System Dynamics Model of Residential and Commercial Lighting Markets

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Abstract

System Dynamics models are developed of the residential and commercial lighting markets. Rate of purchase of new systems are related to the installed base of existing systems, system component reliability, and construction. Buyer preferences are assumed to depend only on the characteristics of the lighting systems. Characteristics considered include price, efficacy, life, and color rendering. The preferences are represented by coefficients of a multinomial logit function are are calibrated against decades of historical data in an econometric fashion. Assuming buyer preferences stay constant for a comparable time into the future, projections are made for the market adoption of LED technology. The disruptive impact of lighting efficiency regulation is examined.

1 Introduction

1.1 Industry Change

The lighting industry is undergoing change at an accelerating rate. Driven by exponentially decreasing costs and steadily increasing performance, the light-emitting diode (LED) is now poised to displace nearly all incumbent light sources used for general illumination. The new LED lamps are being introduced by newcomers to the lighting market, thus changing the competitive landscape. In addition, disruptive global regulations of energy consumption and product efficiency have imposed performance requirements that have practically banned the dominant incumbent light sources. Regulations also provide incentives for LED lamps, also known as solid-state lighting (SSL), tilting the playing field towards LED lamps. How do we make sense of the impact on the market of new technologies and regulations?

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1.2 Intuition

We have developed system dynamics models to help determine the factors that set the size of particular markets. For the lighting industry, the market size is determined by the rate of purchase of lighting equipment, measured (say) in dollars per year. Using historical data, we determine the dominant factors that drive purchasing decisions. We develop a general model of lighting markets, onto which we impose the disruptive factors of new technology and regulation. The models help us to build intuition regarding the dynamics of the industry. While scenarios project market sales into the future, the models presented here are not intended to be used as a forecast.

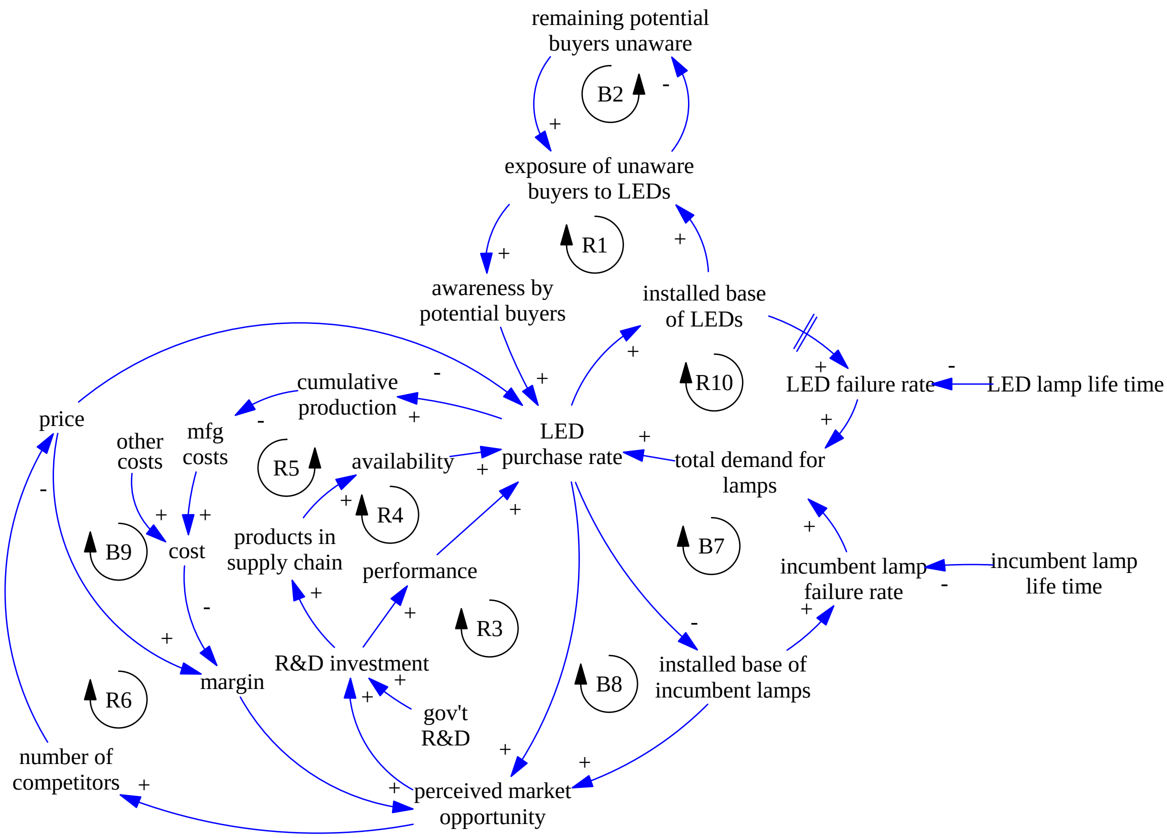


Figure 1: Feedback loops which determine dynamics of lighting industry option of a new technology.

Figure 1 shows the feedback loops that qualitatively describe the adoption of a new technology in the lighting marking, using the example of LED lamps. Reinforcing loop R1 show how exposure of potential buyers to the installed base of LED lamps leads to awareness and to LED lamp sales. Balancing loop B2 shows how the decreasing number of unaware potential buyers will eventually limit novelty purchases. Reinforcing loop R3 shows how R&D investment drives lamp peformance, which drives the rate of purchase, which increases the perceived market opportunity for LED lamps, which in turn drives R&D investment. Reinforcing loop R4 shows the contribution of products in the supply chain and of availability to the rate of purchase. Reinforcing loop R5 shows the learning curve effect, in which the rate of purchase leads to cumulative production, lower manufacturing costs, higher margin, and higher perceived market opportunity. Reinforcing loop R6 shows how the perceived market opportunity attracts competitors, which drives down price and increases purchase rate. Balancing loop B7 shows that with LED lamp purchases comes a decrease in the number of installed lamps, which means that the rate of failure of installed lamps decreases, decreasing the overall demand for lamps. Balancing look B8 shows that as the installed base of incumbent lamps dwindles, the perceived market opportunity decreases too. Balancing loop B9 shows that as competitive pressure decreases prices, the reduced margins also depress the perceived market opportunity. Reinforcing loop R10 shows the complementary dynamics for LED lamps that B7 shows for incumbent lamps; it is the balance between B7 and R10 that determines the equilibrium rate of sales after the adoption phase is complete.

1.3 Organization

This paper will be organized as follows. Sections 2 and 3 present models for the residential market for light bulbs and the commercial market for four-foot fluorescent fixtures, respectively. In each of those sections, we present a reference mode, our assumptions, a stock-and-flow model, a discussion of the factors of buyer preferences, econometric calibration of the model, and a discussion of the results. Section 4 discusses the extensions of the model, and Section 5 provides conclusions. Calculations that are important but not central to the paper are relegated to the appendix.

2 Residential Lighting Market

2.1 Reference Mode

Figure 2 shows the most common lamp types used in residential applications which all fit into the "Edison" medium screw-base socket. Figure 3 shows an index[1] from the National Electrical Manufacturer Association (NEMA) which is proportional to the unit sales of incandescent, halogen, and compact fluorescent lamps.[1] Before 2000, practically all the lamps in residences were incandescent[2], but starting around 2003 compact fluorescent lamps started to command an appreciable fraction of the market at the expense of incandescent lamps. Total unit sales declined, since compact fluorescent lamps have longer service life. Sales of compact fluorescent lamps and incandescent lamps stabilized around 2008. Over the same time period, unit sales of halogen lamps were comparatively small.

[1] The procedure for rescaling the published NEMA indices is described in the appendix.

