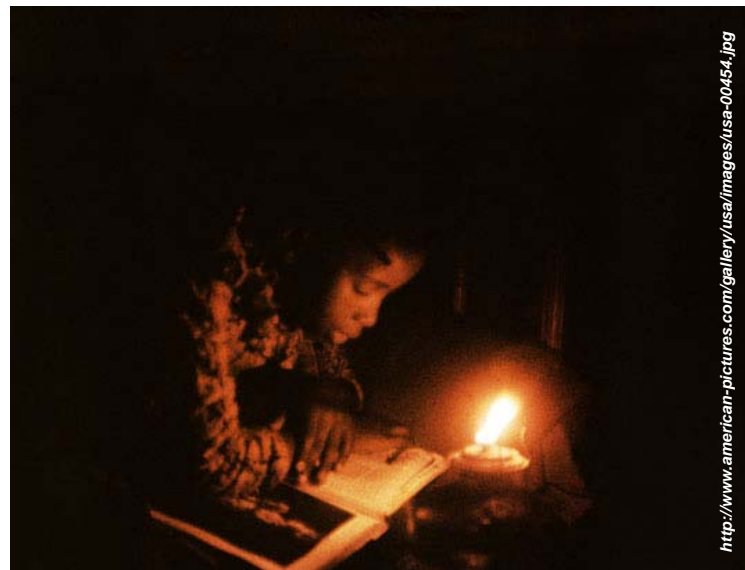
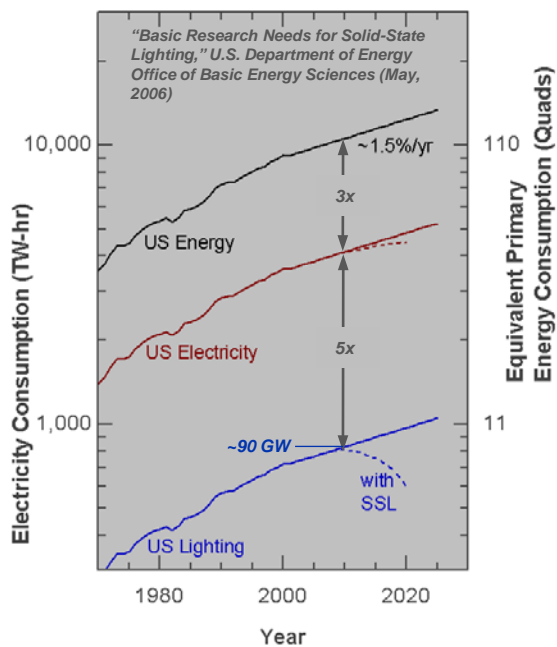


# Lighting Technologies, Costs & Energy Demand: Global Developments to 2030

**Sandia National Laboratories**

**Jeff Tsao, Harry Saunders, Randy Creighton, Mike Coltrin, Jerry Simmons**  
*Decision Processes Incorporated*



**Acknowledgements: Paul Waide (IEA), George Craford (Philips Lumileds), Mary Crawford (Sandia)**

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# State-of-Art Commercial Solid-State Lighting Lamp



78%  
Spectral efficiency  
(match to human eye)

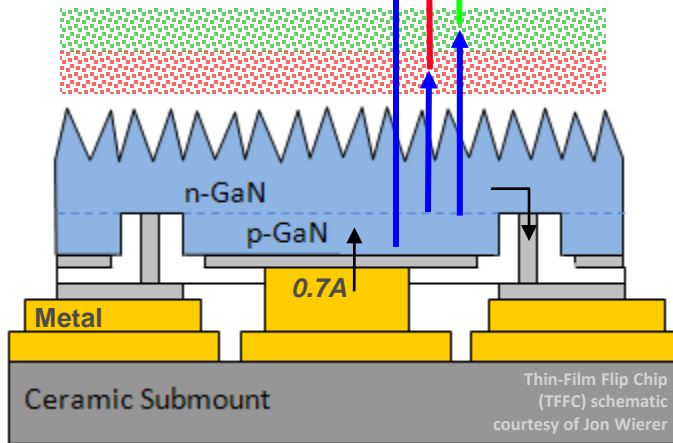
## Thin-Film Flip-Chip Architecture

16%  
Overall efficiency  
(luminous efficacy  $\eta_\phi = 66 \text{ lm/W}$ )

@  
Color rendering index (CRI) 85  
Color temperature (CCT) 3,100 K  
Current density 70 A/cm<sup>2</sup>

