GT-NEMS Modeling of Technology Learning: Case Studies of Commercial Solar PV and Lighting Technologies

XIAOJING SUN
GYUNGWON KIM
MARILYN BROWN

February 26, 2013

Oak Ridge National Laboratory
Georgia Institute of Technology

Endogenous Learning Curve: Commercial Solar PV

Learning Effect

- Inverse relationship between installed cost and cumulative shipments

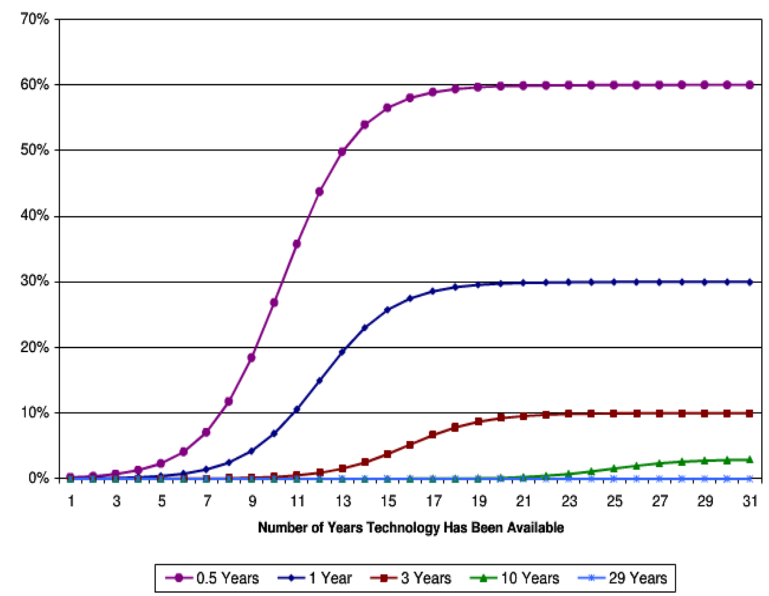
$$C_{adj}=C_{0,t}*CumShip_{\,t,y}^{\,-\beta}$$

- Two parameters
  - C_0: first-of-a-kind unit cost
  - β: learning parameter, an assumed value

Learning rate = (10^(- β *log2))
Learning factor =1-Learning rate, representing the proportion of cost reduction each time the cumulative production doubles .

Penetration

Figure 12. Distributed Generation Technology Penetration Rate Curves for New Construction for Payback Times (percent penetration)



•Penetration rate depends on the economics of the technology.
•The higher the Internal Rate of Return (IRR), the shorter the payback period, the higher the penetration rate.

Source: Commercial Module Documentation, EIA, 2012

GT-NEMS Assumptions

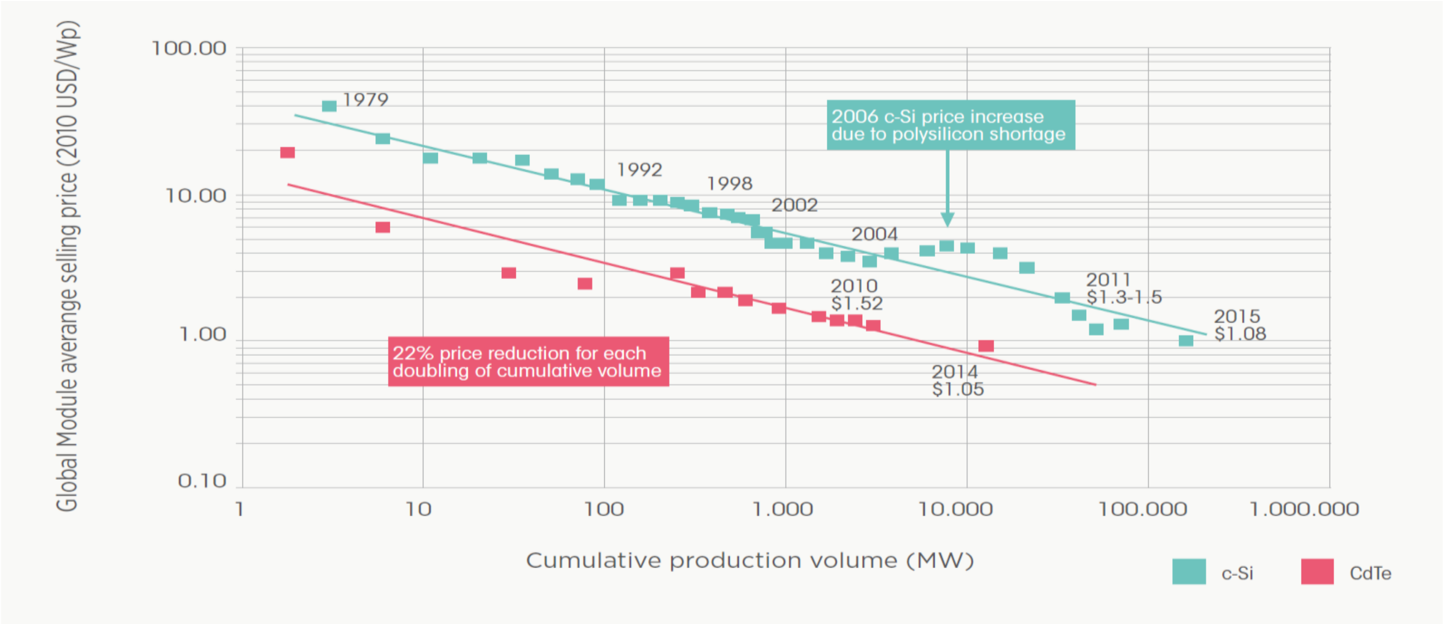
	Reference Case	High Tech Scenario	Best Tech Scenario
First Cost	$30/W	$34/W	$43/W
Beta (Learning factor)	0.2 (0.13)	0.22 (0.14)	0.25 (0.16)
Penetration parameter [1] (New buildings[2])	30% of new roof area	30% of new roof area	30% of new roof area

Notes:

1. Penetration parameter: asymptotically approaches the maximum penetration rate for those technology with one year payback period.
2. Penetration rate in existing buildings is limited to a maximum of 0.5% or one-fortieth of the penetration for new construction, whichever is less.

