year analysis period, as well as their energy use, purchase price, and operating costs, in

analysis cases for which the EISA backstop provision does and does not take effect. The difference in total energy consumption, CO_2 emissions, and discounted consumer expenditures between the two cases represents the impact of the backstop.

To model the impact of the backstop, we first divided the non-EISA-explicit lamps into five categories, defined by lamp shape and base type, based on their typical application. We then developed representative lamps for each lamp category, defined by key attributes such as lumen output, wattage, rated lifetime, and purchase price. We estimated the sector-specific annual energy consumption associated with each representative lamp based on lamp wattage and by developing an estimate of the sector-specific average daily operating hours for each lamp category, along with an estimate of the impact of lighting controls. We also characterized typical usage patterns for each lamp category, as represented by sector-specific distributions of the daily hours of use for each lamp category.

To project lamp shipments over the analysis period, we build a stock-turnover and growth model that accounts for shipments of lamps to the replacement market and to new construction. To estimate demand for replacements, we model the survival probability of each representative lamp, as a function of service life, using Weibull distributions incorporating the rated lifetime of each lamp representative lamp, our estimated sector-specific hours-of-use distributions, effects of dimming on lifetime for incandescent lamps, and the typical sector-specific renovation rate. New construction demand is estimated based on forecasts of growth in the building stock from previous DOE rulemaking analyses. For both the base case and the backstop case, we project the shipments and installed stock, by representative lamp, for each year of the analysis period, based on initial shipments and stock estimates and time-dependent market-share projections for the penetration of LED technology into each lamp category using standard Bass diffusion curves.

We compute the total national energy consumption in each case by summing the annual energy use for each lamp in the projected stock. Combining the annual national energy consumption with projections of electricity prices then yields the annual consumer operating costs, and applying emissions factors for energy generation to the estimated total national energy consumption yields CO_2 emissions in each case. We calculate the total consumer costs associated with lamp purchases in each case by summing the purchase price of all lamps shipped in each case, discounted to the present day, taking into account projected future price reductions for LED lamps. We compute the difference in total national energy consumption, associated CO_2 emissions, and total consumer NPV between the cases to estimate the impact of the backstop.

We examine three holdout scenarios in our shipments projection, corresponding to the fraction of consumers that will continue to purchase incandescent lamps even as LED options become more cost effective, to explore the largest source of uncertainty in our analysis. We find significant differences in the estimated energy savings, CO_2 emissions reduction and NPV arising from the backstop in the three scenarios considered, corresponding to 0%, 25%, and 50% holdout fractions. The differences are even starker if compared to an unrealistic flat-LED

scenario. For example, in the central estimate (25% holdout) scenario we estimate energy savings of 27 quads and a net present value to consumers (discounted at 7%) of $120 billion for lamps shipped between 202 and 2049 with CO_2 emissions reduction of 540 million metric tons through 2030, whereas a flat-LED market share scenario would yield energy savings of 67 quads and consumer NPV (discounted at 7%) of $223 billion for lamps shipped through 2049, with CO_2 emission reduction of 770 million metric tons through 2030. The difference in savings between these two scenarios highlights the importance of carefully projecting future market trends in the absence of policies, before estimating the impact of new efficiency policies.

We find considerable energy savings, carbon dioxide emissions reduction, and net present value arising from the application of the EISA 2007 backstop to the non-EISA-explicit lamps included in DOE's GSL definition rule. The carbon dioxide emissions reduction of 540 million metric tons by 2030 from the central estimate scenario represent 18% of President Obama's goal of carbon reduction of 3 billion metric tons from all efficiency standards for appliances and federal buildings set during his administration. The energy savings of 27 quads for lamps shipped between 2020 and 2049 in the central-estimate scenario is larger than the 20 quads of energy consumed by the entire U.S. residential sector in 2016 (including losses in generation, transmission, and distribution), as projected by DOE's Annual Energy Outlook 2016 report. (EIA, 2016) These results demonstrate the consequential nature of DOE's recent GSL definition rule in combination with the backstop requirement in EISA 2007.

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