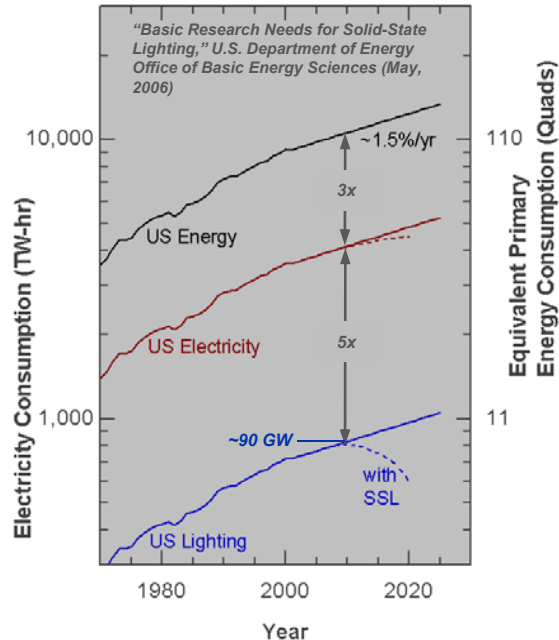


Lighting, Energy Consumption, Human Productivity

Jeff Tsao · Sandia National Laboratories · Albuquerque NM



Acknowledgements

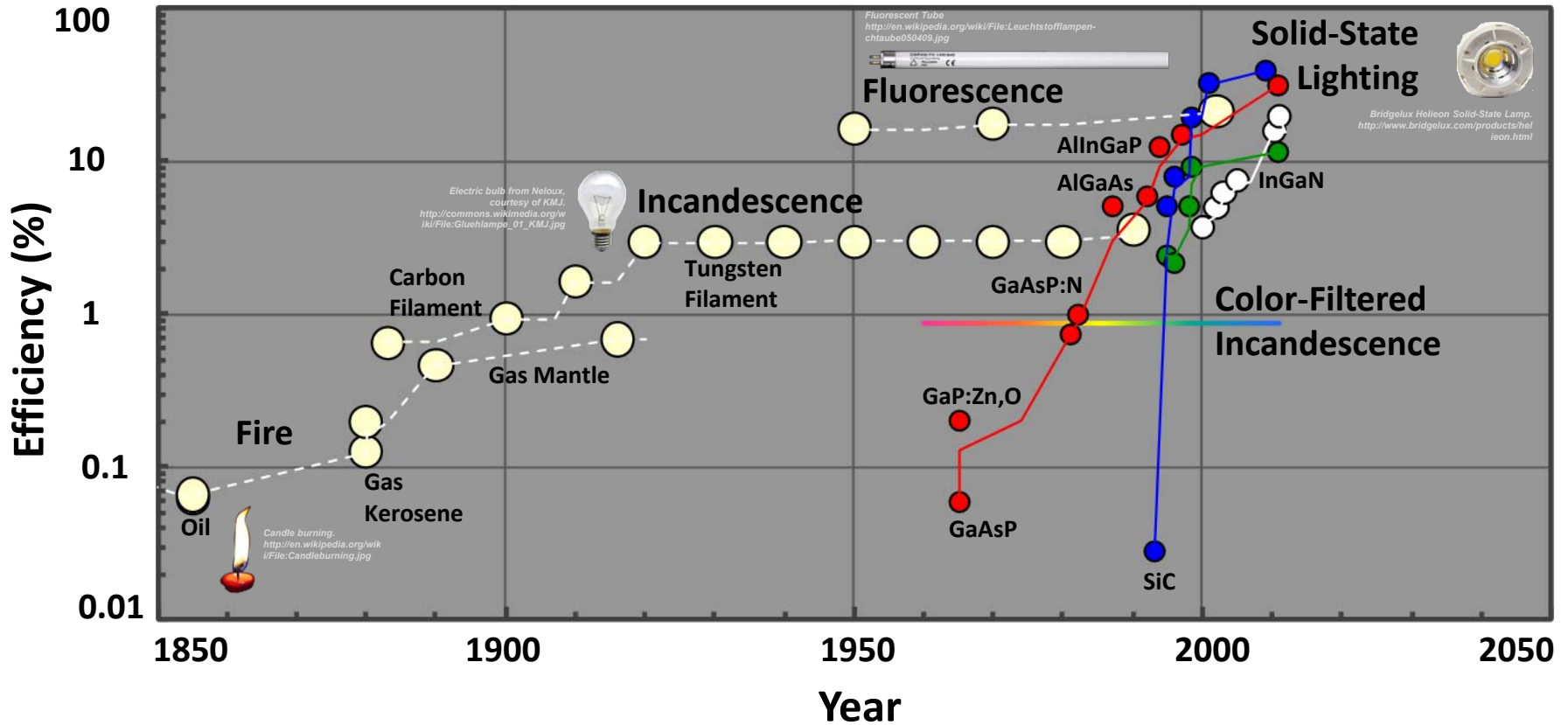
Sandia: Randy Creighton, Mike Coltrin, Jerry Simmons, Mary Crawford