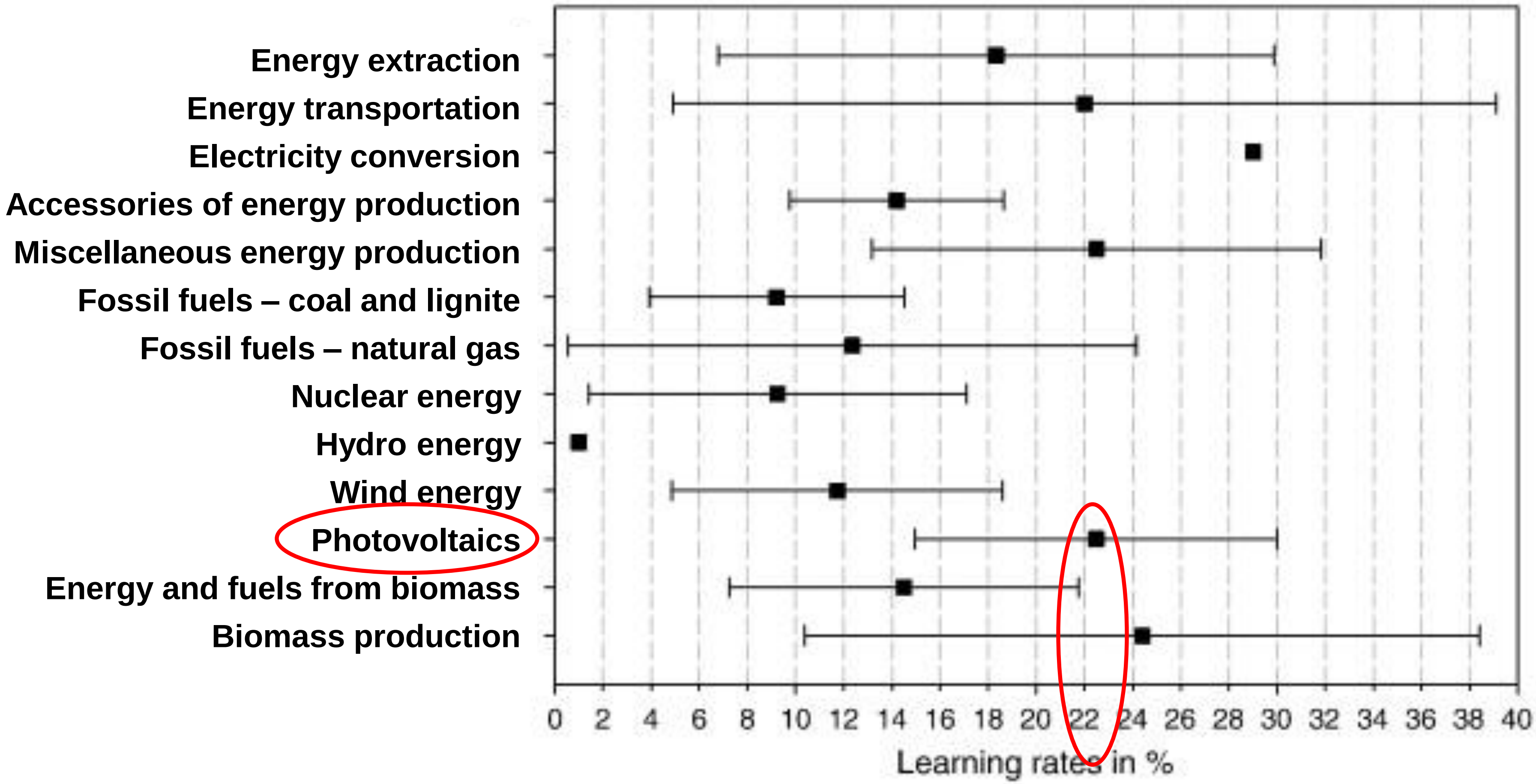
Re-Estimate the Learning Factor

- GT-NEMS reference assumption:
  - 0.13 (Beta= 0.20)
- Literature review suggests a 0.15-0.30 learning factor (Parente et. al, 2002; Weiss et. a. 2010, SEMI PV Group; IRENA, 2012)
- IRENA estimate: Learning factor = 0.22 (Beta= 0.36)



Source: Renewable Energy Technologies: Cost Analysis Series, International Renewable Energy Agency(IRENA), 2012
http://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf

Average Learning Factor with Uncertainty



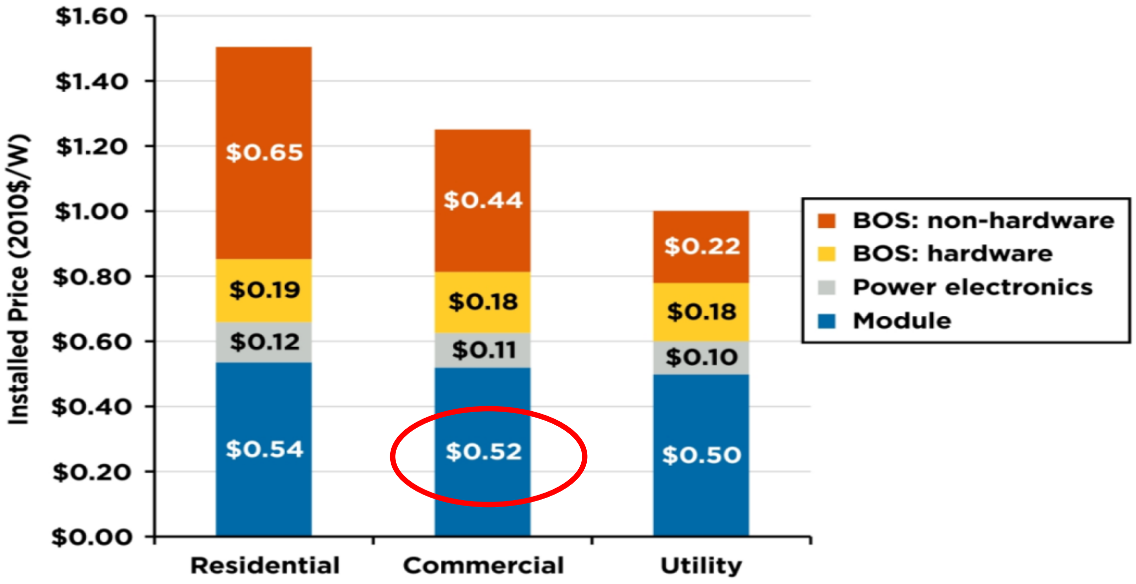
Weiss et. al. (2010) estimate: Learning parameter = 0.36 ± 0.12 (Learning factor = 0.22 ± 0.08)

Source: A review of experience curve analyses for energy demand technologies, Technological Forecasting and Social Change Volume 77

Re-estimate the First Cost

- GT-NEMS reference assumption:
  - $29/W, in 2009-$
- DOE SunShot Initiative Goal
  - Module cost

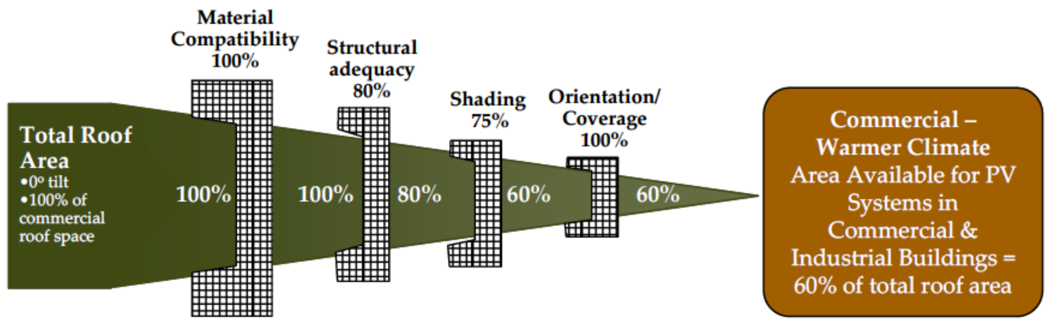
    $0.52/W in 2020



Source: SunShot Vision Study, DOE, 2012

- First cost = $82/W would allow NEMS projection to meet the 2020 cost goal of DOE SunShot Initiative.

Update the Maximum Penetration Rate: Technical Potential



60%-65% of the commercial rooftop area is suitable for solar PV installation.