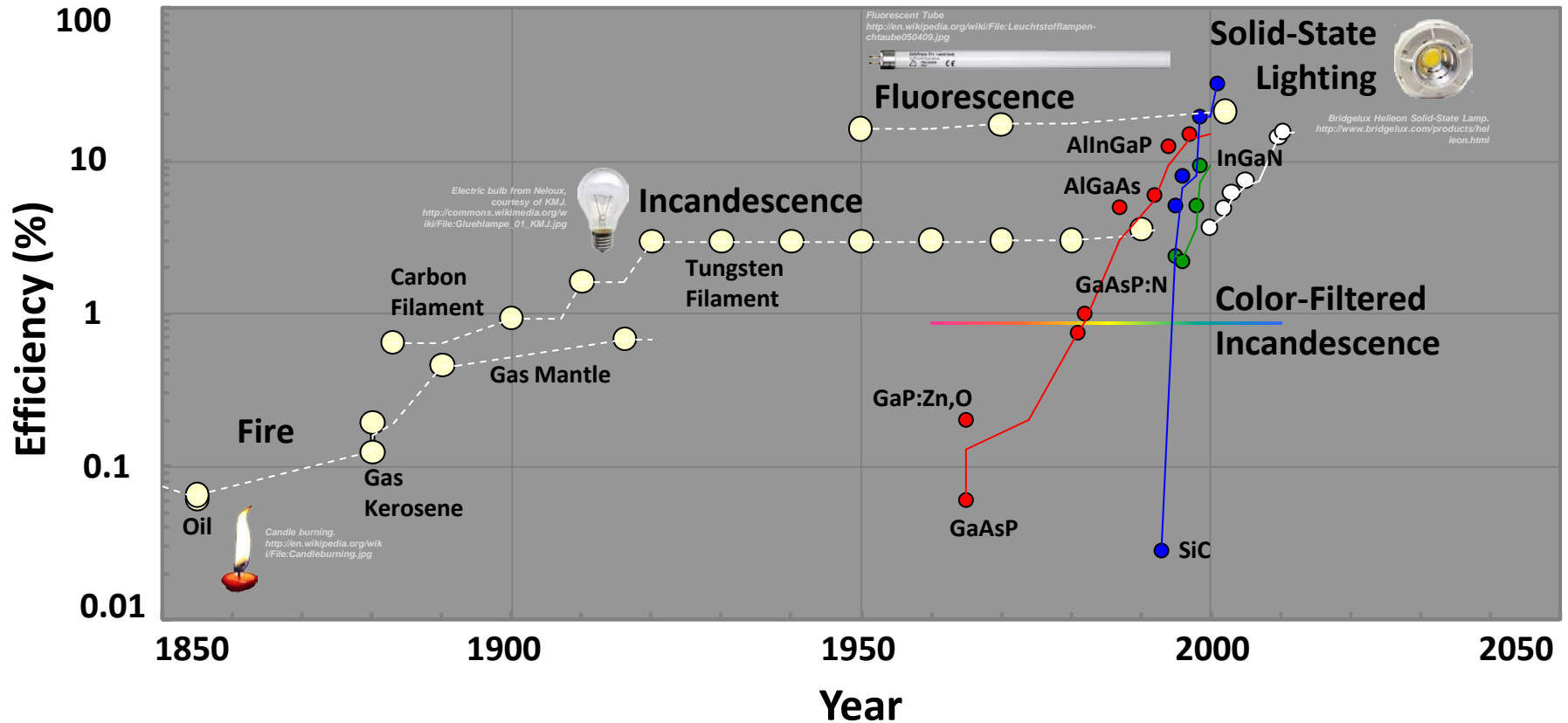
54%  
Phosphor  
(and package)  
efficiency

38%  
Blue LED  
efficiency



1 mm

# 200 Years of Lighting Technology Efficiency



# A Progression of Productive Uses for Colored and White Solid-State Lighting

Center high-mount stop light (CHMSL).  
<http://www.honda-tech.com/showthread.php?t=2413558>



NASDAQ's Giant Video Display in Times Square, New York (Jeff Tsao)



Sharp QuadPixel RGBY LED-backlit LCD Display.  
[http://www.macworld.com/article/145541/2010/01/sharp\\_quadpixel.html](http://www.macworld.com/article/145541/2010/01/sharp_quadpixel.html)