Non-Sandia: Harry Saunders (Decision Processes Inc), Paul Waide (IEA), George Craford (Philips Lumileds)

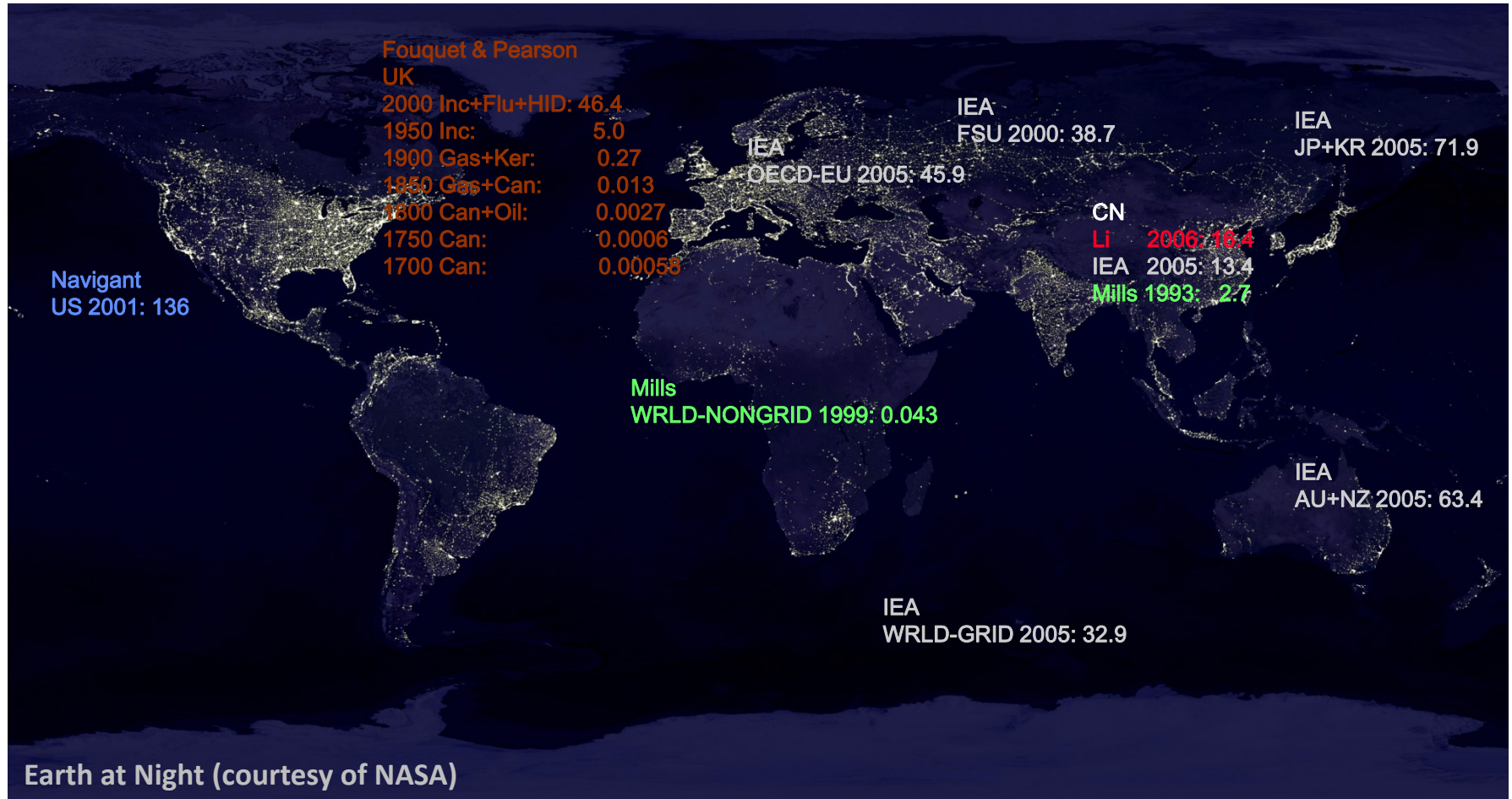
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200 Years of Lighting Technology