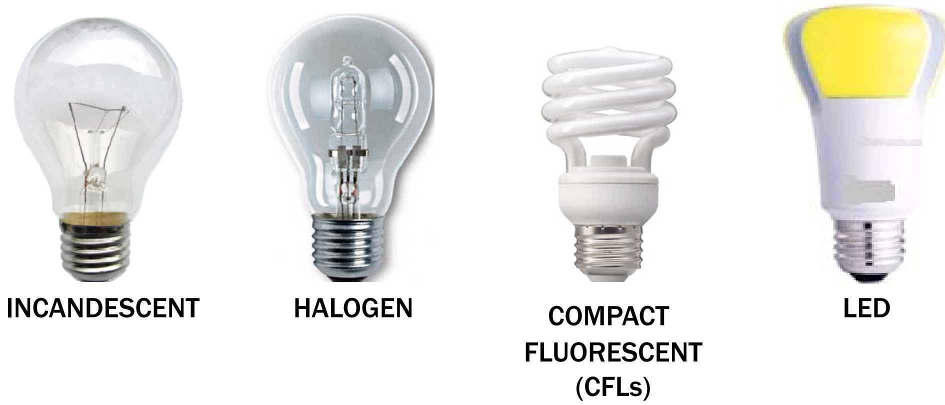


Figure 2: Common lamp types used in residential applications

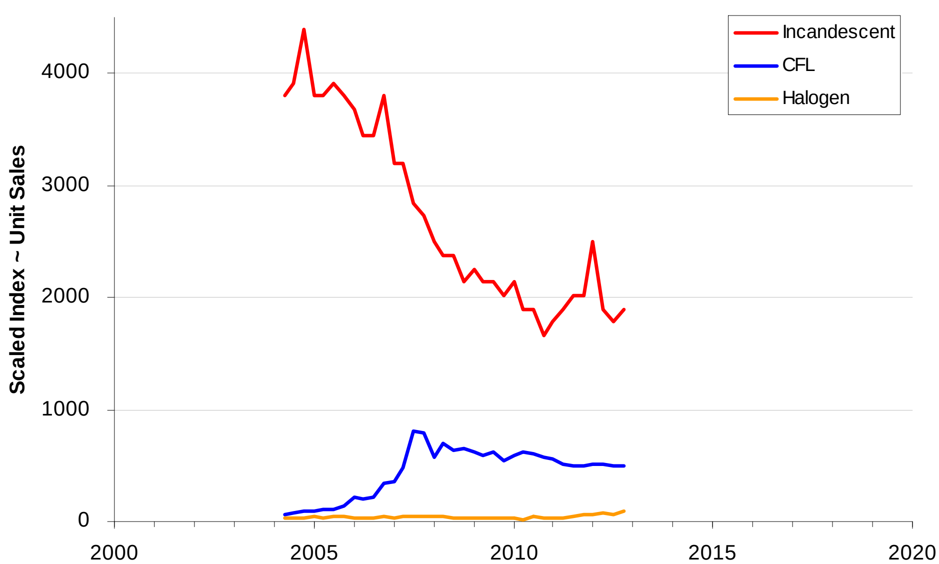


Figure 3: Scaled NEMA Incandescent index, proportional to lamp unit sales. Source: NEMA[1], `http://www.nema.org/Intelligence/Pages/Lamp-Indices.aspx`, scaled according the procedure in the appendix.

The rise of CFL sales was accompanied by an exponential decline in the CFL unit price, and CFL unit sales leveled out when when CFL prices leveled out.

Rated Lumen Ranges	Maximum Rate Wattage	Effective Date	Common A-lamp Incandescent "Banned"
1490-2600	72	1/1/2012	100W
1050-1489	53	1/1/2013	75W
750-1049	43	1/1/2014	60W
310-749	29	1/1/2014	40W

Table 1: Excerpt from Energy Independence and Security Act[3]. Incandescent A-lamps affected can be determined using the approximation $L \approx 5p^{1.28}$, where L is the output in lumens and p is the rated power in watts.

Table 1 shows an excerpt from the US Energy Independence and Security Act of 2007, which imposed performance requirements on lamps which fit into the medium screw-base socket. While not immediately obvious from the table, the law practically bans incandescent lamps. To produce a given lumens of light (first column), incandescent lamps consume more power than allowed by the law (second column). After the effective dates (third column), manufacture and import of common incandescent lamp types (fourth column) will be illegal. Sale of preexisting inventory and ownership of incandescent lamps is still permitted. A backstop provision of the law will likely ban the sale of halogen lamps in 2020.

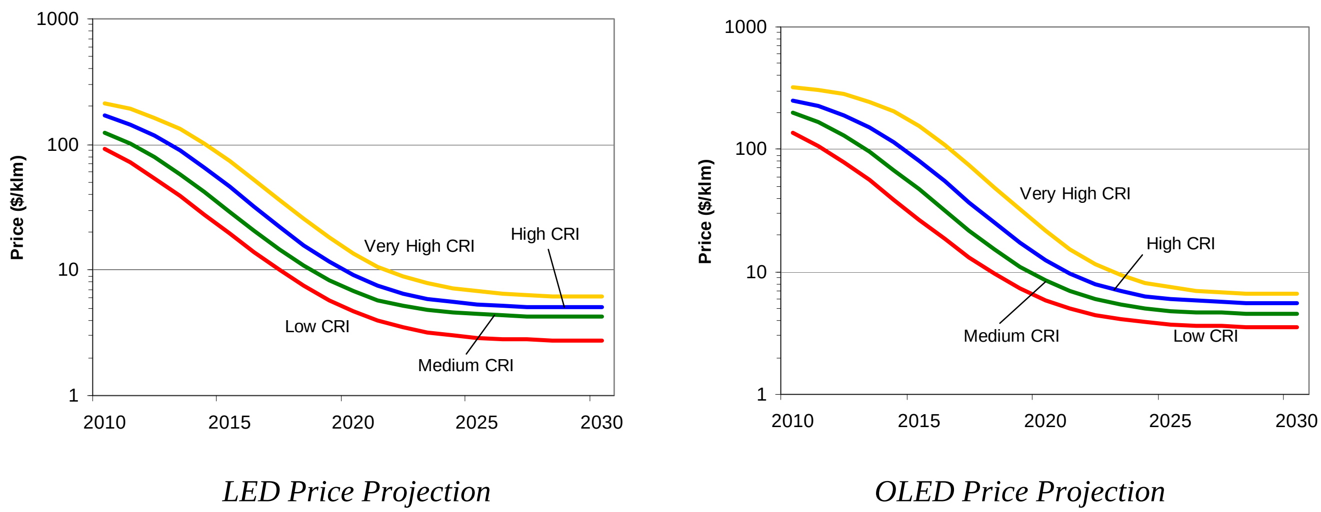


Figure 4: Reference mode for LED prices. (Source: Figure 5.2 in US DOE report "Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030", Feb 2010.[4]) Before leveling out, LED price decay obeys Haitz's law, see [5].

Before 2010, LED lamps commanded a negligible fraction of the residential market unit sales. As projected in Figure 4, LED lamp prices have been declining exponentially, in accordance with "Haitz's Law"[5], and have recently descended to the range considered affordable by the general public.

We develop a System Dynamics model of the residential lamp market to develop insight how the market will respond to the incandescent ban, and how consumers will allocate their preferences amongst the remaining lamp types (halogen, CFL, and LED) as the price of LED lamps continues to drop.

2.2 Assumptions

Residential construction adds about one percent per year to the existing housing stock, and residential demolition is negligible.[6] Since incandescent bulbs have a service life of about one year, we note that the annual sales of replacement bulbs in the existing house stock greatly exceeds the sales of bulbs for new construction. Accordingly we neglect new construction altogether.

Conversely, we assume that residential customers buy a new light bulb only when the light bulb in the existing socket has failed.

Combining the above assumptions implies that the size of the market is determined by the size of the installed base and the reliability of the installed lamps.

The essential structure of the model can be summarized as follows:

1. Lamp Kinetics
   (a) Consumers buy lamps to fill empty lamp sockets.
   (b) The lamp sockets become empty according to usage and lamp life.
2. Consumer Preferences
   (a) Consumers choose amongst the available lamp types based on the economic utility.
   (b) Economic utility is based only on characteristics of the lamp, e.g. price, life, color rendering index, etc.
   (c) Utility coefficients are determined by a fit to historical data.
   (d) Utility coefficients are assumed to remain constant in the future.

2.3 Stock and Flow Model

Figure 5 shows a stock-and-flow model for the residential lamp market, using the notation described by Sterman [7].