Figure 5. PV access factor for commercial buildings in warmer climates

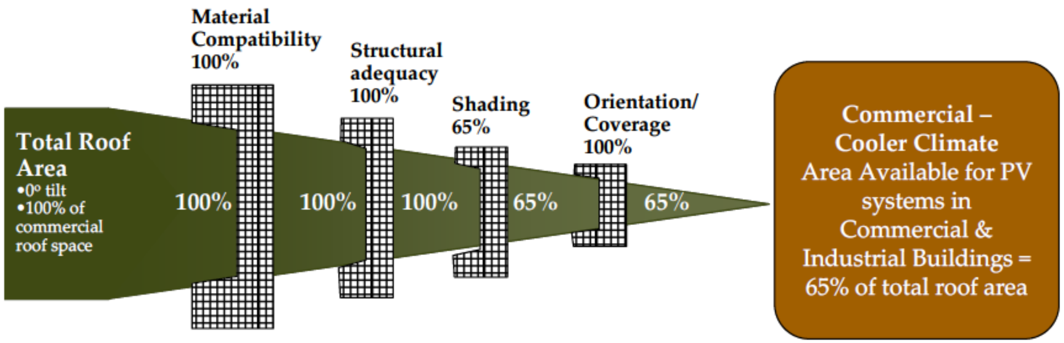
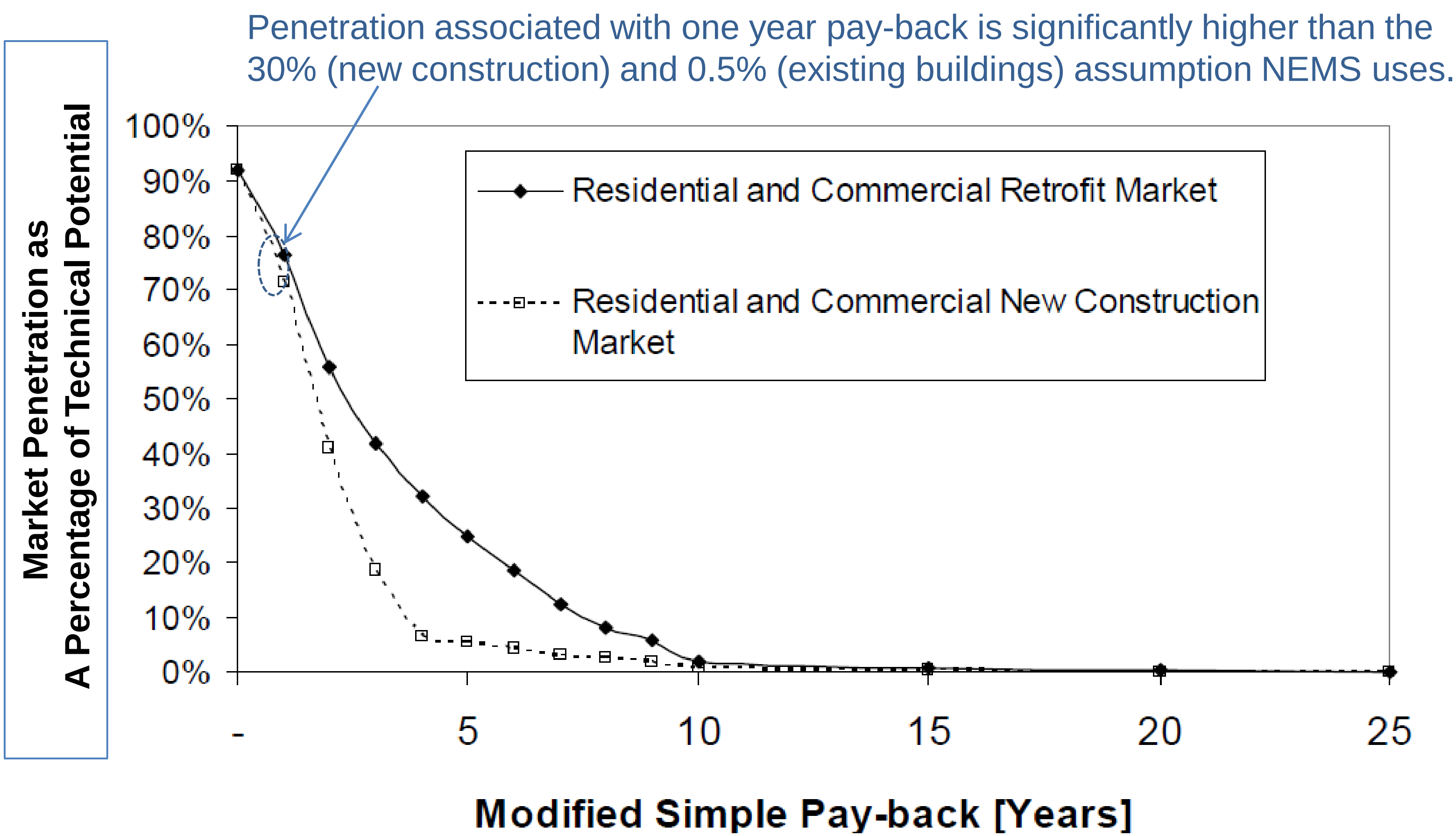


Figure 6. PV access factor for commercial buildings in cooler climates

Source: NREL, 2008, *Rooftop Photovoltaics Market Penetration Scenarios*

Update the Maximum Penetration Rate: Economic Potential



Source: Modified based on *Rooftop Photovoltaics Market Penetration Scenarios,* NREL, 2008

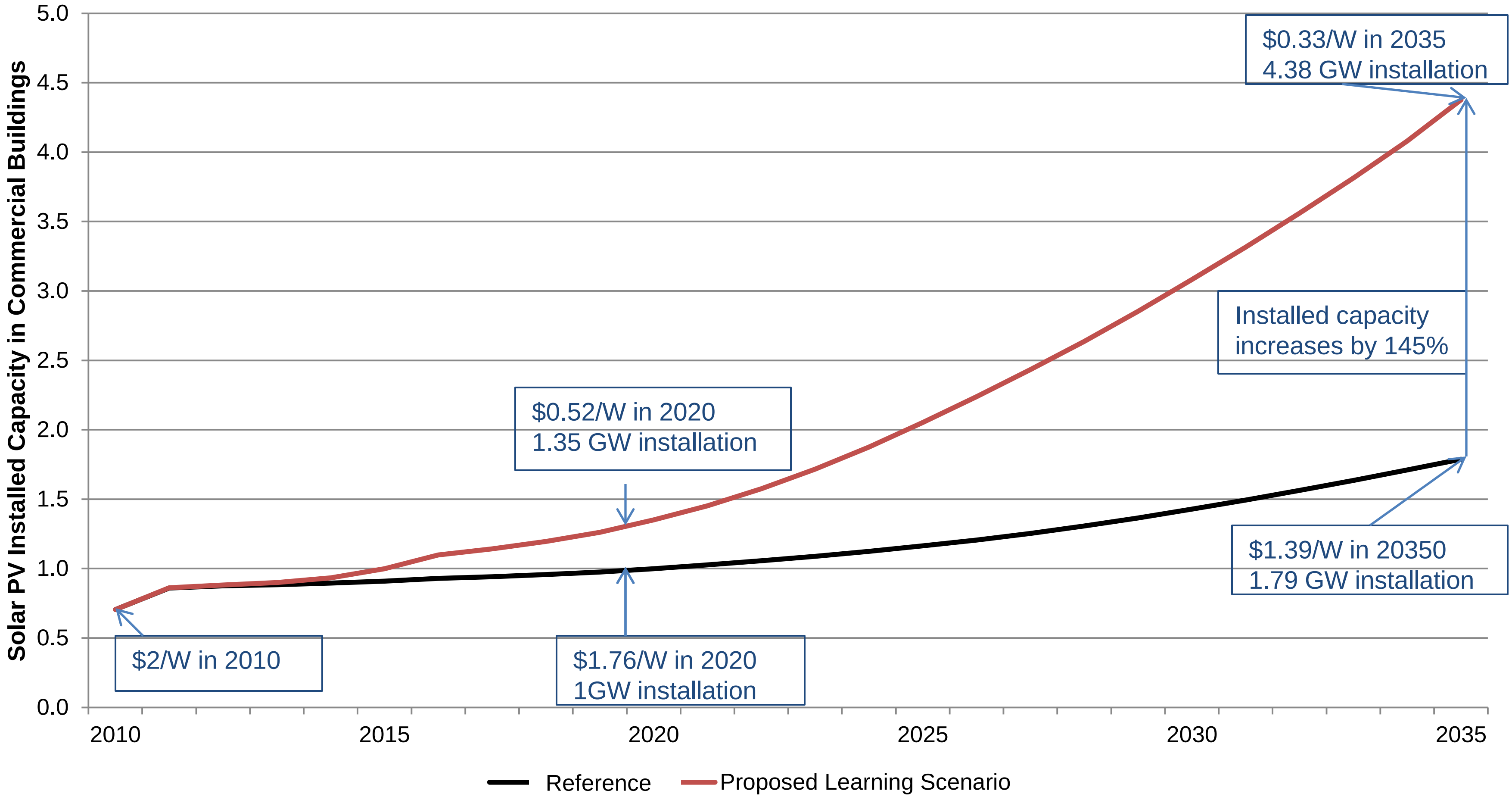
Proposed Scenario for Solar PV Learning Effect

	Reference Case	High Tech Scenario	Best Tech Scenario	Proposed Learning Scenario
First Cost	$30/W	$34/W	$43/W	$82/W
Beta (Learning factor)	0.2 (0.13)	0.22 (0.14)	0.25 (0.16)	0.36 (0.22)
Maximum penetration (New buildings)	30% of new roof area	30% of new roof area	30% of new roof area	42% of new roof area[1]

Notes:

1. Penetration rate in existing buildings, which is a computed value, would also be adjusted upward accordingly, but the 0.5% maximum penetration rate in existing buildings still represents a hurdle.

Updated Learning Assumptions Lead to Lower PV Cost and Increased Installed Capacity



Exogenous Learning Curve: Lighting

Learning Effect

- In GT-NEMS, cost trends for immature technologies are represented by step-wise decline and logistic function.
- Cost decline and shape parameter in *ktek* reflect learning effects.
- In GT-NEMS, lighting is the only service reflecting cost decline trends as an immature technology.