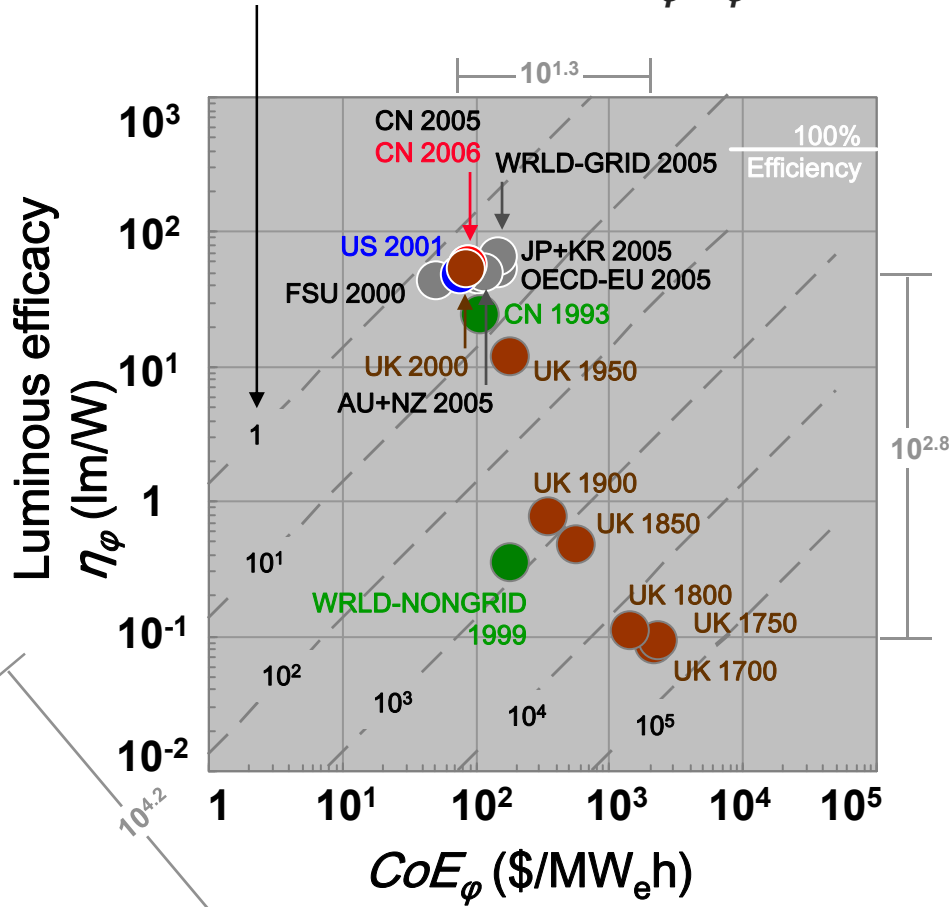


per capita Consumption of Light: ϕ , in Mlmh/(person-yr)