The stock of installed light bulbs decreases as light bulbs are removed from service due to failure. The bulb failure rate depends on the typical usage as well as the life of the particular light bulb type. The stock of installed light bulbs increases with light bulb sales, which for each bulb type depends on the overall demand rate for light bulbs as well as the probability

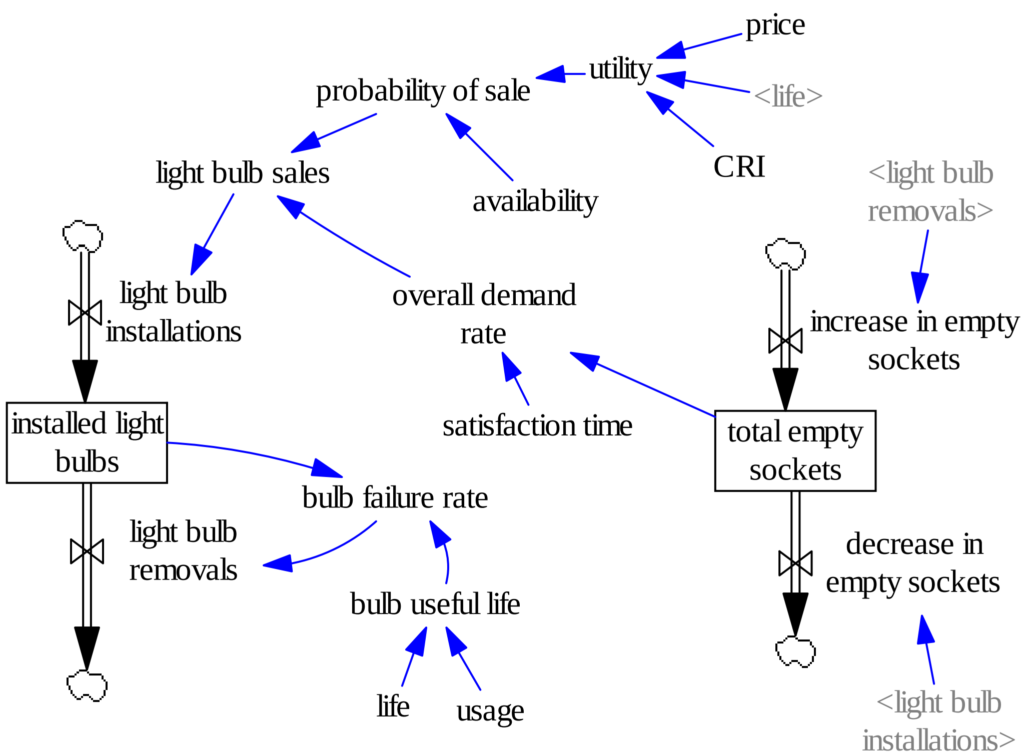


Figure 5: Stock and flow model for types of light bulbs used in residential applications.

of sale for each particular light bulb. The probability of sale depends on the economic utility (described in the next subsection), as well as the availability.

Availability is a simple proxy for both innovation and regulation: a light bulb type cannot be sold before it has been invented, or before the supply chain has been fully primed, and a light bulb cannot be sold after it has been banned.

The overall demand for light bulbs is determined by the total number empty sockets, as well as the typical time between when a light bulb fails and a replacement in purchased. Every time a light bulb fails and is removed from service, the total number of empty sockets increases and thus generates "demand". Demand is satisfied when the number of empty sockets decreases, i.e. when a light bulb is installed after purchase.

Since we neglect new construction and demolition, the total number of sockets is assumed to be constant.

2.4 Buyer Preferences

Buyers of light bulbs are assumed to allocate their preference amongst the (available) light bulbs in a way that depends only on the characteristics of the light bulbs. While there are many characteristics that could potentially influence consumer preference, we are looking those few characteristics that most influence preference. For the market of light bulbs in residential applications, we choose just three characteristics: unit price; life; and color rendering index (CRI).

To model consumer preferences, we start with multinomial logit model as described by Ben-Akiva [8], modified to account for lamptype availability. Let us consider four lamp types (incandescent, halogen, CFL, and LED) which we label with the index i. Let us consider three characteristics of each lamp type (price, life, CRI), which we label with the index j. The lamp characteristics form a matrix, with elements x_{ji}. Let U_i represent the economic utility of the ith lamp type. We assume that the utility is a linear function of the characteristics:

$$U_i = \sum_{j=1}^{3} \beta_j x_{ji}, \tag{1}$$

where the constant coefficients β_j are to be determined. Let A_i represent the availability of the ith lamp type: $0 \leq A_i \leq 1$. We assume the demand share captured by the ith lamp type follows

$$f_i = \frac{A_i \exp(U_i)}{\sum_{i'} A_{i'} \exp(U_{i'})}. \tag{2}$$

In general the characteristics x_{ji} and the availability A_i change as a function of time, and so will the fractions f_i.

Note that the approach for consumer preferences adopted above allows us to project the sales of a completely new lamp type (e.g. LED lamps) for which we have no historical sales data. Along with the assumption that consumer preferences remain constant (coefficients of the utility function), we need only to know the lamp characteristics to determine the utility.

2.5 Econometric Calibration

In an econometric fashion, we "calibrate" the model by adjusting the utility coefficients until we obtain a fit with historical data. This also serves as a partial check that we have selected the right characteristics.

Lamp Type	Average Price (s.d.)		Efficacy	Use	Life	Installed (2001)
units	$/lamp		lum/W	h/d	h/1000	M
Incandescent	0.428	(0.017)	14.5	2.7	1.7	4306
Halogen	2.168	(0.055)	12.3	7.3	3.6	91
CFL	2.219	(0.087)	52.3	5.9	9.5	128

Table 2: Characteristics of incandescent, halogen, compact fluorescent, fluorescent, and high intensity discharge lamps. Average lamp price and sales share derived from unpublished data collected by National Electrical Manufacturer's Association [9]. Typical efficacy, typical usage, typical life, and installed base in 2001 taken from US Department of Energy Lighting Market Characterization [2].

Model projections for sales fraction of incandescent, halogen, and CFL lamps were compared with data from NEMA. [1] Table 2 shows some of the relevant lamp characteristics used for calibration.

2.6 Results

The dashboard in Figure 6 shows light bulb unit price, availability, unit sales, and dollar sales.

The dashboard lower left plot shows the availability of GLS incandescent (red trace), halogen (orange trace), CFL (blue trace) and LED lamps (green trace) as functions of time. Before 2010 all lamp types were available except LED, which were practically unavailable. LED lamp availability in assumed to increase linearly until it is fully available by 2020. [2] The incandescent regulatory ban is modeled by a series of steps on the legislation effective dates. The halogen backstop provision is assumed to force halogen availability to zero 2020.[3]

The dashboard upper left plot shows the unit price on a log scale. LED lamp prices (green trace) have as recently as 2010 been around $100 each, but have been declining exponentially. A decade earlier, CFL price (blue trace) went through a similar exponential decline, until they stabilized around 2007. Halogen and incandescent prices are assumed to be constant.

The model has been calibrated with a decade of data historical unit sales data, shown in the upper right plot.

[2]The model user can select their estimate for the year when LED lamps become fully available.

[3]To address the possibility that the backstop provision is repealed, the model user can select their estimate for the year when halogens become unavailable, if ever.

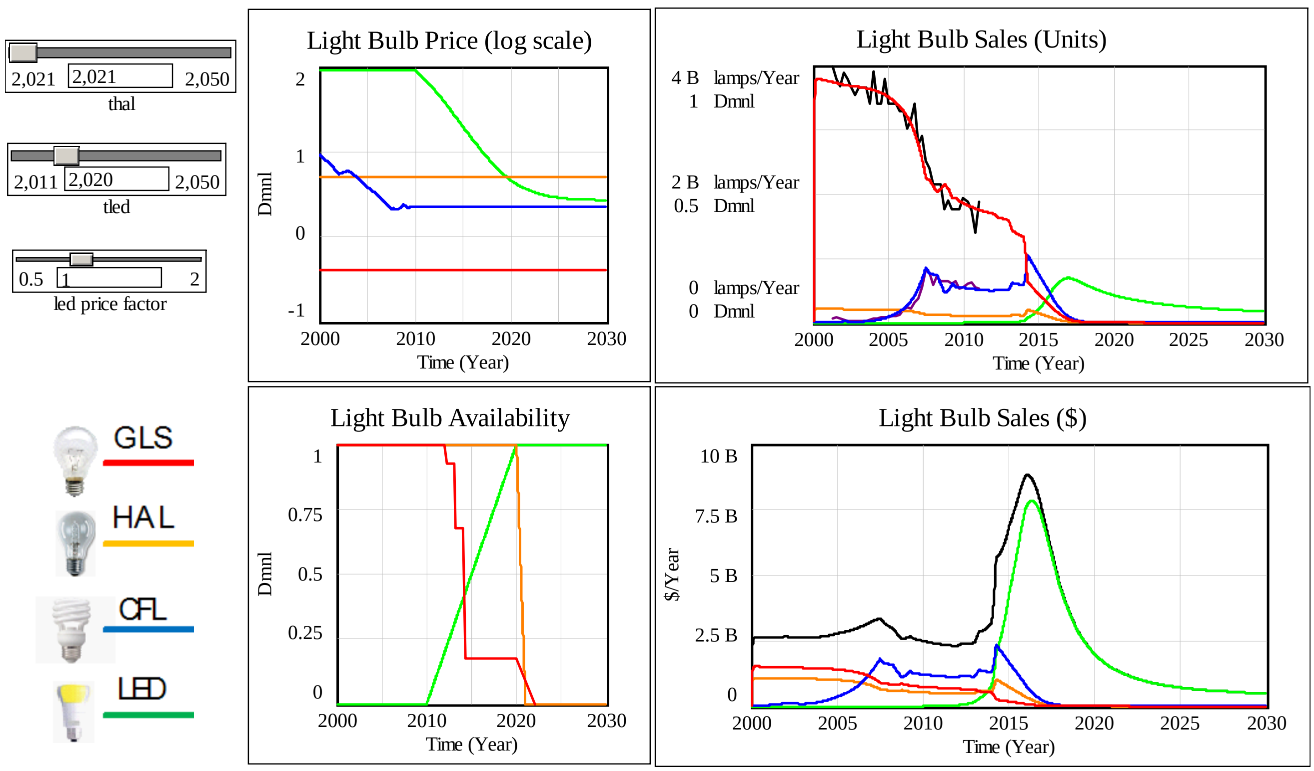


Figure 6: Residential model dashboard.