COLORED



Surefire U2 flashlight.  
<http://en.wikipedia.org/wiki/File:SurefireU2.JPG>



Nokia camera phone with LED flash.  
<http://www.itechnews.net/wp-content/uploads/2009/07/Nokia-3720-Classical-the-most-rugged-mobile-phone.jpg>



<http://tan-moneyonline.com/wp-content/uploads/2008/03/earthatnight-asia1.jpg>

WHITE



# Estimates of Light Consumption, spanning:

- 3 centuries, 6 continents, 6 technologies, and 7 orders of magnitude in light consumption
- Commercial, residential, industrial, outdoor sectors
- Grid, fuel and vehicle lighting

1 Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not  
William D. Nordhaus

Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300-2000)<sup>1</sup>

Roger Fouquet\* and Peter J.G. Pearson\*\*

Before the mid-eighteenth century, most people lived in near-complete darkness except in the presence of sunlight and moonlight. Since then, the provision of artificial light has been revolutionized by a series of innovations in appliances, fuels, infrastructures and institutions that have enabled the growing demands of economic development for artificial light to be met at dramatically lower costs: by the year 2000, while United Kingdom GDP per capita was 15 times its 1800 value, lighting services cost less than one three thousandths of their 1800 value, per capita use was 6,500 times greater and total lighting consumption was 25,000 times higher than in 1800. The economic history of light shows how focussing on developments in energy service provision rather than simply on energy use and prices can reveal the "true" declines in costs, enhanced levels of consumption and welfare gains that have been achieved. While emphasizing the value of past trends, the paper also warns against the dangers of over-reliance on past trends for the long-run forecasting of energy consumption given the potential for the introduction of new technologies and fuels, and for rebound and saturation effects.

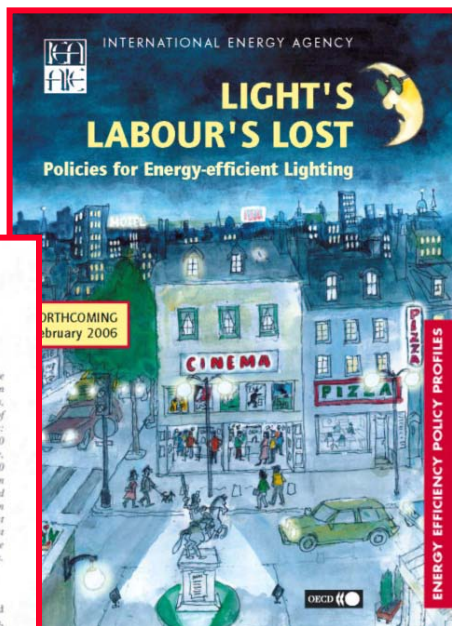
## I. INTRODUCTION

Over the last three centuries, industrialised societies have been freed from dependence on sun and moonlight for illumination: technological innovation, mass production of lighting appliances, expansion of energy infrastructures and

<sup>1</sup> The Energy Journal, Vol. 27, No. 1, Copyright ©2006 by the IAAE. All rights reserved.

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1. An earlier version of this paper was presented at the British Institute of Energy Economics/IAEE conference, Government Intervention in Energy Markets, St John's College, Oxford, 25-26 Sept 2003. The authors would like to thank David Woodcock and Jon Newman, four anonymous referees and Campbell Watkins for their constructive comments. All errors are the authors' responsibility.



## Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

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Qinglin, China, 265021

EVAN WILLES  
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Department of Industrial Engineering and Operations Research, University of California  
Berkeley, California, USA, 94720

April 1996

## ENERGY-EFFICIENT LIGHTING IN CHINA: PROBLEMS AND PROSPECTS<sup>1</sup>

## U.S. Lighting Market Characterization

## Volume I: National Lighting Inventory and Energy Consumption Estimate

Final Report

Prepared by  
Navigant Consulting, Inc.

for  
U.S. Department of Energy

Office of Energy Efficiency and Renewable Energy  
Building Technologies Program

September 2002

## ENVIRONMENT

## The Specter of Fuel-Based Lighting

Evans Mills

Thomas Edison's seemingly forward-looking estimate that "we will never use electricity so cheap that only the rich will burn candles" (1) was true for the industrialized world, but it did not anticipate the plight of 1.8 billion people (2)—more than half the world's population in Edison's time—who have had no access to electricity. While electricity was becoming available in the wealthier countries, leaders of the oil industry (3, 4) promoting lighting alternatives in China and elsewhere. The legacy of costly and low-grade lighting for the world's poor remains. For those without access to electricity, lighting is derived from a diversity of sources, including kerosene, diesel, propane, biomass, candles, and solar lamps. Many of the 35 million people living in camps for refugees and internally displaced people have light at all.