Cost Trend Function

$$KEqCost(t, v, y, "CAP") \equiv$$

for Infant technologies:

$$\frac{TechCost_{t,v,1} \cdot \delta}{1+\left(\frac{y-y_1}{y_0-y_1}\right)^{\gamma}} + (1-\delta) \cdot TechCost_{t,v,1}$$

for Adolescent technologies:

$$\frac{TechCost_{t,v,1} \cdot 2\delta}{1+\left(\frac{y-y_1}{y_0-y_1}\right)^{\gamma}} + (1-\delta) \cdot TechCost_{t,v,1}$$

for Mature technologies

$$TechCost_{t,v,1}$$

$\gamma \equiv$ shape parameter corresponding to the rate of price decline,

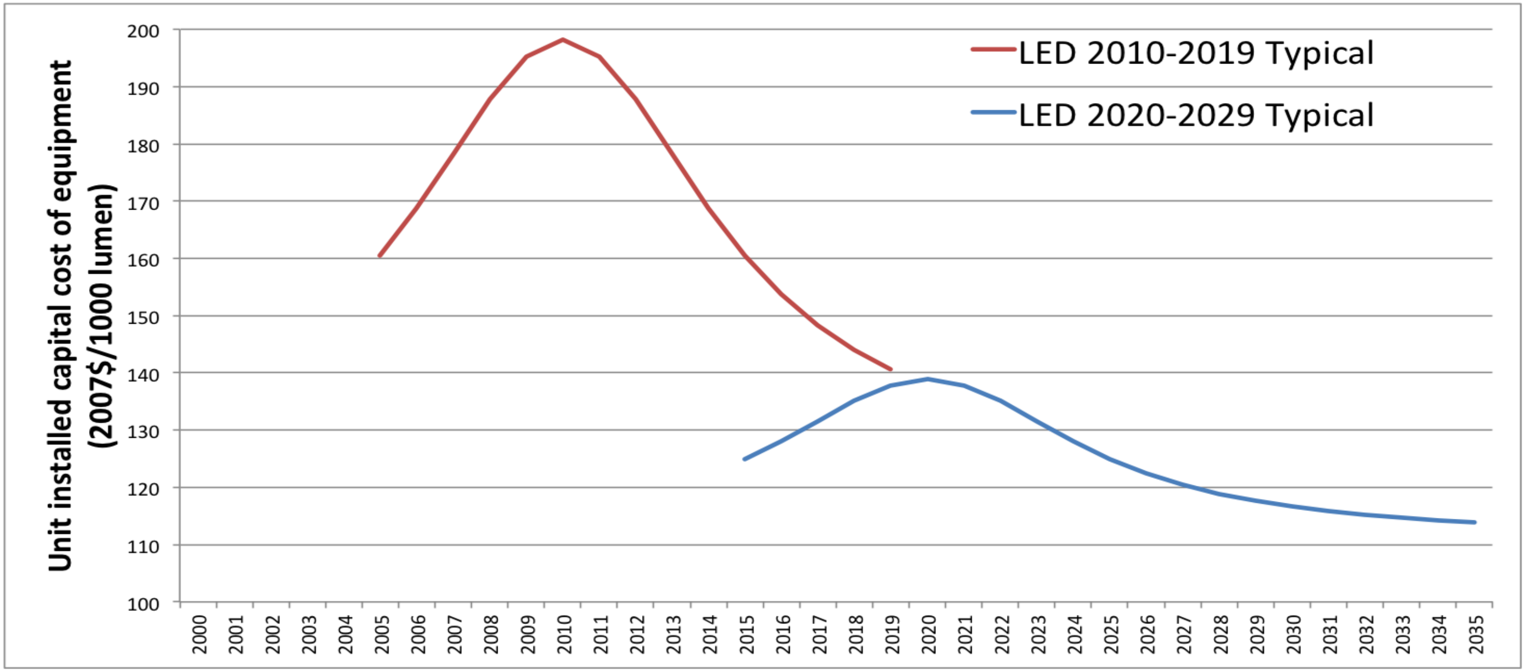
$\delta \equiv$ total anticipated percentage decline in real cost from the initial value,

$y_0 \equiv$ year dictating the curve's inflection point,

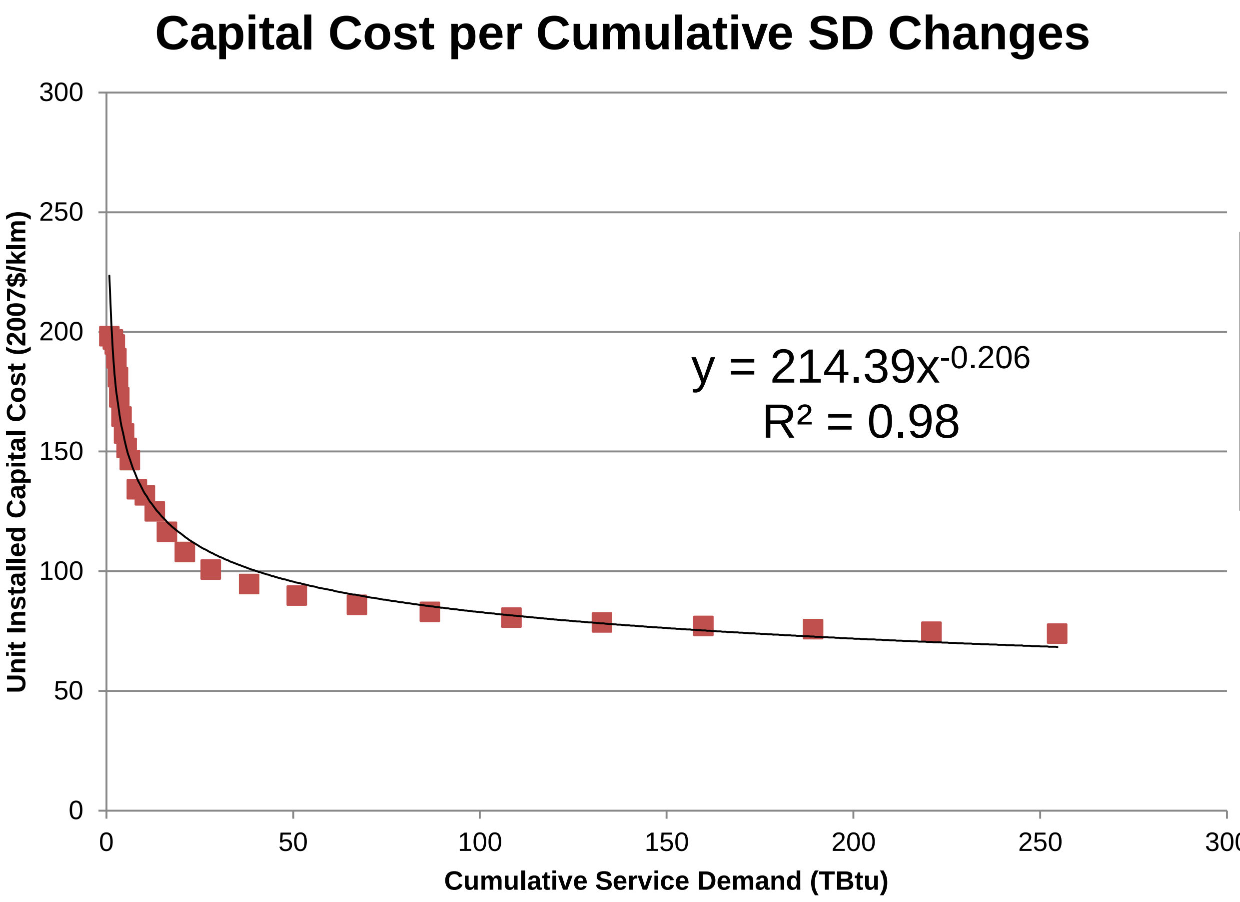
$y_1 \equiv$ effective year of introduction for the given technology

Manual Projection of Cost Trends for LEDs

- Using GT-NEMS' cost trend function and "ktek" input data, the trend of reduction in unit cost can be manually calculated between vintages of immature lighting technologies.
- The unit cost is defined as the capital cost per unit of service demand (2007$/klm).