The lower right plot shows the total dollar sales (black trace) was historically stable at around \$2.5 B/y, split amongst cheap incandescent and expensive halogen light bulbs. A slight bump accompanied the arrival of affordable CFLs in 2007, and the market settled into a new equilibrium, with CFLs commanding the majority of market dollars. The arrivals of affordable LED lamps coincides with the regulatory ban of incandescent lamps.

LED lamps are expected to have life exceeding 30,000 hours, amounting to nearly thirty year service life. LED color rendering index is expected to be better than CFL, approaching incandescent. Thus once the LED lamp price descends to the range of the incumbent light sources, the LED lamp economic utility is the highest amongst all light sources and the market share dominates.

Total dollar sales for the lamp market rises (in this scenario) to nearly \$8 B/y, but then collapses to a value less than one third before the LED revolution. To understand why, consider: (a) The long LED life means the light bulb replacement rate is approximately 1/30 of the value during the reign of incandescent. (b) LED prices are projected to decline below the price of halogen light bulbs.

How sensitive is collapse of the residential light bulb market to the unknown parameters of LED availability and LED price? The model user can adjust those factors and confirm that while the timing and abruptness of the collapse , the existence of the collapse persists.

For simplicity, we neglected new housing construction. But perhaps by considering new housing construction we would not observe a collapse? Adding new housing construction to the model adds realism (and complexity), but does not fundamentally change the dynamic behavior. (In the commercial market we will consider new construction and retrofit in detail.)

We can trace this behavior in the model to the one of the original assumptions: that light bulb sales are driven by replacement of failed previously-installed light bulbs. A company could alter this dynamic if they could persuade consumers replace lamps *before* they have failed by offering a characteristic that customers value more than price, life, or CRI. For example, in late 2012 Philips introduced an LED light bulb whose intensity and color can be controlled through an Apple iPhone.[10]

3 Commercial Lighting Market

3.1 Reference Mode

Figure 7: Examples of commercial lamps, ballasts, and LED fixtures.

Commercial lighting has been dominated by energy-efficient fluorescent lighting since before 1990. A complete fluorescent luminaire is comprised of cylindrical lamps, a ballast which drives current through the lamps, and mounting hardware to hold the lamps and ballast and to direct the light. Typical components are shown in Figure 7.

Fluorescent lamps are described by their length, measured in feet, and their diameter, measured in eighths of an inch. The “T12” lamps have a diameter of one and a half inches, and were first introduced in 1939. T8 lamps have a diameter of one inch and became commercially available in the 1980s. T5 lamps have a diameter of five eighths of an inch were introduced in the mid 1990s. In general T8 lamps have a higher efficacy than T12 lamps: T8 lamps produce more visible light, measured in lumens, for each watt of electrical power they consume. In addition, smaller diameter lamps permit fixture optics to direct the light with more precision.

As lamps have evolved, so have the associated ballasts. In fact, lamps and ballasts have often been designed to work with each other to provide cost-effective solutions. The T12 ballasts were of so-called “magnetic” design, consisting of a simple iron-core transformer driving the lamp current at the mains frequency, 60 Hz. Around the time T8 ballasts were introduced, ballast had evolved to “electronic” design, consisting of a switched-mode power supply driving the lamp current at high frequency, greater than 20 kHz. Driving the fluorescent lamp at high frequency improves the efficacy, so T8 systems have a significant performance advantage over T12 systems.

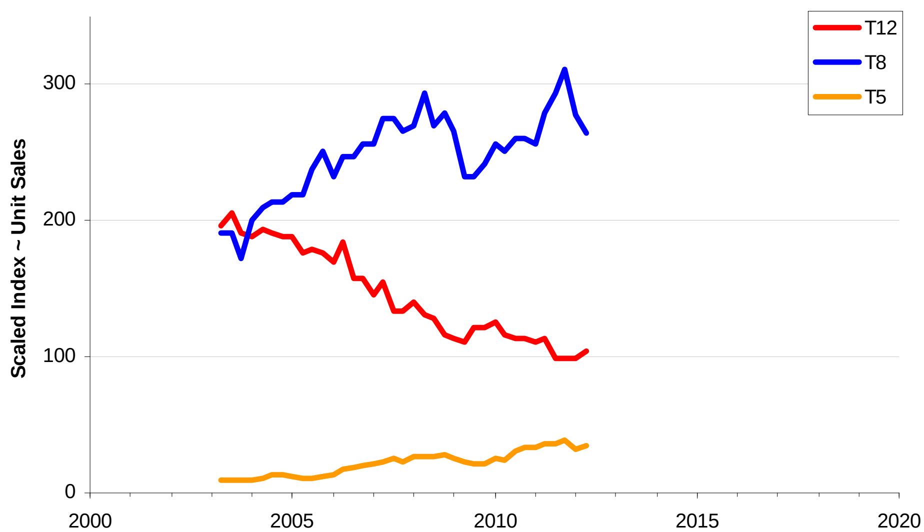


Figure 8: Scaled NEMA Fluorescent index, proportional to lamp unit sales.[1].

Figure 8 shows an index[1] from the National Electrical Manufacturer Association (NEMA) which is proportional to the unit sales of T12, T8, and T5 fluorescent lamps. T8 systems have gradually taken market share from T12, and T5 systems have grown to occupy a stable niche.

In the United States, the Energy Policy Act of 1992 first established performance requirements for fluorescent lamps. Table 3 shows the original requirements for lamp efficacy, and the requirements that were revised effective 2012. Similar performance requirements are shown in Table 4 for ballasts. While not immediately obvious, the lamp performance requirements practically ban the old-style T12 lamp in favor of the newer, more efficient T8 lamps. At the same time, the ballast performance requirements practically ban the old-style T12 magnetic ballasts in favor of the newer, more efficient T8 electronic ballasts.

The lighting components shown in Figure 7 also show a much newer style of LED fixture which is intended to replace the entire fluorescent “troffer” fixture. As we saw in Figure 4,

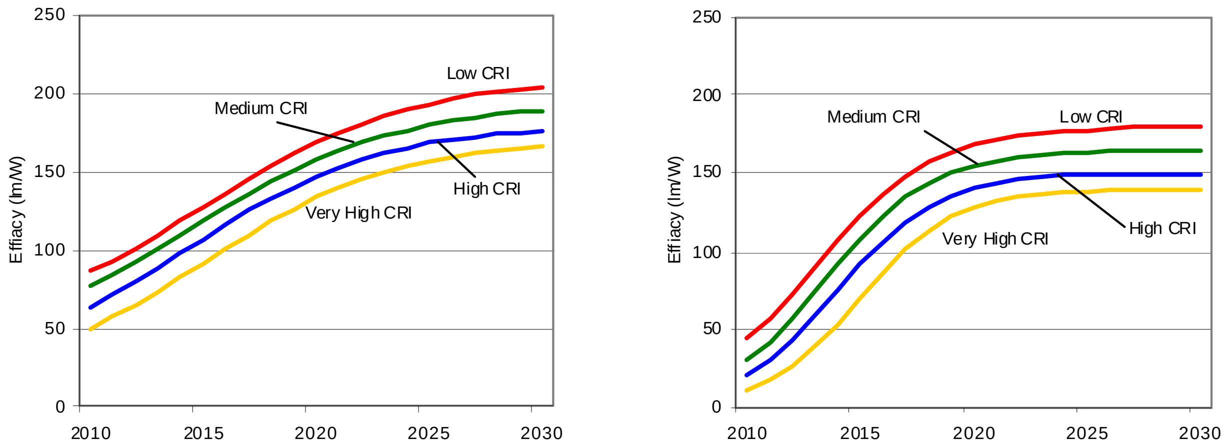
	Energy Policy Act Standards, Effective 1/3/1992		
Lamp Type	Nominal Lamp Wattage (W)	Minimum CRI	Minimum average efficacy (lum/W)
4-Foot Medium Bipin	> 35	69	75
	< 35	45	75