Throughout the developing world, 14% of urban households and 49% of rural households were without electricity as of the year 2000 (5). In extreme cases, e.g., Ethiopia and Uganda, only 1% of rural households are electrified (6). An unknown additional number of people have intermittent access to electricity in their homes or back in shantytowns in their neighborhoods, markets, schools, or clinics (6). The number and proportion of people having electricity is growing in South Asia and parts of Latin America and the Caribbean, the Middle East, and South Asia (7). Population growth, swelling rates of urbanization, and doubling household sizes (8) exacerbate the problem. The number of people without access to electricity is globally projected to double or more (9) before year 2100 (10).

Distinctions in use of electricity and use of energy services sought by society and its equity obtained by some at efficiencies on the order of 100 times per watt and by others at well below 1 kilowatt per watt (11). Comparing this disparity, the least efficient sources also deliver low—and low-cost—light. A single-watt kerosene lamp provides about 1 lux (lumens/m<sup>2</sup>) at 1 meter from the source,

## POLICY FORUM



Taller working by candlelight in an "informal" shop with charcoal power generation. Power that would reach 40% in some countries (2).

## Off-Grid Solid-State Lighting: An Opportunity for Technological Leapfrogging

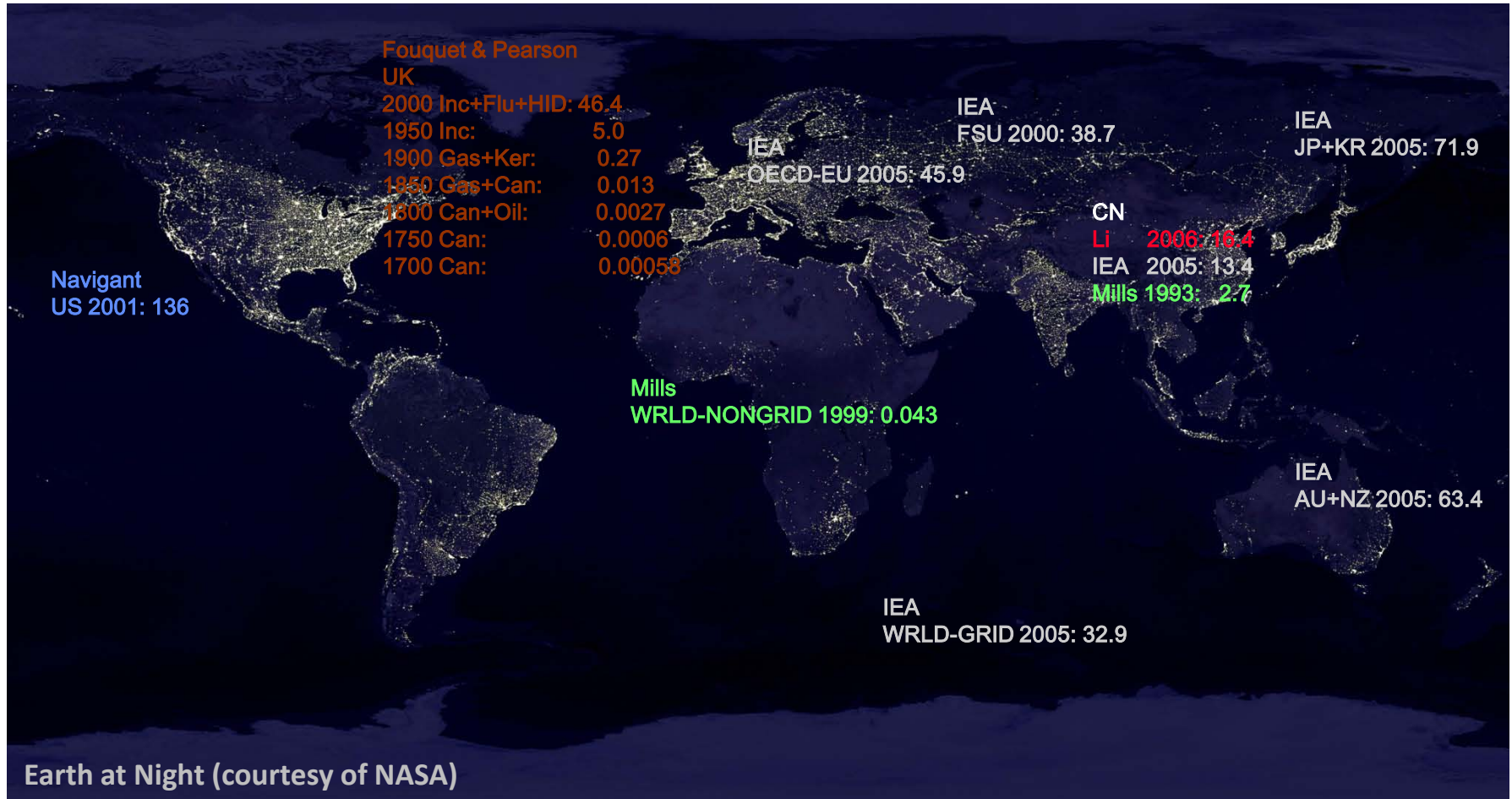
As they proliferate, developing countries can select better technologies and in so doing narrow the efficiency gap between industrial and developing countries (17). The latter improvement in lighting energy efficiency in the solid state white-light-emitting diode (LED) (18), distinguished from other lighting technologies by a six-order-of-magnitude increase in efficiency, doubling costs per unit and output, and rising efficiencies.