GT-NEMS Exogenous Learning Curve for LED Lighting

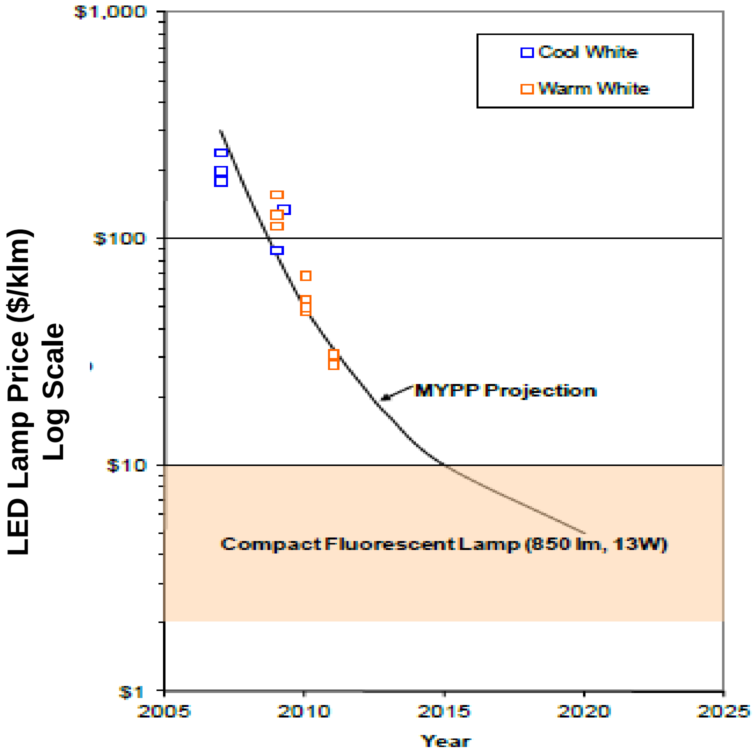


Learning Rate
= (10^(-0.206*log2))
= 0.87
Learning Factor
= 1-0.87 = 0.13

Literature Review:
Gaps Between GT-NEMS and Literature

- DOE (2012)* estimates LEDs' greater market penetration with higher efficacy values as well as downward pressure on retail prices due to;
  - Manufacturing improvements
  - Market competition
  - Industry and government investments

- In 2010, the Navigant Consulting Inc.** also estimated greater energy savings potential from learning effects.



[Figure] White Light Integrated LED Lamp Price Projection (Logarithmic Scale)
(Source: DOE, 2012*)

Note: Assumes current prices for compact fluorescent price range (13W self-ballasted compact fluorescent; non-dimmable at bottom, and dimmable at top).

- U.S. DOE (2012) Solid-State Lighting Research and Development: Multi-Year Program Plan

** Navigant Consulting, Inc. (2010) Energy Savings Potential of Solid-State Lighting in General Illumination Applications 2010 to 2030

Identify Potential Improvements

- Possible Improvements to Modeling Learning Effects on Lighting Technology Choice in GT-NEMS:
  - Adjust the rate of cost decline
  - Re-estimate the learning factor for LED lighting

- Run sensitivity models reflecting the latest technology developments and cost trends that Navigant (2010) and DOE (2012) identified.

- Compare the learning impacts on energy savings potential between reference and scenario cases

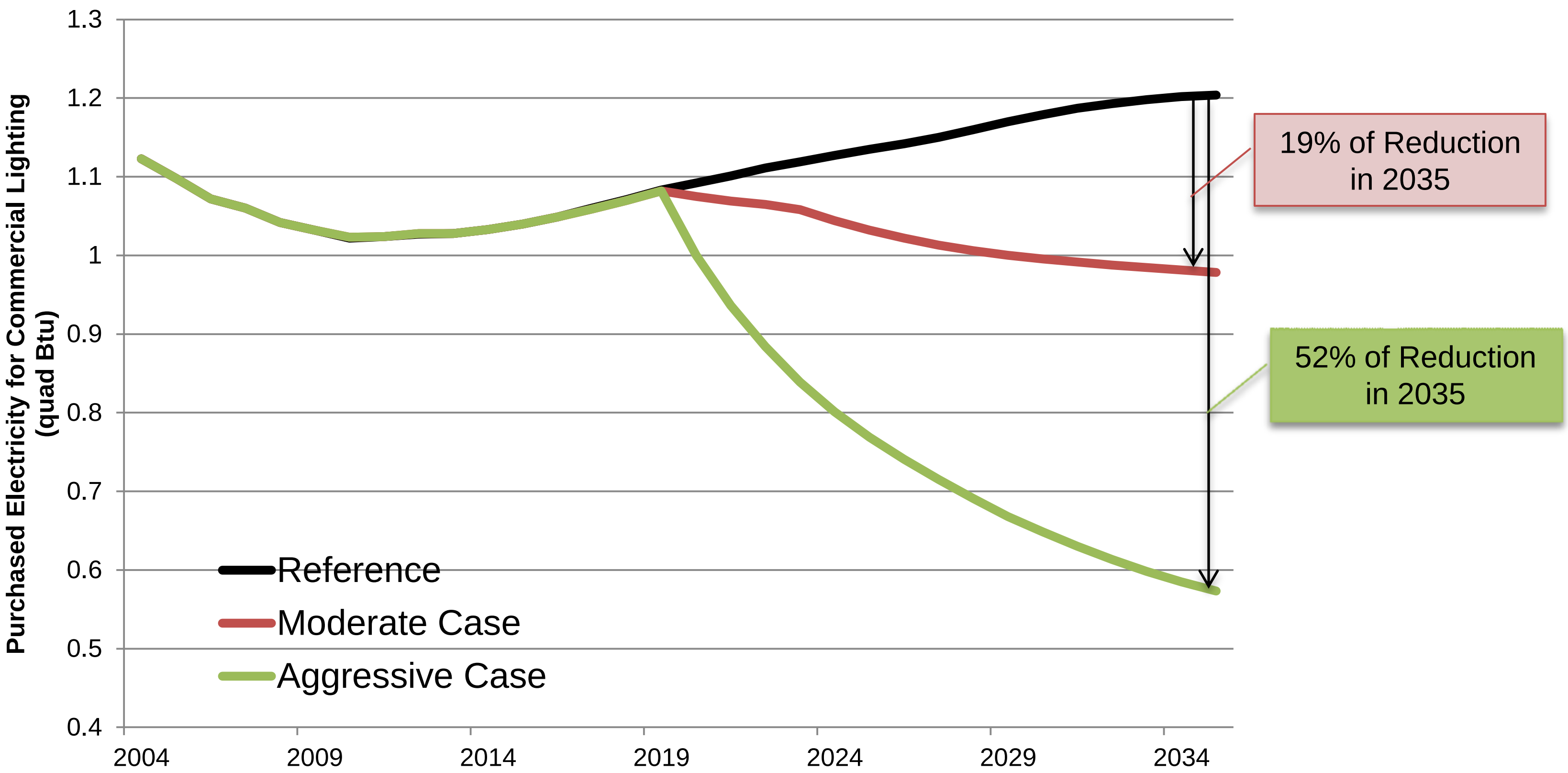
Alternative Cost Scenarios

Technologies	Literature (Navigant, 2010)			vs	GT-NEMS		
	Vintage Start	Efficacy (lm/W)	Cost ($/klm)		Vintage Start	Efficacy (lm/W)	Cost ($/klm)
LED	2010	50.2	213.68		2010	84.6	198.19
	2011	57.2	191.70		2011	86.6	196.79
	2020	133.5	13.54 (-94%)		2020	181.0	134.18 (-32%)

Technologies	Proposed Cost Decline Scenarios			
	Vintage Start	Efficacy (lm/W)	Moderate Cost Scenario	Aggressive Cost Scenario
LED	2010	84.6	198.19	198.19
	2011	86.6	187.30	177.80
	2020	181.0	71.35 (-64%)	11.89 (-94%)