	Ammended Standards, Effective 7/14/2012	
Lamp Type	Correlated Color Temperature (K)	Minimum average efficacy (lum/W)
4-Foot Medium Bipin	< 4,500	89
	> 4,500 and < 7,000	88

Table 3: Regulations for General Service Fluorescent Lamps. Top: standards in place for in 2009. Bottom: standards which became effective July 2012. (Source: Federal Register, Vol. 74, No. 133, July 14, 2009.[11])

	Manufactured after	1/1/1990	4/1/2005	6/30/2010
	Sold by manufacturer after	4/1/1990	7/1/2005	
	Incorporated into a luminaire after	4/1/1991	4/1/2006	
Marked "FOR REPLACEMENT USE ONLY"		No	No	Yes
Application for operation of	Total nominal lamp watts (W)	Ballast efficacy factor (%/W)	Ballast efficacy factor (%/W)	Ballast efficacy factor (%/W)
One F40 T12 lamp	40	1.805	2.290	1.805
Two F40 T12 lamps	80	1.050	1.170	1.050
Two F96T12 lamps	150	0.570	0.630	0.570
Two F96T12HO lamps	220	0.390	0.390	0.390

Table 4: Regulations for Ballasts for General Service Fluorescent Lamps. Top: standards in place for in 2009. Bottom: standards which became effective July 2012. (Source: Federal Register, Vol. 65, No. 182, September 19, 2000.[12])



LED Efficacy Projection *OLED Efficacy Projection*

Figure 9: Reference mode for LED efficacy. (Source: Figure 5.1 in US DOE report "Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030", Feb 2010.[4])

LED lamp prices are projected to decline exponentially. Figure 9 projects the increase of LED lamp efficacy, measured in lumens of light produced per watt of electricity consumed. Eventually the price of an LED luminaire is projected to approach the price of a comparable fluorescent luminaire, and the efficacy is already superior.

In contrast with the residential lighting market, where incandescent lamps have approximately one year service life, the service life of the lamps and ballasts in fluorescent luminaires is approximately one decade. Existing commercial building stock is renovated approximately every seven to twelve years, and typically involves replacement of the lighting luminaires. The surface area added annually from new construction is comparable to the surface area renovated annually. Therefore a model of commercial lighting must accommodate both renovation and new construction. Figure 10 shows monthly spending on commercial construction by building type. The spending shows clear seasonality and a collapse in almost all sectors following the financial crisis around 2008.

3.2 Assumptions

To make the model[4] tractable, we consider just the portion of commercial lighting market consisting of four foot fluorescent luminaires. We do consider the LED luminaires that would replace an entire fluorescent luminaire, but we neglect to treat LED replacement lamps (lamps comprised of multiple LEDs but arranged in a package shaped like a fluorescent lamp, and driven by the same fluorescent ballast). We do not assume (as we did for the residential

[4] An overview of the commercial lighting model was presented at the Strategies in Light 2013 conference.

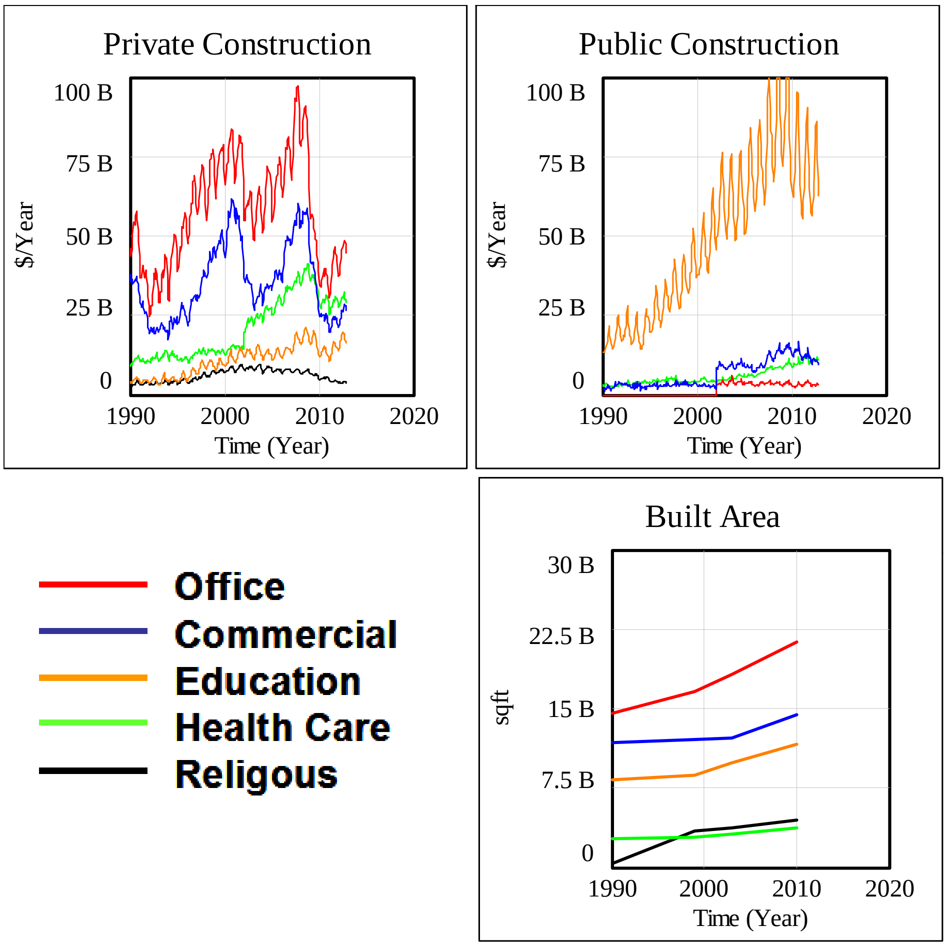


Figure 10: Commercial reference mode, construction. Sources: US Census. `http://www.census.gov/construction/c30/prexcel.html`

lighting market) that system wear-out dominates the overall demand. We assume that when lamps fail, they must be replaced by a lamp of the same kind. If a replacement lamp is unavailable, then the luminaire must be replaced. We assume that when a ballast fails, it must be replaced by a ballast of the same kind, and that the lamps are replaced at the same time. If a replacement ballast is unavailable, then the entire luminaire must be replaced.

3.3 Stock and Flow Model

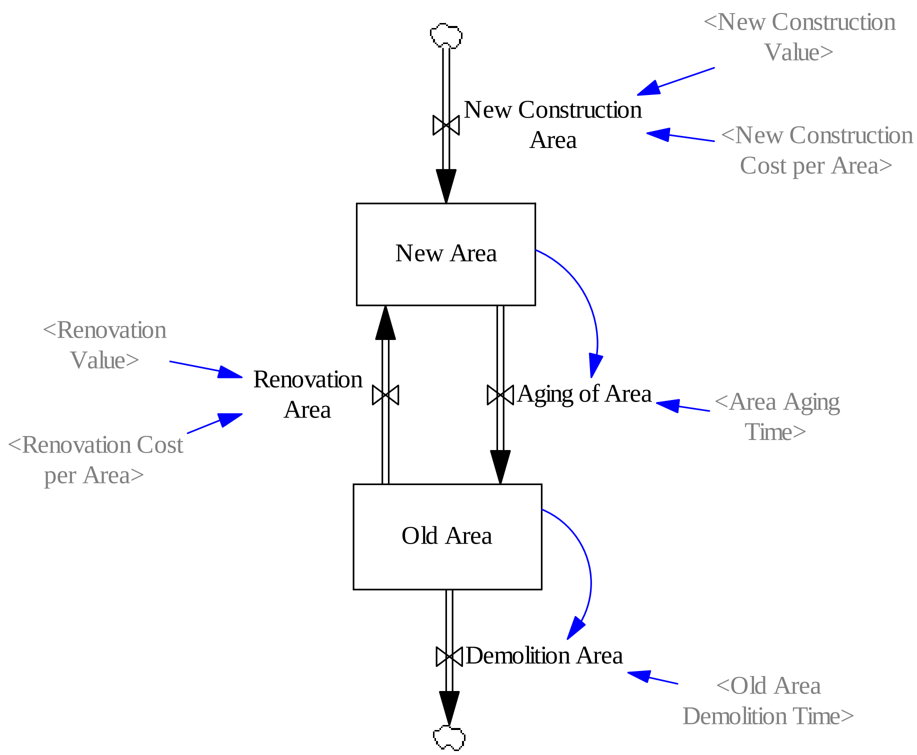


Figure 11: Commercial stock and flow model, construction.

