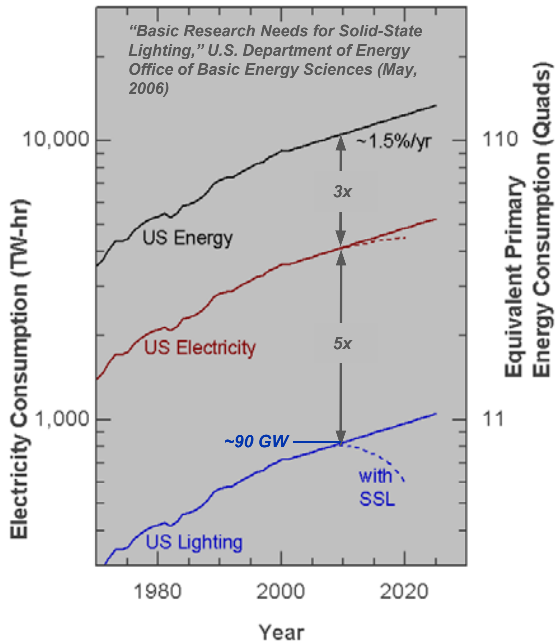
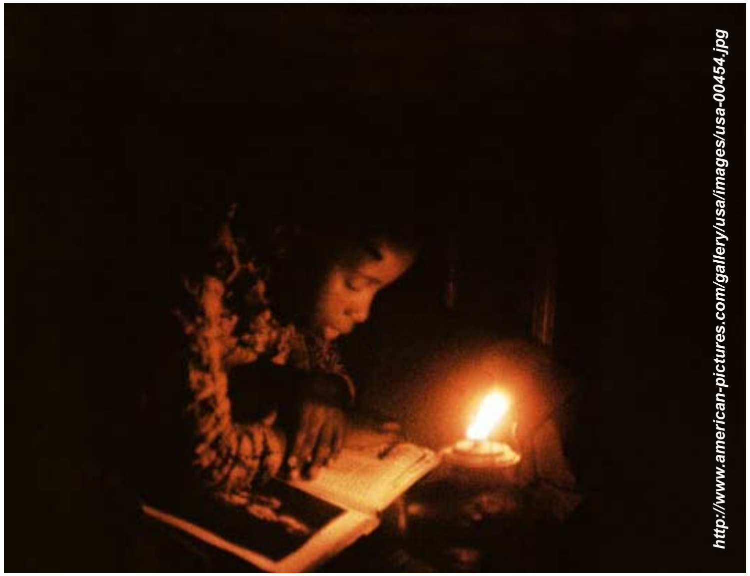
Lighting, Energy Consumption, Human Productivity