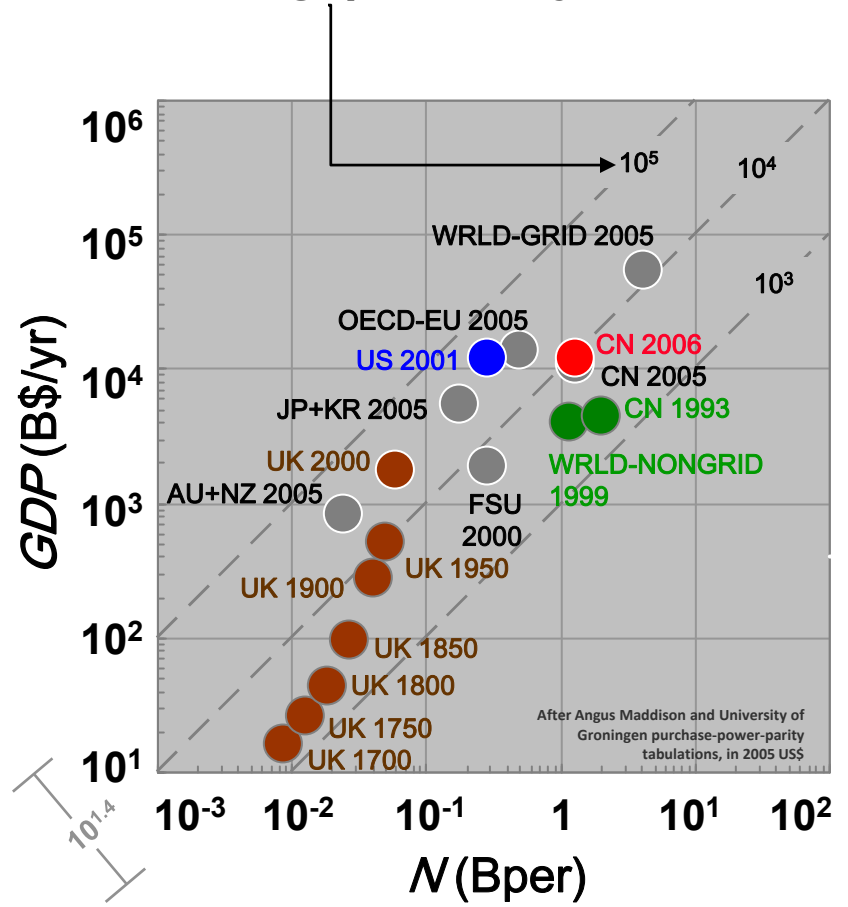
Cost of Light:

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



per capita gross domestic product:

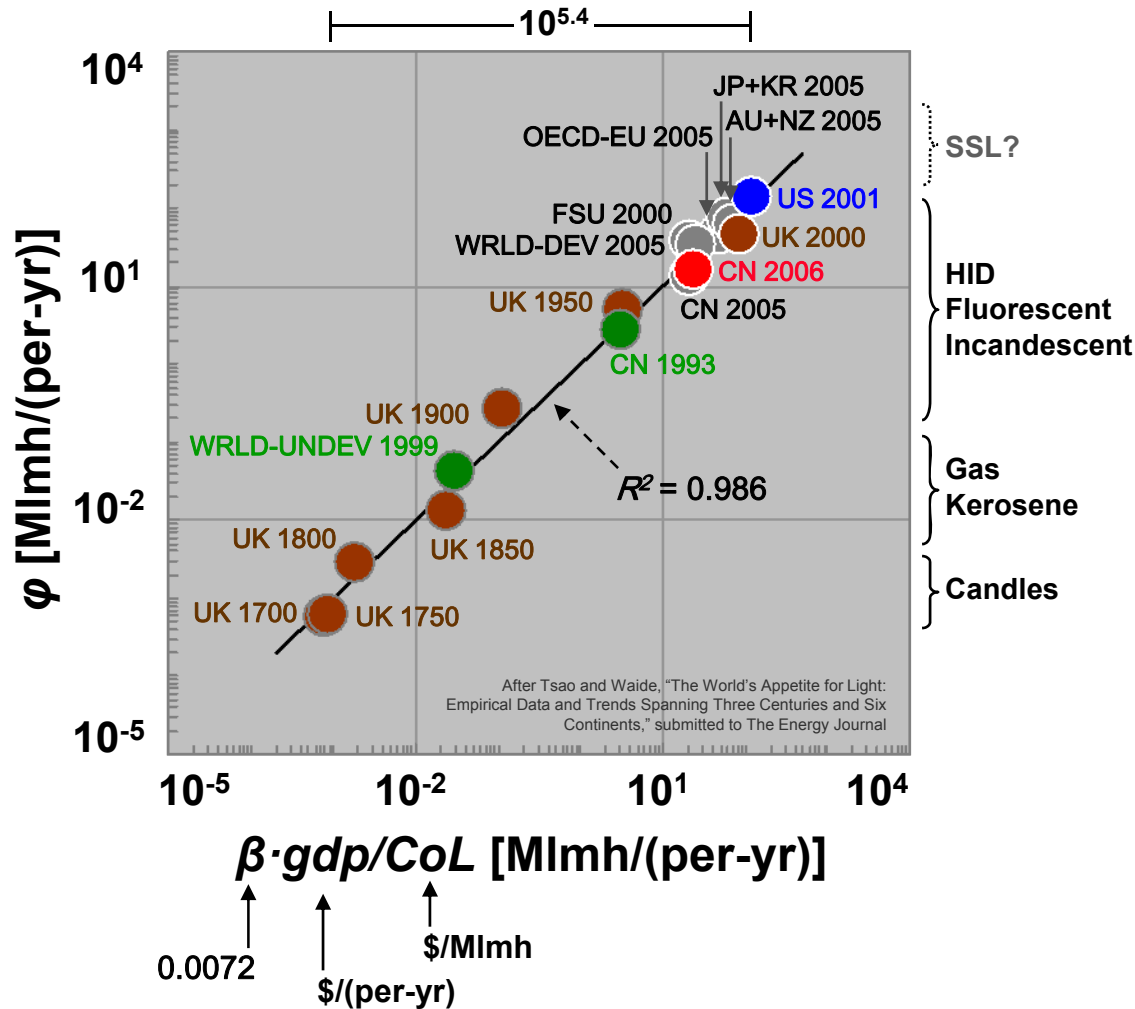
$$\text{gdp (\$/[per-yr])} = \text{GDP}/N$$



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_c / 16 TW_c

Implication 2:

Price and income elasticity of consumption of light is ~unity

Rebound is likely driven by human productivity:

If light is cheaper, we consume more so that we will be more productive (we're not just treading water)

Possible Future Research

- **New tools and applications of tools**
 - Measures for consumption of light, in anticipation of “smart lighting” technology
 - “Census from the heavens” population measurements: satellite measurements of artificial light from the earth, corrected for *gdp* and *CoL*
 - Apply methodology to other energy services: transportation, heating/cooling, computation/communication
- **Understand**
 - Validity of combining historical (longitudinal) and contemporary (cross-sectional) data sets
 - Transition between short (months) and long (decades) term rebound
 - How to fold results into growth economics framework (growth of human productivity vs growth of energy consumption)

Back-up slides

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 φ and χ

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

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

Profit-maximizing gdp and \dot{e}

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

$$\begin{aligned}
 \dot{e} &= \chi / \eta_\chi + \varphi / \eta_\varphi \\
 &= \frac{\alpha \cdot gdp}{CoX \cdot \eta_\chi} + \frac{\beta \cdot gdp}{CoL \cdot \eta_\varphi} \quad \text{These cancel!} \\
 &\quad \uparrow \\
 &\quad CoE_\varphi / \eta_\varphi
 \end{aligned}$$