Figure 11 shows the stock-and-flow diagram relating annual spending on new construction and renovation to the stocks of new (or renovated) commercial building surface area and old commercial building surface area. New area "ages", or depreciates, with an average time, after which it is categorized as old. Old area may be either renovated or demolished. Total commercial surface area is shown in Figure 10, and must be related to construction spending by the construction costs per unit area. The demand for lighting systems (luminaires) is related to the commercial surface area and the light requirement per unit area.

Figure 12 shows the stock-and-flow diagram for the number of installed lighting systems. In equilibrium, the ratio of the installed systems and the commercial area would be a constant. The number of installed systems decrease as systems are deactivated. In some cases deactivation constitutes actual removal of the fixture from the ceiling, as for renovation, replacement, and demolition. In other cases, deactivation is simply temporary, as for lamp failure and ballast failure.

The number of installed systems increases with system activations. The reasons for activation are the logical compliments to the reasons for deactivation. In some cases system

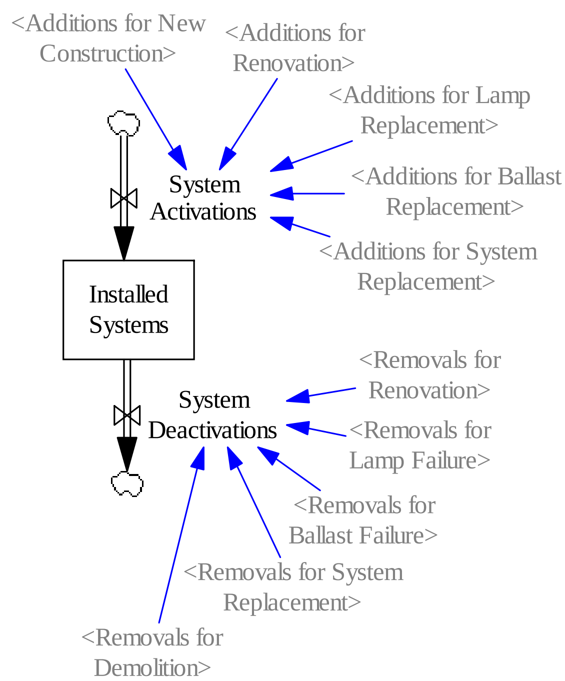


Figure 12: Commercial stock and flow model, systems.

activation constitutes physically installing a system in the ceiling, as for new construction, renovation, and system replacement. In other cases the system activation occurs when a replacement lamp or ballast is installed, bringing the existing system back online.

As for the residential market, an important component of overall market demand is the number of systems that have been removed from service, as shown in Figure 13.

Consider first systems that have been removed for renovation (upper left stock in the figure). As systems are removed for renovation, the stock of "Unrenovated systems" increases, and eventually factors into a term for system demand. As systems are added for renovation, the number of Unrenovated systems decreases, and demand is satisfied.

As lamps fail, the systems in which they are a part are brought offline, thus increasing the number of Systems with Unreplaced lamps. The number of Systems with Unreplaced lamps creates a demand for lamps, and when Replacement Lamps are installed the number of Systems with Unreplaced Lamps decreases. If replacement lamps are unavailable, then eventually the entire system must be replaced. Thus the number of Unreplaced Systems is increased and the number of Systems with Unreplaced Lamps is correspondingly decreased. Similar kinetics hold for ballasts.

The other reason that Unreplaced Systems increases is due to the Removals of System Replacement (perhaps due to energy retrofit affecting only the lighting).

Example causal loop diagrams showing the relationships between the types of construction and Additions and Removals are shown in Figure 14. The full set of relationships is

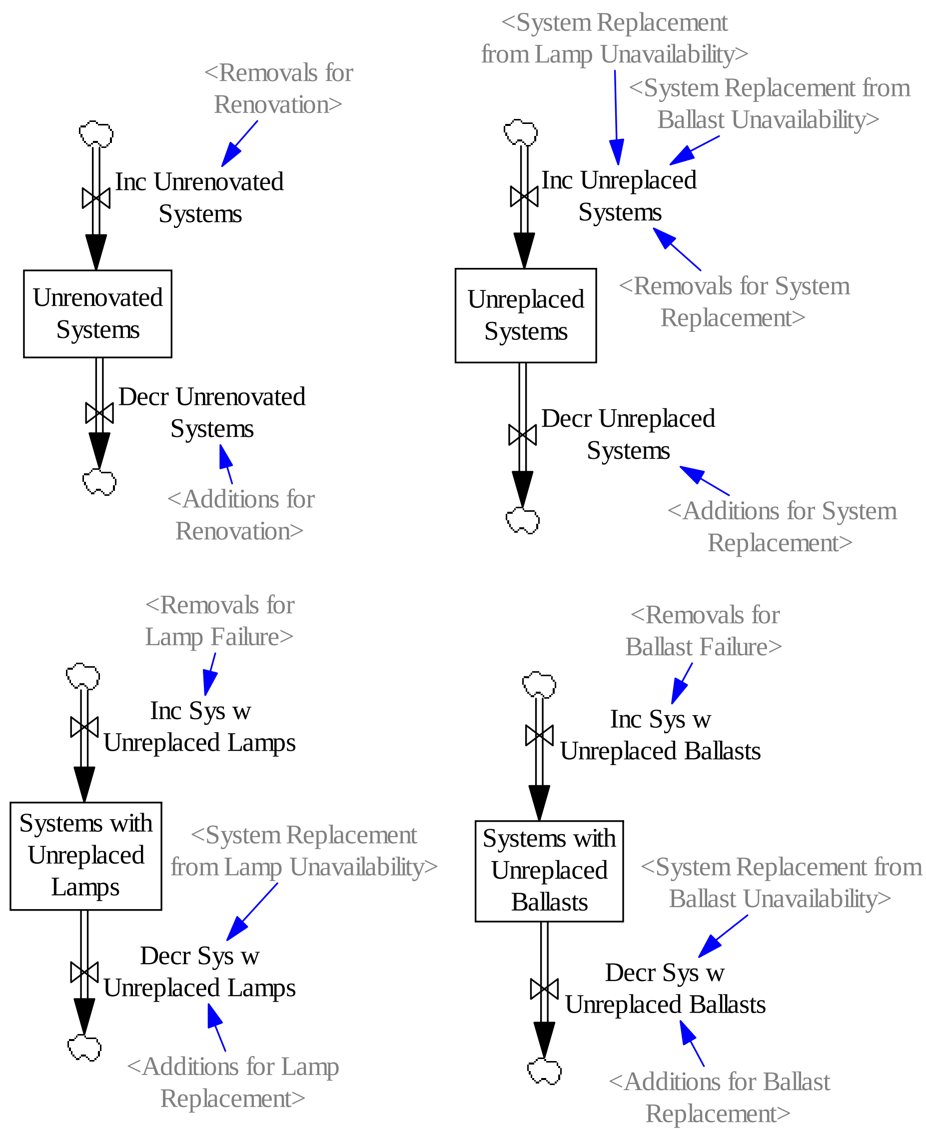


Figure 13: Commercial stock and flow model, systems.

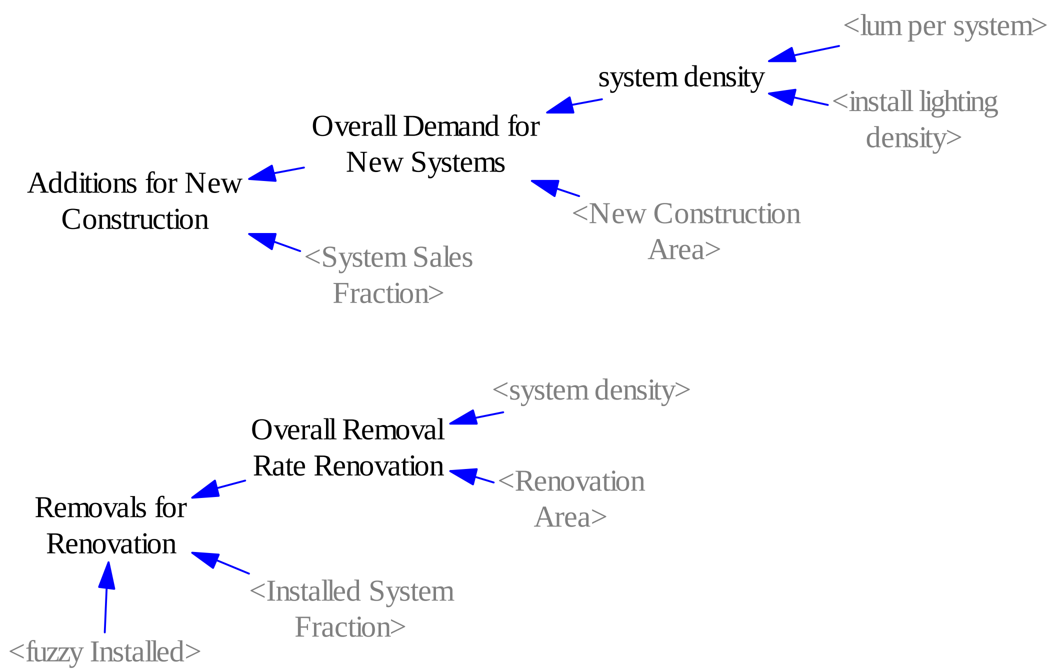


Figure 14: Commercial causal loop diagram, adding and removing systems.

provided in the accompanying simulation, and is not described further here.