LED technologies provide more and better illumination (with some special caution) than do fuels (Fig. 3A), dramatically reducing operating costs (19) and greenhouse gas emissions, while increasing the quality and quantity of lighting services. Efficiency of only four different fixtures per watt in the mid-1990s are saving nearly 100 times per watt (compared with 61 fixtures per watt for a flame-based incandescent). Relative

<sup>1</sup> The author is at the U.S. Department of Energy, Lawrence Berkeley National Laboratory, 94720 Berkeley, CA 94720. USA. E-mail: evans@lbl.gov

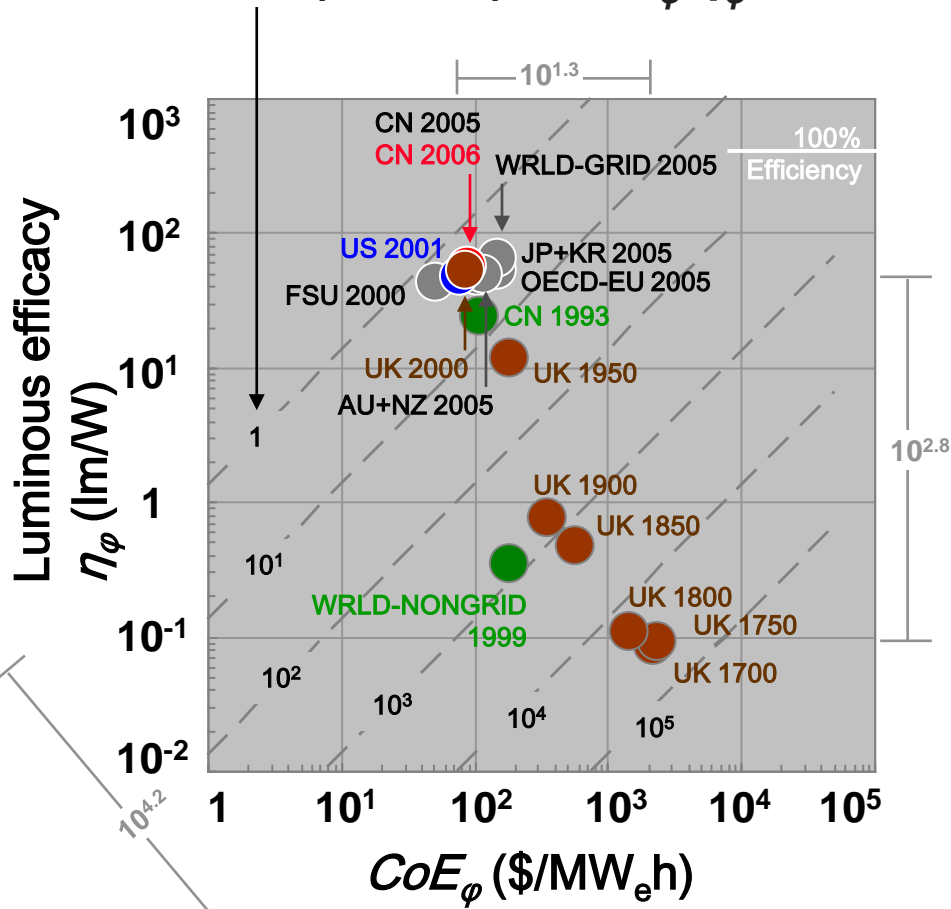


# per capita Consumption of Light: $\phi$ , in Mlmh/(person-yr)



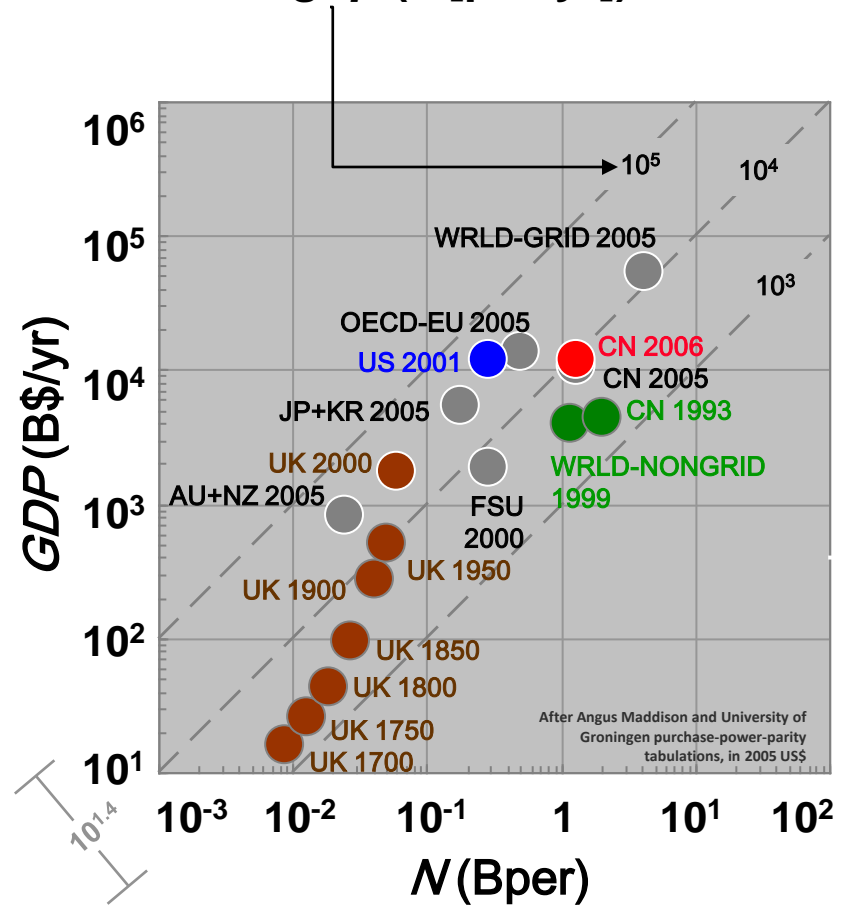
# Cost of Light:

$$\text{CoL (\$/Mlmh)} \approx \text{CoE}_\phi / \eta_\phi$$



# per capita gross domestic product:

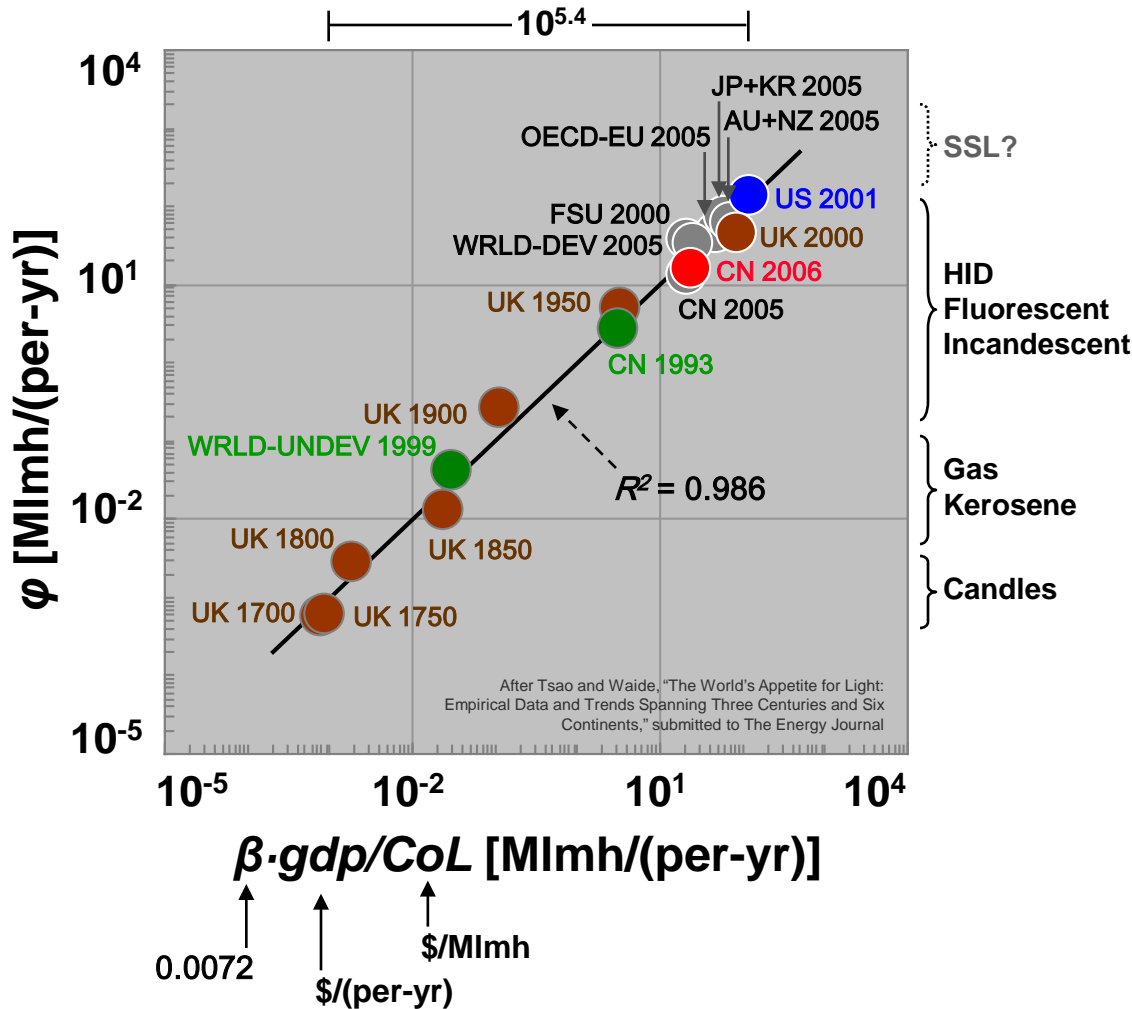
$$\text{gdp (\$/[per-yr])} = \text{GDP}/N$$



After Angus Maddison and University of Groningen purchase-power-parity tabulations, in 2005 US\$



$$\varphi = \beta \cdot (\text{gdp}/\text{CoL})$$



**Implication 1:**

*World has spent, and spends, ~0.72% of GDP on artificial light*

*The world in 2005:*

*0.72% = US\$440B / US\$60T*

*6.5% = 1 TW<sub>c</sub> / 16 TW<sub>c</sub>*

**Implication 2:**

*Price and income elasticity of consumption of light is ~unity*

*Are we treading water or not?*



# Profit maximization in a two-factor economy

$$\underbrace{\pi(\chi, \varphi)}_{\substack{\text{per capita consumption} \\ \text{of light} \\ \text{per capita consumption of} \\ \text{everything else}}} = \underbrace{[A \cdot \chi^\alpha \varphi^\beta]}_{\substack{\text{Cobb-Douglas} \\ \text{with constant returns to scale} \\ (\alpha + \beta + 0.7 = 1) \\ \text{Labor component}}} - \underbrace{[\chi \cdot CoX + \varphi \cdot CoL]}_{\substack{\text{Cost of everything else } (\chi) \\ \text{Cost of Light } (\varphi)}}$$