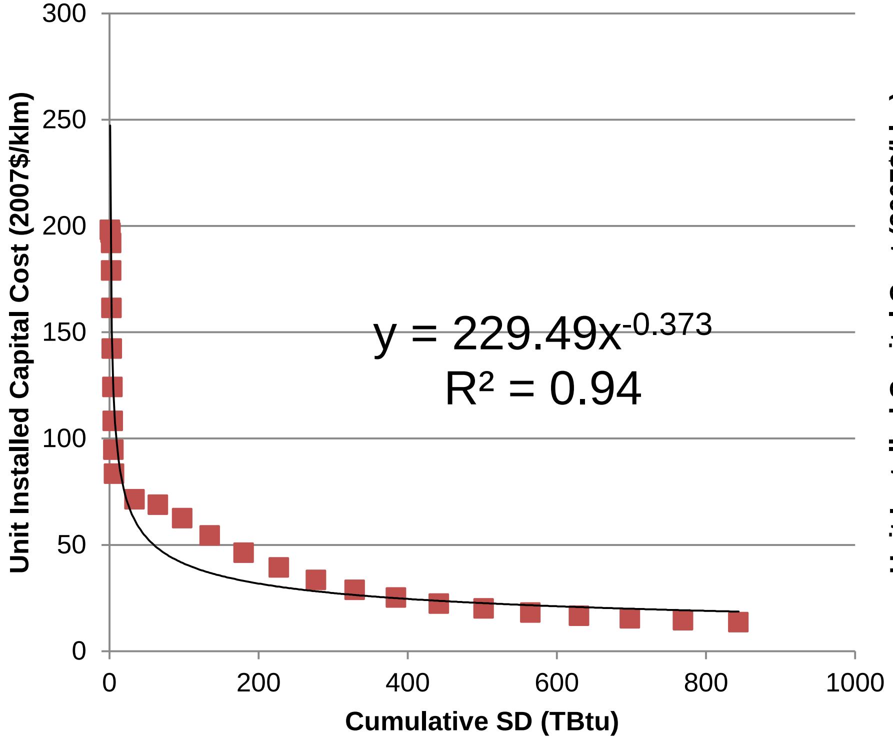
Sensitive Analysis on LED Lighting

- Reference : 32% of LED's cost reduction, 2010-2020, Learning Factor=0.13
- Moderate Case : 64% of LED's cost reduction, 2010-2020, Learning Factor=0.23
- Aggressive Case : 94% of LED's cost reduction, 2010-2020, Learning Factor=0.32