3.4 Buyer Preferences

For commercial buyers, many factors could potentially influence the purchasing decision:

- Price per lamp, ballast and fixture
- System efficacy
- Energy cost per kilowatt-hour
- Efficiency due to controls
- Legislative inducement for controls
- Reliability of LED technologies vs incumbent fluorescent technology
- Incentives and rebates
- Channel profit by type
- Ease of implementing controls
- Cost of capital
- Other factors of economic utility, e.g. photobiology, color control, dimmability, etc.

For our model we consider only the first two factors: system price and system efficacy. In the spirit of Principle Component Analysis, we attempt to find the smallest number of variables which explain most of the variance between the model and historical data. We have assumed that buyers are rational on average: while some people may pay a premium for a fixture with the latest technology, they are not the majority.

Just as we did for the residential lighting market, we assume a linear relationship between the system characteristics and the economic utility, Eq. (1). We also assume that the sales fraction is related to utility and availability through a modified multinomial logit function, Eq. (2).

3.5 Econometric Calibration

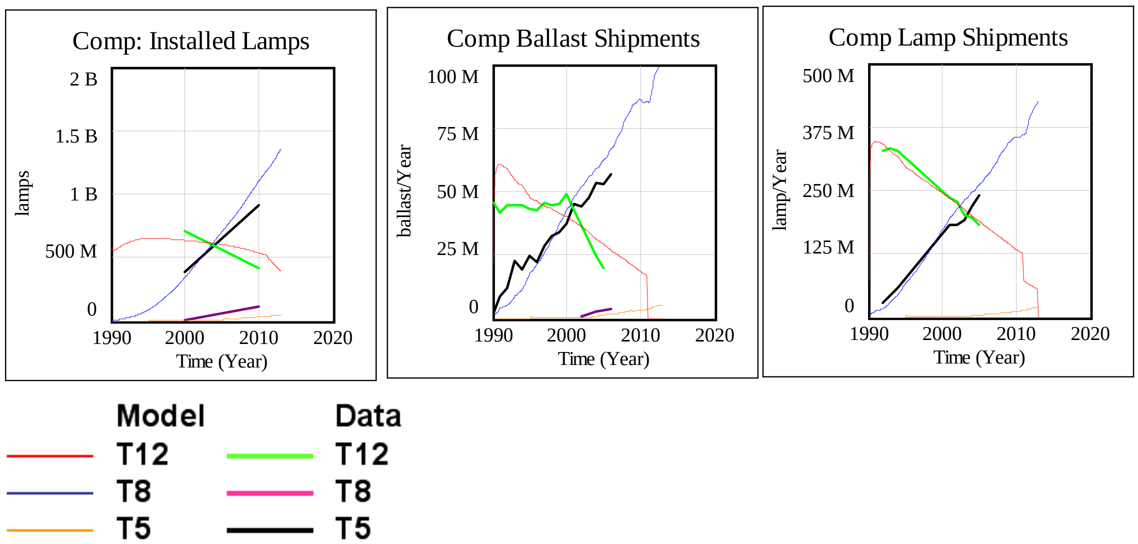


Figure 15: Commercial model calibration. Data sources: US DOE Lighting Market Characterization reports (installed lamps); US Census (Ballast and Lamp shipments).

Figure 15 shows the results of calibration, comparing the model output to historical data for the number of installed lamps, lamp shipments, and ballast shipments. Published data is used to constrain coefficients of the model, primarily the coefficients in the economic utility function corresponding to system price and system efficacy. Additional agreement was obtained by adjusting certain parameters near known values to accommodate our assumption that all commercial lighting is provided only by four-foot fluorescent fixtures: installed lighting density, lumens per system, average service life of lamps and ballasts.

While the resulting calibrated model does not perfectly reproduce the historical data, it does gets the major trends correct. Over two decades, T8 systems have taken market share from T12. The introduction of T5 systems a decade ago has resulted in only stable niche penetration. The model also projects total number of annual system shipments consistent with (the very sparse) publicly available data.

3.6 Results

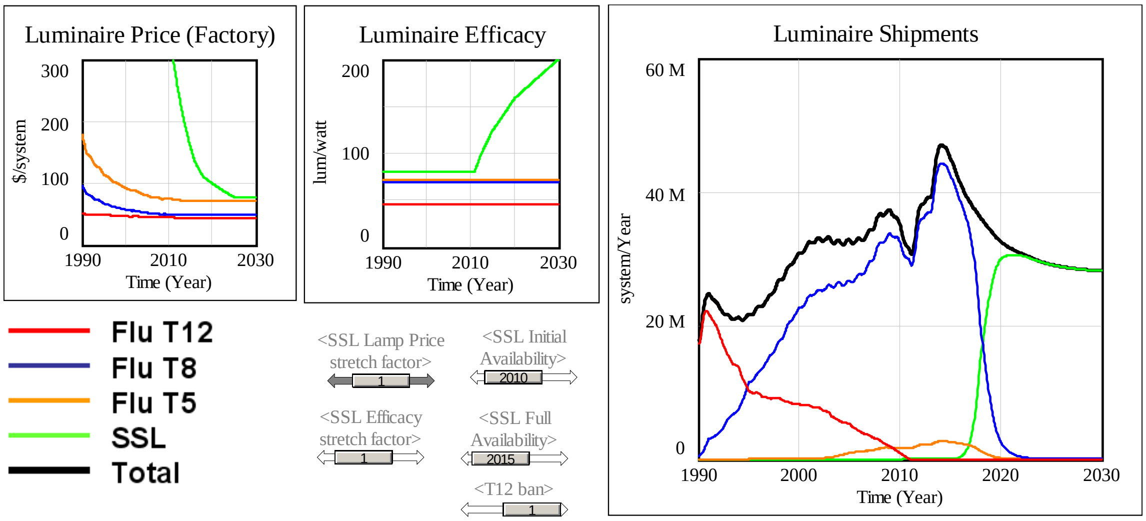


Figure 16: Commercial model dashboard.

Figure 16 shows a dashboard for the results. The two driving variables, system price and system efficacy, are shown in the first two, smaller, panels. The model output is summarized by the annual system shipments in the larger panel to the right. The total system shipments tracks construction spending, especially the collapses of construction spending after 1990 and 2008.

T12 system shipments show a slow decline as T8 systems gain market share. T12 system shipments decrease to zero as the provisions of the T12 ballast and T12 lamp regulations become effective. T5 system shipments never achieve more than niche status.

Moving beyond 2013, the model projects a dramatic increase in the number of shipments which is not driven by new construction. After about five years the rise of system shipments collapses. The "bump" in system shipments is the result of the T12 regulations. Installed T12 systems last a very long time, since the magnetic ballasts have few parts to wear out. As long as the balance of the system functions, the most cost effective approach is to continue to replacement T12 lamps as they fail. However once T12 lamps become unavailable, the entire system must be replaced. The timescale of the "bump" corresponds to the service life of the installed T12 lamps.

Figure 17 shows the "what-if" scenario for the hypothetical case that T12 regulations had never been imposed: compared with the baseline scenario, the "bump" is clearly missing.