## Profit Maximization

$$\frac{\partial \pi}{\partial \chi} = 0$$

$$\frac{\partial \pi}{\partial \varphi} = 0$$

## Profit-maximizing $\varphi$ and $\chi$

$$\chi = \alpha \frac{gdp}{CoX} \quad 0.2928$$

$$\varphi = \beta \frac{gdp}{CoL} \quad 0.0072$$

## Profit-maximizing $gdp$ and $\dot{e}$

$$gdp = A^{\frac{1}{1-\alpha-\beta}} \cdot \left(\frac{\alpha}{CoX}\right)^{\frac{\alpha}{1-\alpha-\beta}} \cdot \left(\frac{\beta}{CoL}\right)^{\frac{\beta}{1-\alpha-\beta}} \quad 0.01$$

$$\begin{aligned} \dot{e} &= \chi / \eta_\chi + \varphi / \eta_\varphi \\ &= \frac{\alpha \cdot gdp}{CoX \cdot \eta_\chi} + \frac{\beta \cdot gdp}{CoL \cdot \eta_\varphi} \end{aligned}$$

*These cancel!*

$CoE_\varphi / \eta_\varphi$

# Possible Worlds in 2030

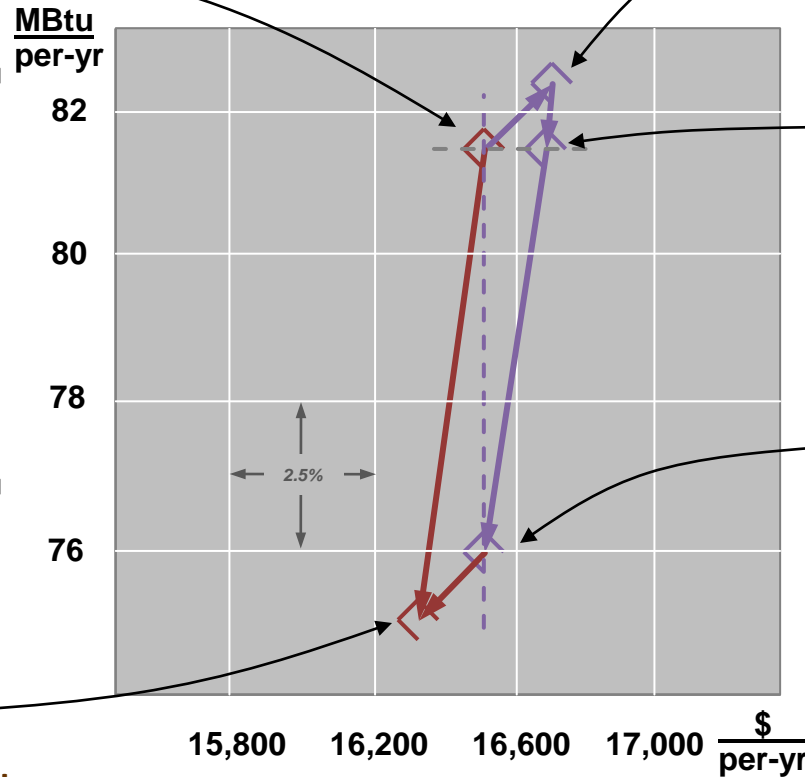
## FLU-L

$\eta_\phi$  87 lm/W<sub>e</sub>  
 CoE<sub>φ</sub> 119 \$/MW<sub>e</sub>h  
 Baseline EIA projection  
 for world in 2030  
 (fluorescent lighting  
 dominant)

## FLU-H

$\eta_\phi$  87 lm/W<sub>e</sub>  
 CoE<sub>φ</sub> 369\$/MW<sub>e</sub>h  
 (Fluorescent lighting dominant with  
 high increase in energy cost for  
 lighting)

$$\dot{e} = gdp \cdot \left[ \frac{\dot{e}_o}{gdp_o} + \left( \frac{4\beta/3}{CoE_\phi} - \frac{4\beta/3}{CoE_{\phi_o}} \right) \right]$$



## SSL-L

$\eta_\phi$  268 lm/W<sub>e</sub>  
 CoE<sub>φ</sub> 119 \$/MW<sub>e</sub>h  
 (SSL dominant)

## SSL-M

$\eta_\phi$  268 lm/W<sub>e</sub>  
 CoE<sub>φ</sub> 133 \$/MW<sub>e</sub>h  
 (SSL dominant but  
 moderate increase in  
 energy cost for lighting)

## SSL-H

$\eta_\phi$  268 lm/W<sub>e</sub>  
 CoE<sub>φ</sub> 369 \$/MW<sub>e</sub>h  
 (SSL dominant but high  
 increase in energy cost  
 for lighting)

$$gdp = gdp_o \cdot \left( \frac{CoE_{\phi_o} \cdot \eta_\phi}{CoE_\phi \cdot \eta_{\phi_o}} \right)^{\frac{\beta}{1-\alpha-\beta}}$$