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



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>

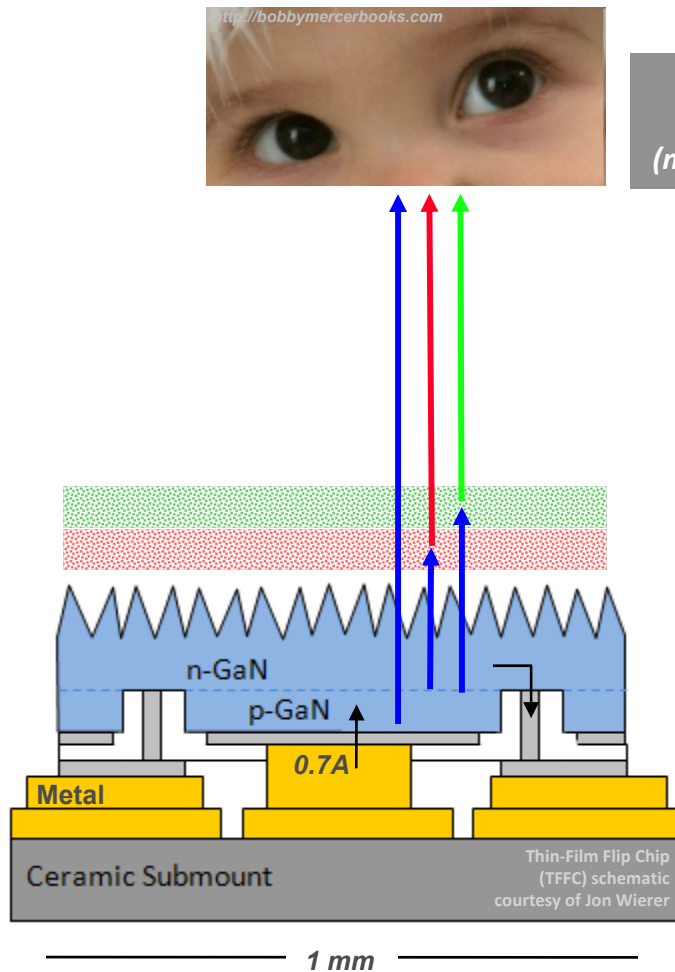


<http://tan-moneyonline.com/wp-content/uploads/2008/03/earthatnight-asia1.jpg>

COLORED

WHITE

State-of-Art Commercial Solid-State Lighting Lamp



78%
Spectral efficiency
(match to human eye)

54%
Phosphor
(and package)
efficiency

38%
Blue LED
efficiency

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/cm²

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)

Roger Fouquet* and Peter J.G. Leonard**

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 focusing 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 experience, 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.

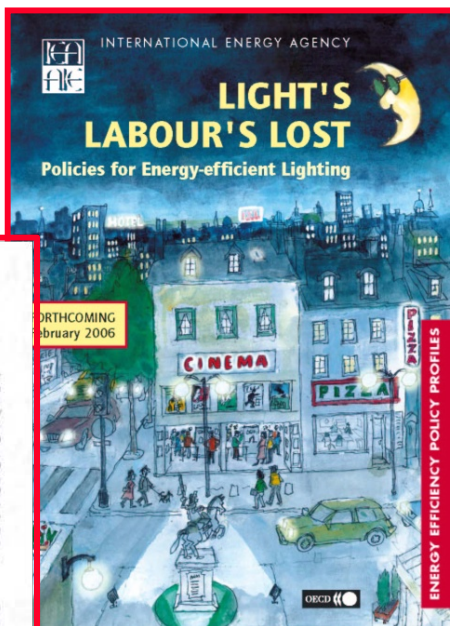
1. INTRODUCTION

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

The Energy Journal, Vol. 27, No. 1, Copyright ©2006 by the IAEE. All rights reserved.

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Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications

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April 1995

ENERGY-EFFICIENT LIGHTING IN CHINA: PROBLEMS AND PROSPECTS*

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

POLICY FORUM

ENVIRONMENT

The Specter of Fuel-Based Lighting

Evan Mills

Thomas Edison's seemingly forward-looking statement that "we will trace electricity so deep that only the rich will burn candles" (1) was true in the industrialized world, but it did not anticipate the plight of 1.6 billion people (2)—more than the world's population in Edison's time—who must still burn candles for their basic lighting needs. In the developing world, the total production of electricity (and hence lighting) is only 10% of that in the United States, and the average person in the developing world has only 10% of the electricity available in the United States. In the United States, the average person has access to 100 kilowatt-hours (kWh) of electricity per year, while the average person in the developing world has only 10 kWh per year. This means that the average person in the developing world has only 10% of the electricity available in the United States. In the United States, the average person has access to 100 kilowatt-hours (kWh) of electricity per year, while the average person in the developing world has only 10 kWh per year. This means that the average person in the developing world has only 10% of the electricity available in the United States.