The efficacy of LED systems already exceeds the best-in-class fluorescent systems. Therefore as the price of LED systems approaches the price of T8 systems, the model projects that LED luminaires eventually win the entire market. In contrast with the residential lighting market, the entire commercial market does not collapse after the transition to LEDs: the service life of the LED systems is comparable to the incumbent fluorescent systems, and the

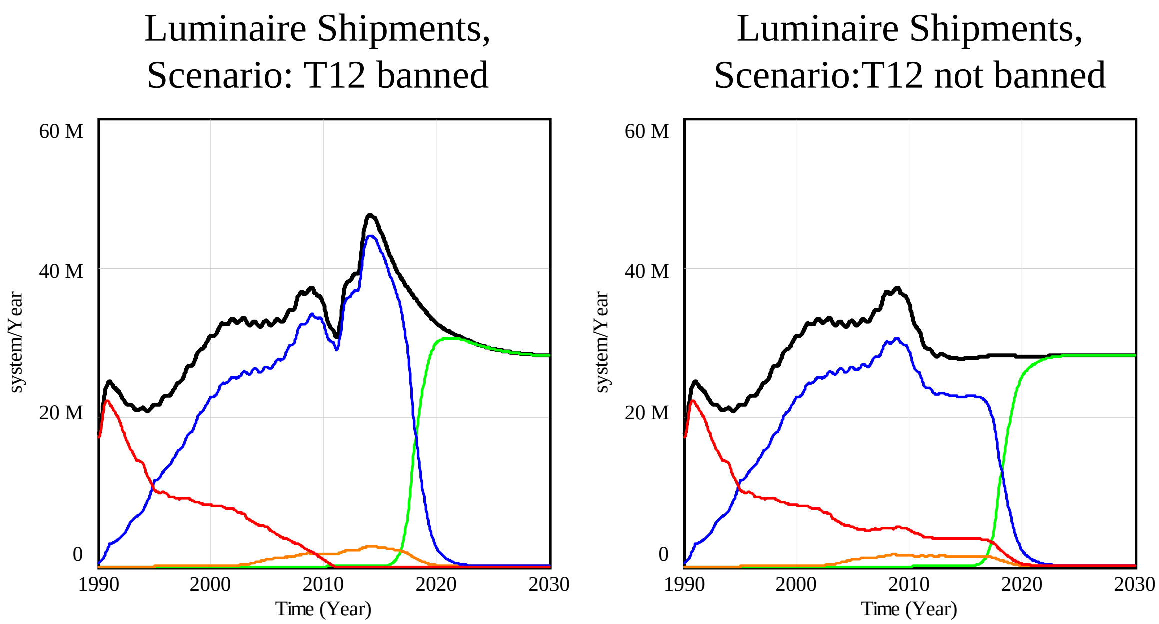


Figure 17: Commercial model scenarios, with and without the T12 ban.

commercial market is driven by construction rather than replacement of failed components.

4 Discussion

4.1 Other Features

The models for the residential and commercial lighting markets assume that there is only one kind of "new" technology to challenge the incumbent sources: LEDs. What about other technologies, like organic light-emitting diode (OLED), quantum dot, etc.? As the price and efficacy projections in Figures 4 and 9 show, OLED lamp price declines slower than LED lamps, and OLED lamp efficacy climbs slower that LED lamps. Since the model assumes that buyer preference depends sensitively on price and efficacy, we would expect that the share of the market won by OLED lamps will never be as large as LED lamps. Of course this conclusion depends on the implicit assumption that the shape of the light sources does not significantly change (A-lamp for residential market, four-foot troffer for commercial market). OLED lamps may have an advantage if the nature of general illumination changes, e.g. the entire ceiling area is the light source.

The economic utility function completely neglects other features of light systems which are known to be important now, and are likely to become even more important, e.g. dimming, color control, and interactive control ability. In principle we could add a term to the utility function and calibrate the coefficient against historical data. But if those features have no precedent, there is no historical data against which to calibrate the model. In this case, the approach we recommend is to leave a generic term in the utility function whose coefficient is a free parameter. Then scenarios can be analyzed as follows: "if the economic utility of this new feature is as large as β, then the effect on shipments will be…"

4.2 Other Markets

We have considered just two of the lighting markets: residential A-lamps and four-foot fluorescent commercial lighting. We suggest the next markets to consider should be: compact downlights; outdoor lighting; and schools. All the data for this study came from publicly available sources for the United States. However, the model could just as easily apply to any other country. The only requirement to study a different market is the historical data with which to calibrate the coefficients.

4.3 Model Improvements

The most obvious improvement to the model is a more realistic treatment of cost. Figure 18 shows one way to capture the total cost of ownership, including operation as well as first purchase. Many of the variables mentioned in Section 3.4 would be included. In addition, regional differences such as cost of electricity would be included naturally, and potentially explain differences in regional preference.

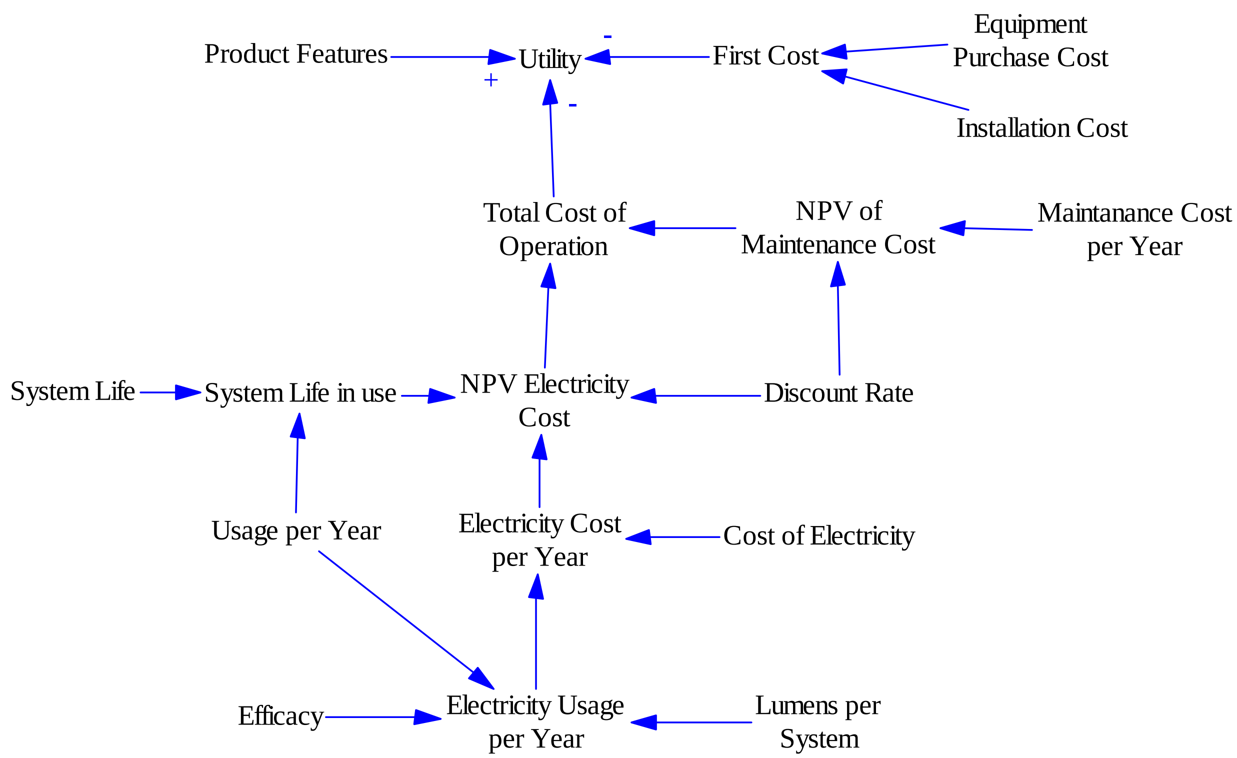


Figure 18: Improved utility function, considering total cost of ownership in addition to purchase cost.

5 Conclusion

System Dynamics models have been developed of the residential and commercial lighting markets. Rates of purchase of new systems were related to the installed base of existing systems, system component reliability, and construction, using stock-and-flow models. Buyer preferences were assumed to depend only on the characteristics of the lighting systems. Characteristics considered in the residential market were price, life, and color rendering; characteristics considered in the commercial market were price and efficacy. The buyer preferences were represented by coefficients of a multi-nomial logit function are were calibrated against decades of historical data in an econometric fashion. We assuming buyer preferences stayed constant for a comparable time into the future, and made projections for the market adoption of LED technology. The disruptive impact of lighting efficiency regulation was examined.

A NEMA Index Rescaling

Let S_i represent the sales of the ith model, $y_i = S_i/k_i$ the NEMA index, and $f_i = S_i/\sum_i S_i$ the sales fraction. Combining we have

$$f_i = \frac{k_i y_i}{\sum_i k_i y_i}$$

We are given y_i and f_i at several different instances of time t. We can find the constants k_i by minimizing

$$E^2 = \sum_t \sum_j \left(f_j(t) - \frac{k_j f_j(t)}{\sum_i k_i f_i(t)} \right)^2 .$$

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