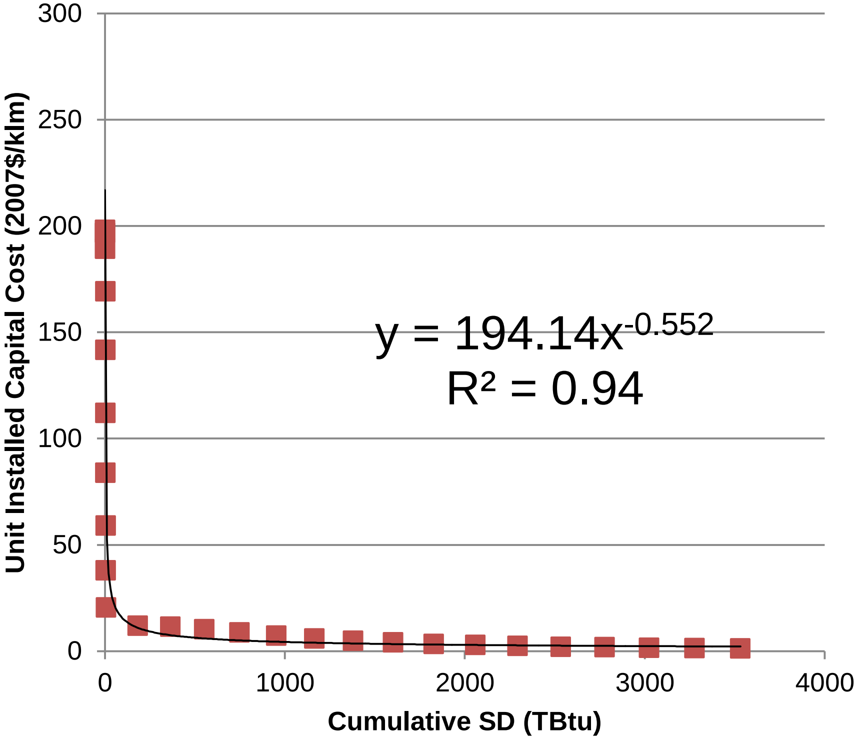
Learning Factors for LED Lighting

Moderate Case



Learning Factor = 0.23

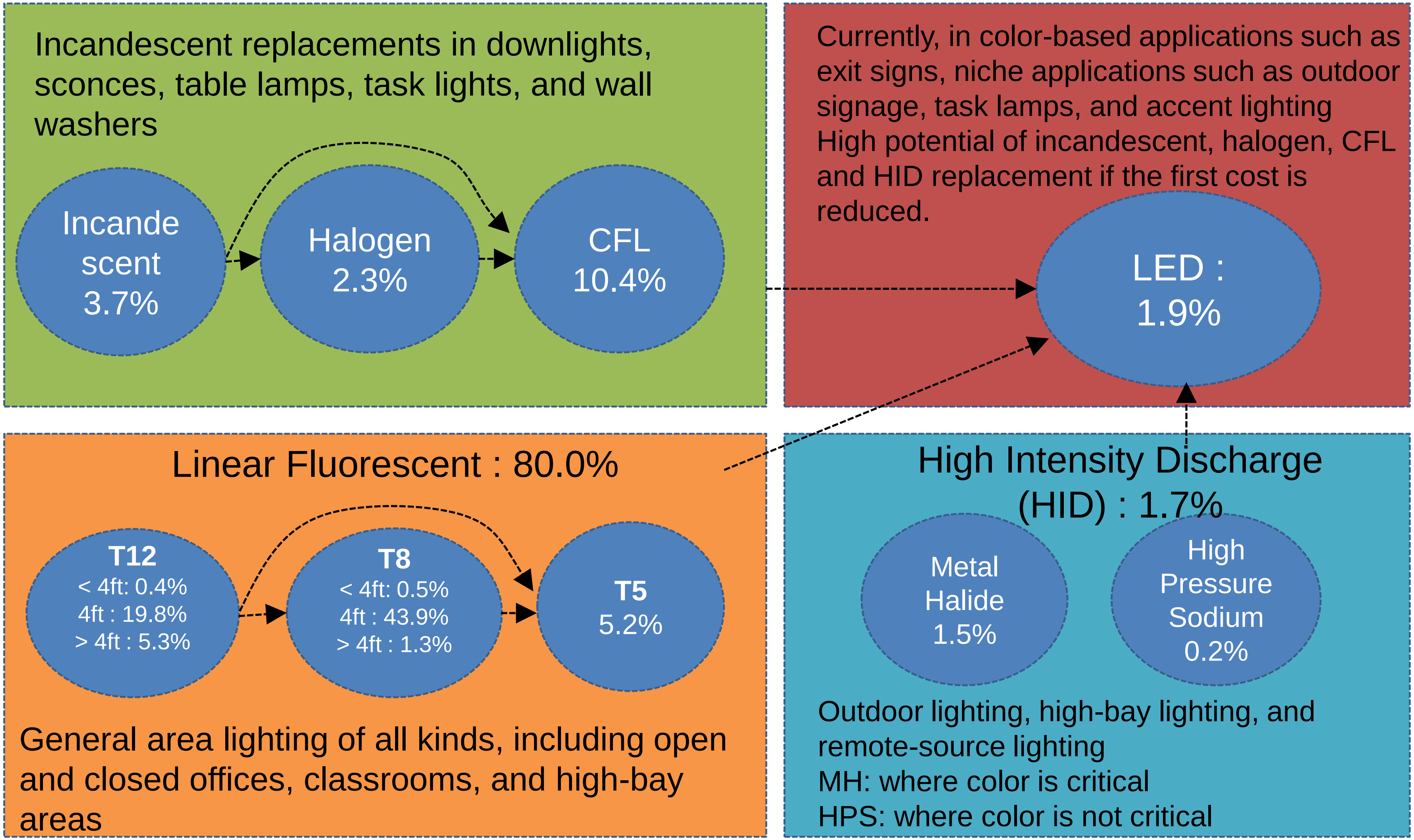
Aggressive Case



Learning Factor = 0.32

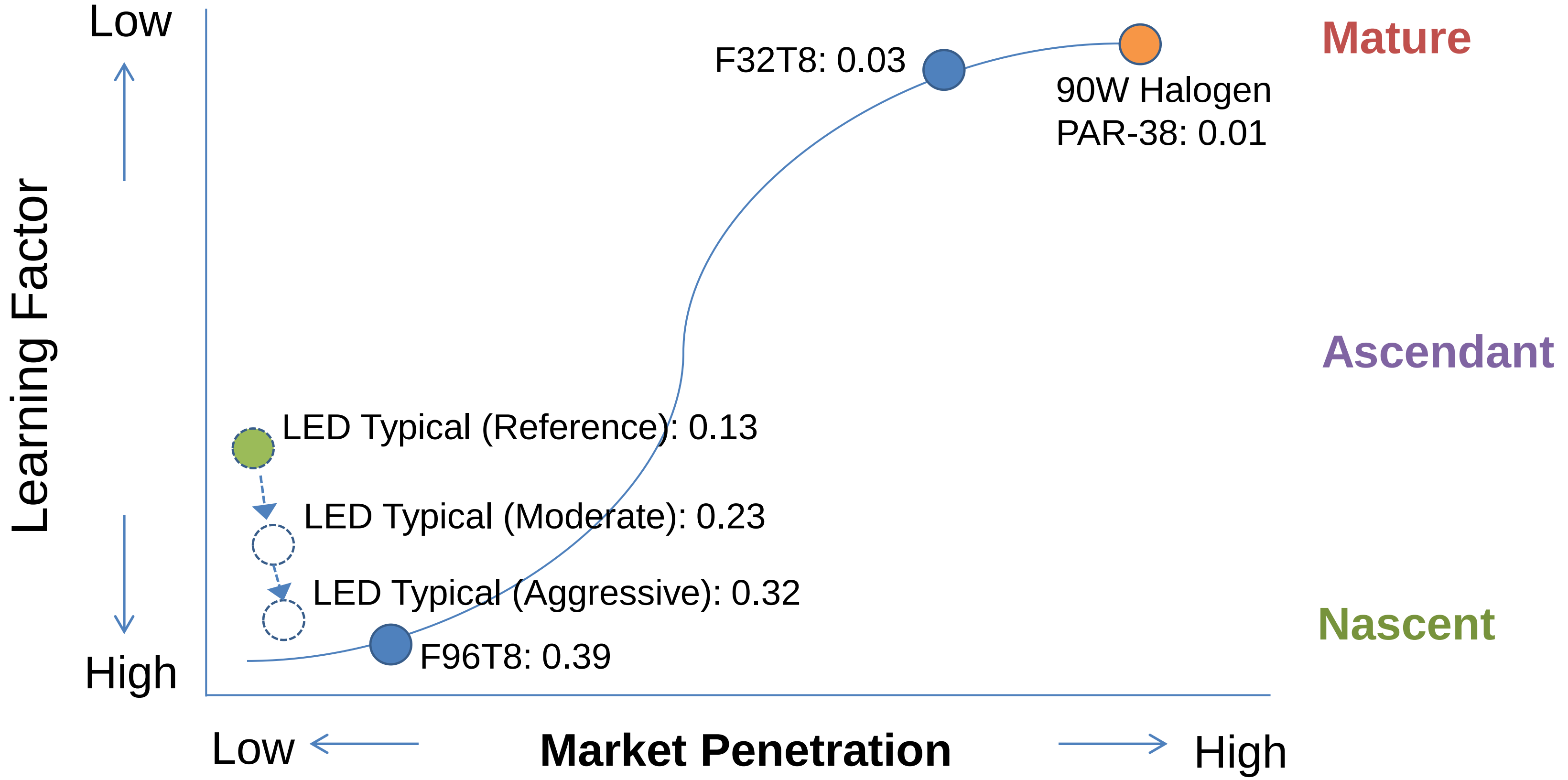
Niche Market Characterization

Percentage : Market share of lamps in commercial sector in 2010 (Navigant, 2012)* / ---▶ : Replacement availability



* Navigant Consulting, Inc. (2012) 2010 U.S. Lighting Market Characterization, U.S. DOE

Learning Factors:
Application to Technology Diffusion Curve



	LED Typical (Reference)	LED Typical (Moderate)	LED Typical (Aggressive)	F96T8	F32T8	90W Halogen PAR-38
Cumulative SD by 2013	3 TBtu	3 TBtu	3 TBtu	238 TBtu	1,386 TBtu	758 TBtu
Market share in 2013	0.1%	0.1%	0.1%	14.8%	78.9%	88.7%
Cumulative market share by 2013	0.1%	0.1%	0.1%	14.6%	76.2%	98.9%
Cumulative SD by 2035	255 TBtu	844 TBtu	3,532 Tbtu	995 TBtu	5,219 TBtu	1,252 TBtu
Market share in 2035	10.9%	24%	82.9%	15.5%	79.9%	5.3%
Cumulative market share by 2035	3%	10%	41.9%	15.0%	78.9%	48.4%

Conclusions

- GT-NEMS models learning effects in two ways: endogenous and exogenous learning.
- GT-NEMS appears to underestimate the learning potential of commercial solar PV and LED lighting technologies.
- The learning parameters for three other lighting technologies are more consistent with their market maturity.

Topics for Further Discussion

- Does the current GT-NEMS representation of learning adequately characterize solar PV learning? How might it be improved?
- How to represent multiple solar PV technologies in GT-NEMS? Should they have different learning factors?
- Should the learning factor change as the maturity of technologies improve? Is market penetration a good measure of technology maturity?
- How to represent the market share of a niche technologies in GT-NEMS? Is the service demand output a good basis?
- Should GT-NEMS reflect regional variations in technology learning?

For More Information

Please contact the researchers

Xiaojing Sun

xsun44@gatech.edu

Gyungwon Kim

joykim@gatech.edu

Marilyn Brown

marilyn.brown@pubpolicy.gatech.edu

Supplemental Material

Calculate PV Penetration Rate in NEMS

1. Cash Flow

$$NetCashFlow_{[t],...,[y],Y} = ValElecSave_{[t],...,[y],Y} + TaxDeduct_{[t],...,[y],Y} - OutLay_{[t],...,[y],Y} - FuelCost_{[t],...,[y],Y} - MaintCost_{[t],...,[y],Y}$$

2. Internal Rate of Return (IRR)
   - A Gauss-Sidel search that finds the discount rate that makes the net case flow equal to zero.
3. Payback

$$SimplePayback_{[t],...,[y]} = \min\left\langle 29, \log(2)/(\log(1 + \mathrm{IRR}_{[t],...,[y]})\right\rangle$$

4. Maximum penetration to new constructions . Solar PV PenParm=0.3

$$MaxPen_{[t],...,[y]} = \frac{PenParm_t}{SimplePayback_{[t],...,[y]}}$$

Penetration Rate Cont.

- Penetration in new construction

$$Pen_{[t],[y]} = \left[MaxPen_{[t],[y]} - \frac{1}{\frac{1}{MaxPen_{[t],[y]}} + e^{\left[\alpha_t \cdot \left(y - CogHistYear - SimplePayBack_{[t],[y]}\right)\right]}} \right] \cdot Inxdecay_{r,y}$$

- t: technology y: year
- Penetration in existing buildings
  - Capped at 0.5%

DOE Efficacy Standards for Incandescent Reflector Lamp (IRLs) and General Service Fluorescent Lamp (GSFL)

- The DOE has regulated the energy efficiency standards for incandescent and fluorescent bulbs since EPACT 1992.
- The Energy Independence and Security Act (EISA) was signed into law in 2007 and has regulated the new EE standards since July 14, 2011.
- Only a few halogen reflector lamps (e.g., PAR 20, PAR 30, PAR 38) can meet the Final Rule standards that make lamps more expensive than standard halogen lamps (Halcolighting.com, 2011).