Jeff Tsao · Sandia National Laboratories · Albuquerque NM





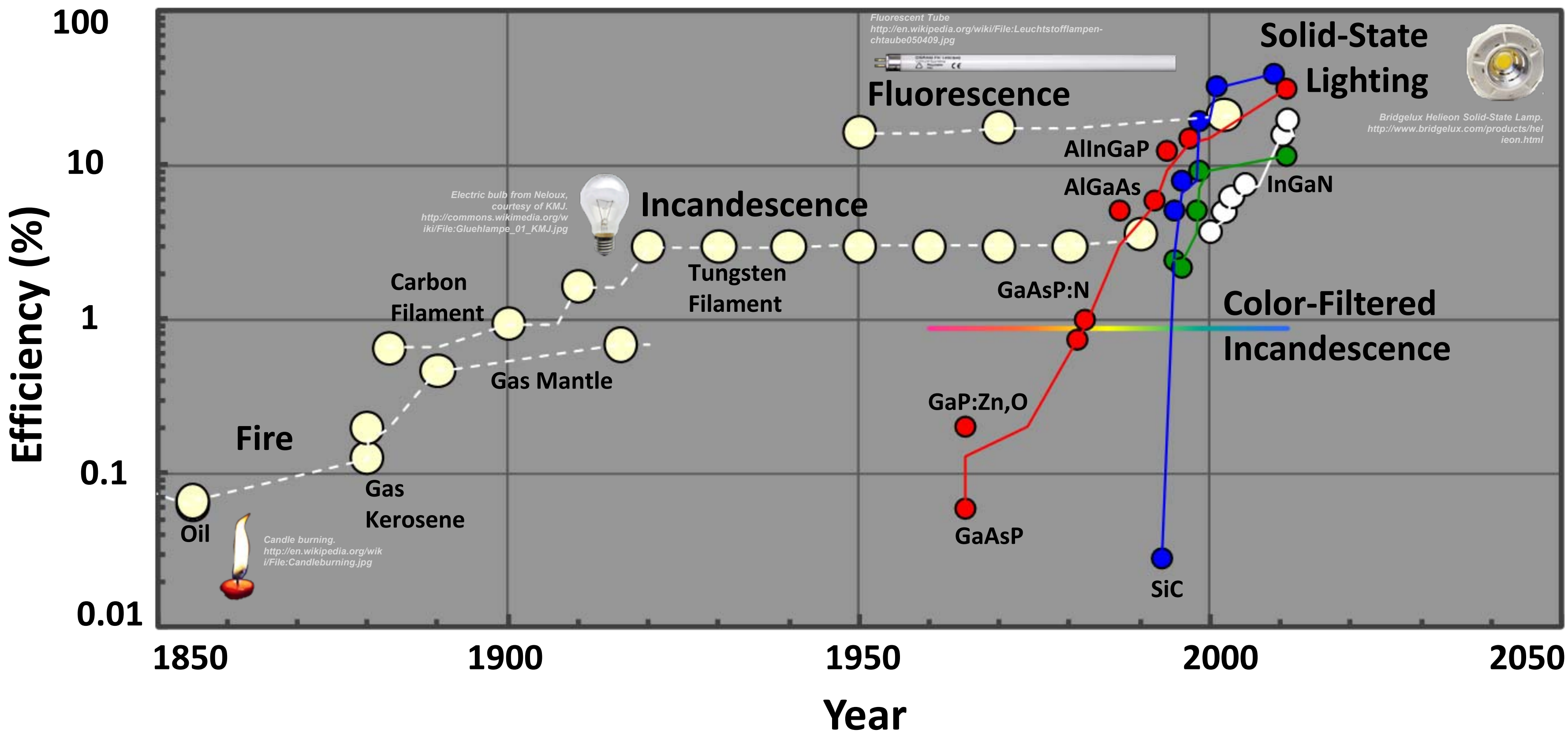
Acknowledgements

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