Worker working by candlelight in a "modernized" village in the developing world.

with total power generation. Power that would reach 40% in some countries (3).

Off-Grid Solar State Lighting: An Opportunity for Technological Leapfrogging

As early as the 1970s, developing countries can leapfrog technologies and in doing so bypass levels of efficiency typical of industrial and developed nations (4). The first generation of lighting energy efficiency in the world came with the lighting energy saving CFL (Compact Fluorescent Lamp) technology. CFLs are 20-30% more efficient than incandescent bulbs, and their energy consumption is only 10-15% of that of incandescent bulbs. CFLs are 20-30% more efficient than incandescent bulbs, and their energy consumption is only 10-15% of that of incandescent bulbs.

LED technologies provide more and better illumination with even greater energy efficiency (Fig. 5a). Commercially available LED lighting is 20-30% more efficient than CFLs, and its energy consumption is only 10-15% of that of incandescent bulbs. LED technologies provide more and better illumination with even greater energy efficiency (Fig. 5a). Commercially available LED lighting is 20-30% more efficient than CFLs, and its energy consumption is only 10-15% of that of incandescent bulbs.

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CEDM Rebound Effect Workshop 2011 Jun 26-27

11/6



Possible Worlds in 2030

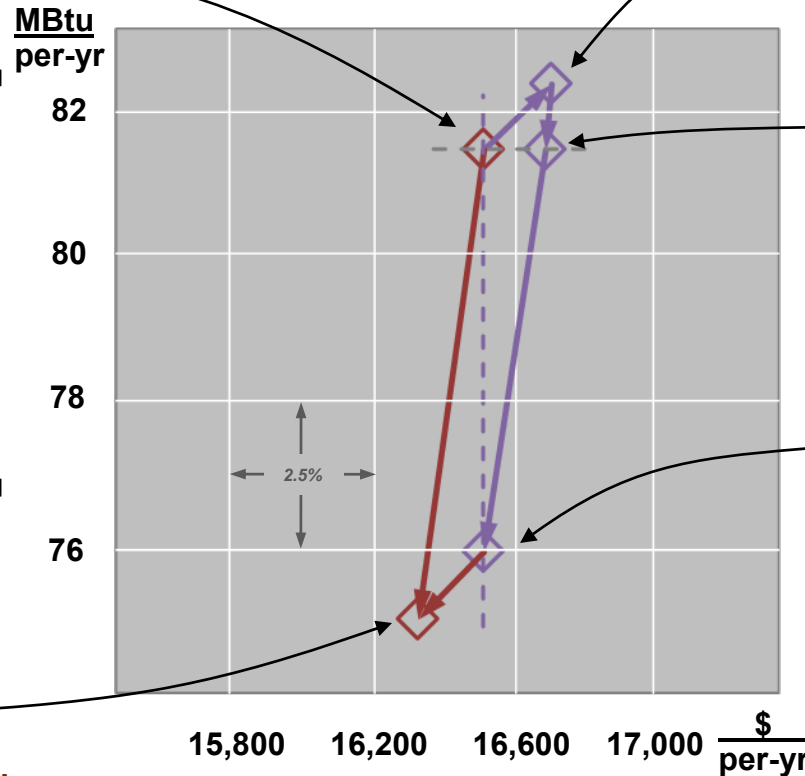
FLU-L

η_ϕ 87 lm/W_e
 CoE_φ 119 \$/MW_eh
 Baseline EIA projection
 for world in 2030
 (fluorescent lighting
 dominant)

FLU-H

η_ϕ 87 lm/W_e
 CoE_φ 369\$/MW_eh
 (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

η_ϕ 268 lm/W_e
 CoE_φ 119 \$/MW_eh
 (SSL dominant)

SSL-M

η_ϕ 268 lm/W_e
 CoE_φ 133 \$/MW_eh
 (SSL dominant but
 moderate increase in
 energy cost for lighting)

SSL-H

η_ϕ 268 lm/W_e
 CoE_φ 369 \$/MW_eh
 (SSL dominant but high
 increase in energy cost
 for lighting)

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