Table. Energy Conservation Standards for Incandescent Reflector Lamps

Rated lamp wattage	Spectrum Modification	Lamp diameter (inches)	Rated voltage	Minimum average lamp efficacy (lm/W)
40-205	Standard Spectrum	>2.5	>=125V	$6.8*P^{0.27}$
			<125V	$5.9*P^{0.27}$
		<=2.5	>=125V	$5.7*P^{0.27}$
			<125V	$5.0*P^{0.27}$
40-205	Modified Spectrum	>2.5	>=125V	$5.8*P^{0.27}$
			<125V	$5.0*P^{0.27}$
		<=2.5	>125V	$4.9*P^{0.27}$
			<125V	$4.2*P^{0.27}$

Note 1: P is equal to the rated lamp wattage, in watts

Note 2: Standard Spectrum means any incandescent reflector lamp that does not meet the definition of modified spectrum in 430.2.

DOE Efficacy Standards for Incandescent Reflector Lamp (IRLs) and General Service Fluorescent Lamp (GSFL)

Table. Energy Conservation Standards for General Service Fluorescent Lamps

Lamp type	Correlated color temperature	Minimum average lamp efficacy (lm/W)
4-foot medium bipin **(F32T8 HE)**	<=4,500K >4,500K and <=7,000K	89 88
2-foot U-shaped	<=4,500K >4,500K and <=7,000K	84 81
8-foot slimline	<=4,500K >4,500K and <=7,000K	97 93
8-foot high output **(F96T8 High)**	<=4,500K >4,500K and <=7,000K	92 88
4-foot miniature bipin standard output **(F28T5)**	<=4,500K >4,500K and <=7,000K	86 81
4-foot miniature bipin high output	<=4,500K >4,500K and <=7,000K	76 72

(Source: DOE (2009) Energy Conservation Program, http://www.regulations.gov/#!documentDetail;D=EERE-2006-STD-0131-0005)

Technical Description and Maturity Stage

(Source: Navigant (2005) U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options)

	Description	Characteristics	Technical Maturity	Cost & Efficacy
90W Halogen PAR 38* 	• A type of incandescent lamp • Produce light by heating a tungsten filament within a quartz capsule under high pressure with a halogen fill-gas • The halogen gas carries the evaporated tungsten particles back to the filament and re-deposits them, enabling the tungsten filament to operate at higher temperatures without shortening its operating life. • 90 Watts, 120 V • Length: 5-5/16 Inch • Diameter: 4-3/4 Inch	• Longer life than regular incandescent lamps • Hotter than regular incandescent lamps • The most efficacious commercially available incandescent source (incandescent light source has at least efficacy.) • The efficacy, at constant lamp life, increases as the tungsten wire diameter is increased.	• Commercialization and sales • Applied research for higher operating temperatures to achieve higher efficacy	PAR 38 60W 120V: $ 3.59-$7.47 (2005$) Efficacy Old: 15 lm/W New: 26.5 lm/W ** Minimum **Efficacy Standard: 19.9 lm/W (=5.9*90W^ 0.27).**

* PAR 38 (parabolic aluminized reflector or pressed-glass aluminized reflector) is a type of halogen light bulb. The gas within PAR 38 bulbs rebuilds the filament and creates a bulb that is longer-lasting than many other type of halogen lighting.

Technical Description and Maturity Stage

(Source: Navigant (2005) U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options)

	Description	Characteristics	Technical Maturity	Cost & Efficacy
F32T8 HE 	• When the gas is excited by electricity, it emits invisible ultraviolet radiation then converts into visible light when it hits the white (phosphors) coating inside the tube wall. • A ballast supplies the initial electricity that creates the light, and then it regulates the amount of electricity flowing through the bulb so that the right amount of light is emitted. • Power: 32W • T8: 1 inch tube diameter • Length: 4ft	• A typical fluorescent lamp • Most common lighting application for commercial buildings • Smaller diameter results in less surface area, making rare-earth phosphor coatings more cost-competitive, and improve the efficacy of luminaire. • (However, smaller diameter linear lamps require different sockets and ballasts.) • Possible applications such as overhead office lighting, retail store lighting, and industrial warehouse lighting	• Commercialization and sales • Most installed lamps are T12 and T8.	F32T8: $ 1.76 (2003$) Efficacy: 87-92 lm/W **** Minimum Efficacy Standard: 88-89 lm/W**
F96T8 High	• Power: 49W-86W • Length: 8ft	• Used in warehouses and in areas with high ceilings	• Commercialization and sales	F96T8: $ 7.45 – 13.78 (2012$) Efficacy: 87-96 lm/W **** Minimum Efficacy Standard: 88-92 lm/W**

Technical Description and Maturity Stage

(Source: Navigant (2005) U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options)

	Description	Characteristics	Technical Maturity	Cost & Efficacy
F28T5 	• Power: 28W • T5: 5/8 inch tube diameter • Length: 4ft	• More effectively operated at higher temperature than T8 lamps • Smaller cross section and size • Better luminous efficacy • Smaller ballasts • Good color temperature availability • Better photometric performance • Well suited for applications such as hospitality, commercial display cases, upscale retail, wall washing, and other places where light output control is important.	• Commercialization and sales • The market share of T5 is increasing.	F32T8: $ 5.7 (2003$) Mean Efficacy: 93-103 lm/W **** Minimum Efficacy Standard: 81-86 lm/W**

Technical Description and Maturity Stage

(Source: DOE (2012) Solid-State Lighting Research and Development: Multi-Year Program Plan)

	Description	Characteristics	Technical Maturity	Cost & Efficacy
LED Typical 	• LEDs are semiconductors with a narrow-band optical emission that can be manufactured to emit in the ultraviolet (UV), visible or infrared regions of the spectrum. • There are three approaches: 1) phosphor-conversion, 2) discrete color-mixed, or 3) hybrid approach. • Most LEDs use the phosphor-converted approach to create white light.	• One of the most efficacious lighting options available • Commercial LED-based light sources have the potential to surpass the efficacy of the most efficient conventional light sources-incandescent, halogen, linear fluorescent, and HID. • The higher first cost deter the building contractors to choose LEDs in spite of lower lifecycle costs. • Costs need to be reduced to further accelerate adoption.	• In 2010, the installed base still represented only 1 % of the total lighting inventory. • Nearly half of these LEDs were installed in commercial and industrial exit signs. • LEDs have become increasingly competitive with HID lamps for outdoor lighting. • Indoor LED-based lighting is rapidly growing.	LED lamp cost (A19 60W; 800 lumens dimmable): $39.97 (2010$) Efficacy: 74 – 144 lm/W (e.g. - LED A19 Lamp: 93 lm/W, - LED PAR38 Lamp: 74 lm/W, - LED White Package: 111-144 lm/W)

Alternative Cost Scenarios of Learning Effect

Technologies	Literature (Navigant, 2010)			NEMS				Proposed Cost Decline Scenarios		
	Vintage Start	Cost [1] ($/klm)	Efficacy (lm/W)	Vintage Start	Cost ($/klm)	Efficacy (lm/W)	Estimated LF	Vintage Start	Moderate Cost Scenario	Aggressive Cost Scenario
LED	2010	213.68	50.2	2010	198.19	84.6		2010	198.19	198.19
	2011	191.70	57.2	2011	196.79	86.6		2011	187.30	177.80
	2020	13.54 (-94%)	133.5	2020	134.18 (-32%)	181.0	0.11	2020	71.35 (-64%)	11.89 (-94%)
Fluorescent (F96T8 High) (8200 lumens)	2010	11.10	84.0	2003	12.35	83.1		2003	12.35	12.35
	2030	9.99 (-10%)	88.2	2010	9.56 (-23%)	107.1	0.31	2010	9.56	9.56
								2030	8.60 (-10%)	6.69 (-30%)
Fluorescent (F32T8 HE) (2900 lumens)	2010	30.00	83.0	2003	22.14	60.6		2003	22.14	22.14
	2030	27.00 (-10%)	86.6	2012	21.09 (-4.7%)	63.6	0.03	2012	21.09	21.09
								2030	19.19 (-9%)	15.40 (-27%)
Fluorescent (F28T5) (2900 lumens)	2010	37.41	95.0	2003	31.98	71.5	N/A	2003	31.98	31.98
								2020	29.26 (-8.5%)	23.83 (-25.5%)
	2030	33.67 (-10%)	99.8					2030	27.66 (-13.5%)	19.03 (-40.5%)

Service Demand and Capital Cost Changes from Updated Lighting Parameters