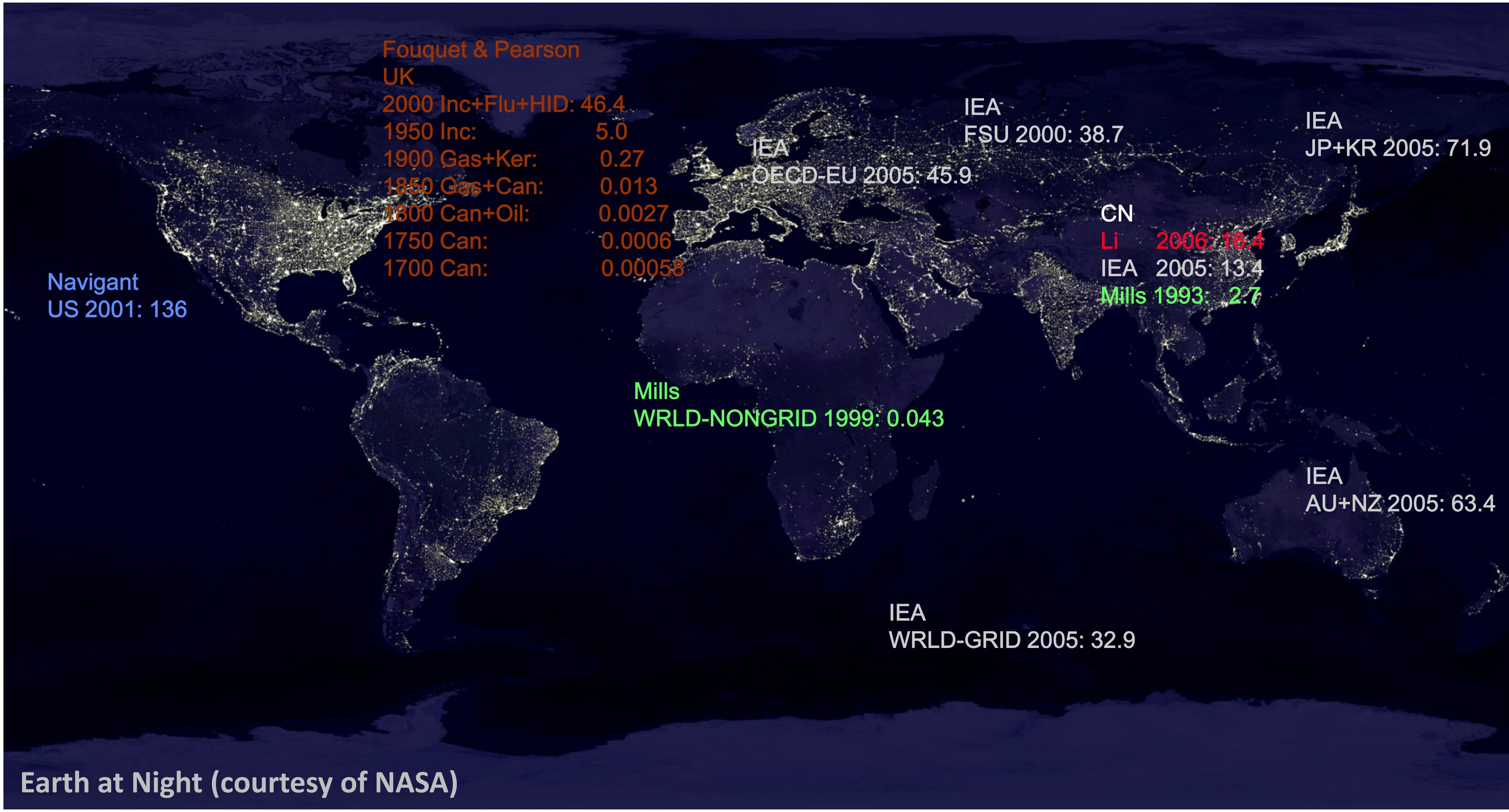
Non-Sandia: Harry Saunders (Decision Processes Inc), Paul Waide (IEA), George Craford (Philips Lumileds)

Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

200 Years of Lighting Technology

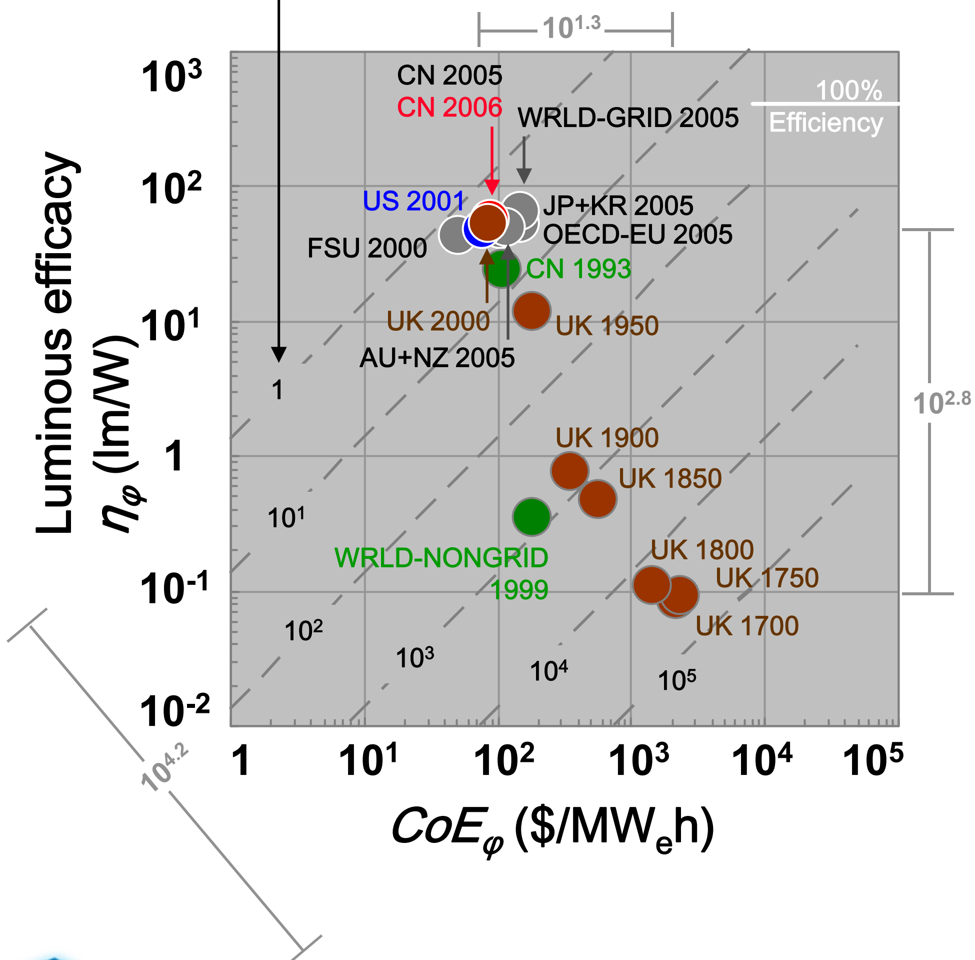


per capita Consumption of Light: φ, in Mlmh/(person-yr)



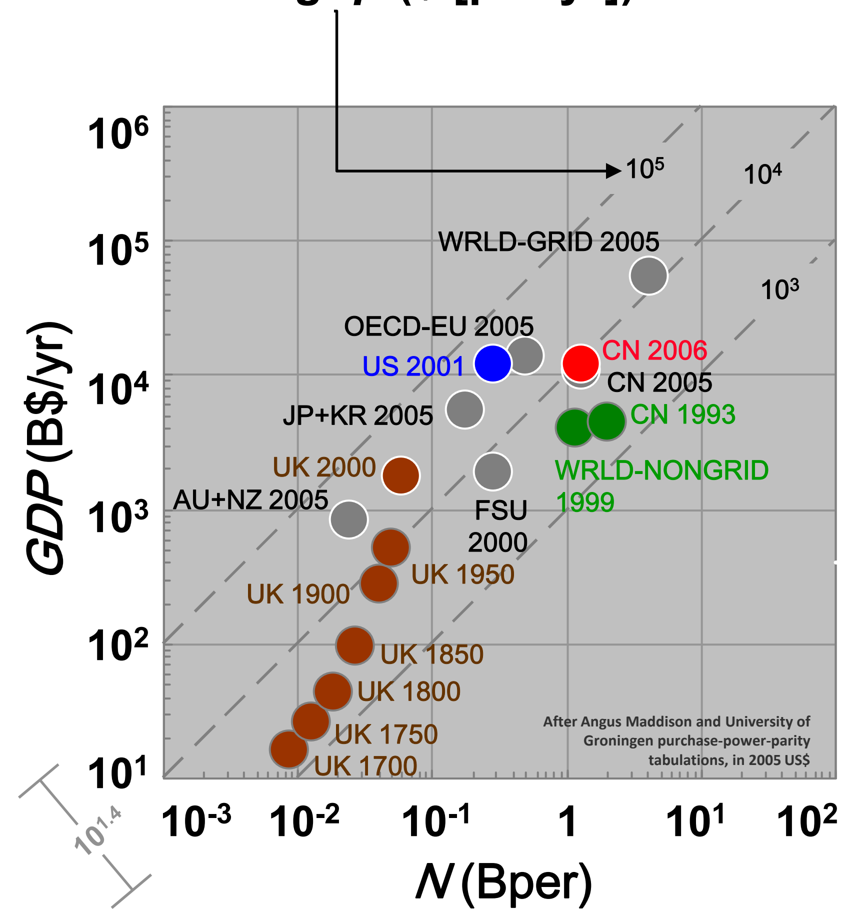
Cost of Light:

CoL ($/Mlmh) ≈ CoE_φ/η_φ

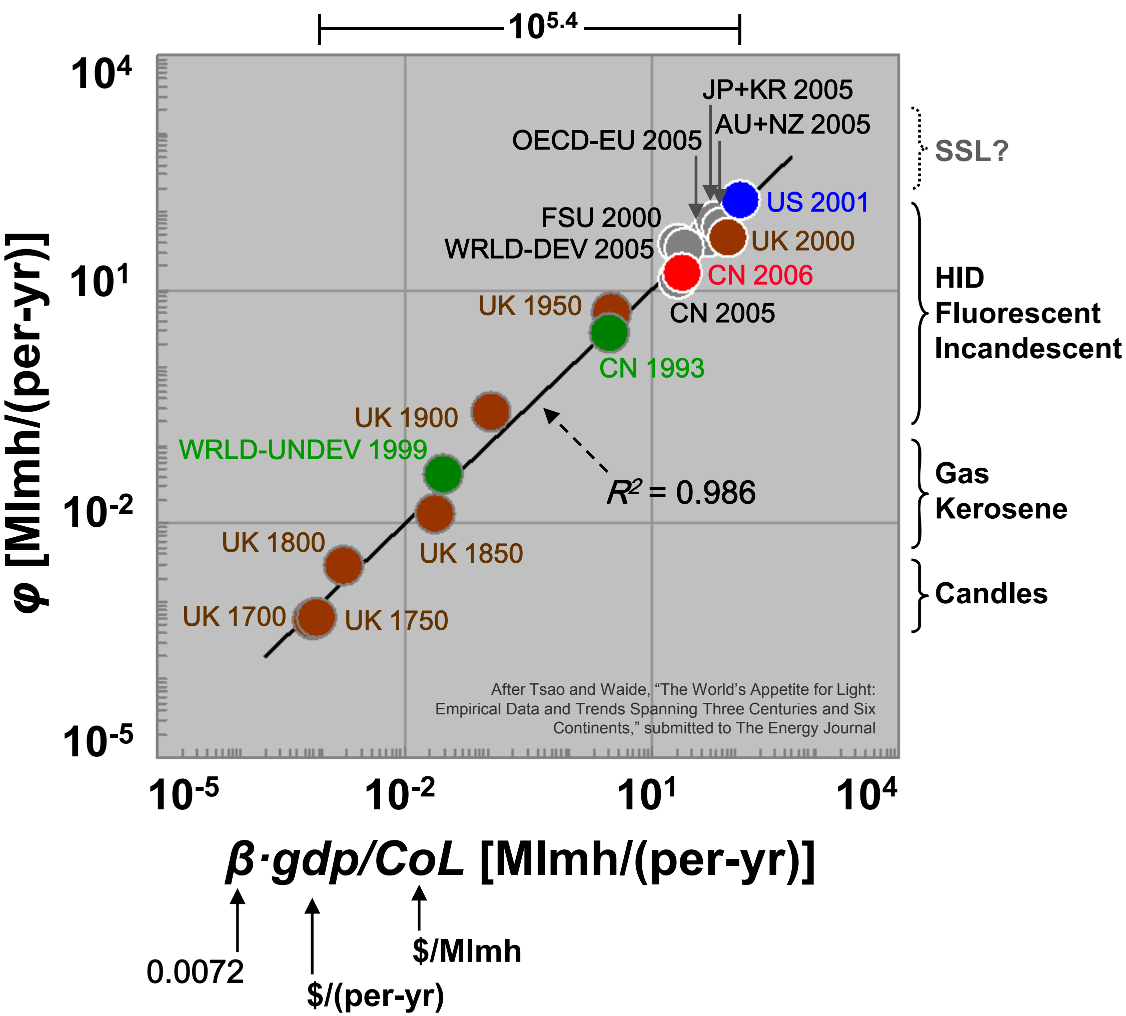


per capita gross domestic product:

gdp ($/[per-yr]) = *GDP/N*



$\varphi = \beta\cdot(gdp/CoL)$



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

$$\underbrace{\pi(\chi,\varphi)}_{\text{profit}} = \underbrace{[A\cdot\chi^{\alpha}\varphi^{\beta}]}_{\text{production (gdp)}} - \underbrace{[\chi\cdot CoX + \varphi\cdot CoL]}_{\text{cost}}$$

per capita consumption of light (φ)

per capita consumption of everything else (χ)

Cobb-Douglas with constant returns to scale ($\alpha + \beta + 0.7 = 1$)

Labor component (0.7)

Cost of Light (φ)

Cost of everything else (χ)

Profit Maximization

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

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

Profit-maximizing φ and χ

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

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

0.2928 (α)

0.0072 (β)

Profit-maximizing *gdp* and *ė*

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

0.01 ($\frac{\beta}{1-\alpha-\beta}$)

$$\dot{e} = \chi/\eta_{\chi} + \varphi/\eta_{\varphi}$$

$$= \frac{\alpha\cdot gdp}{CoX\cdot\eta_{\chi}} + \frac{\beta\cdot gdp}{CoL\cdot\eta_{\varphi}}$$

$CoE_{\varphi}/\eta_{\varphi}$ (CoL)

These cancel!

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

COLORED

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

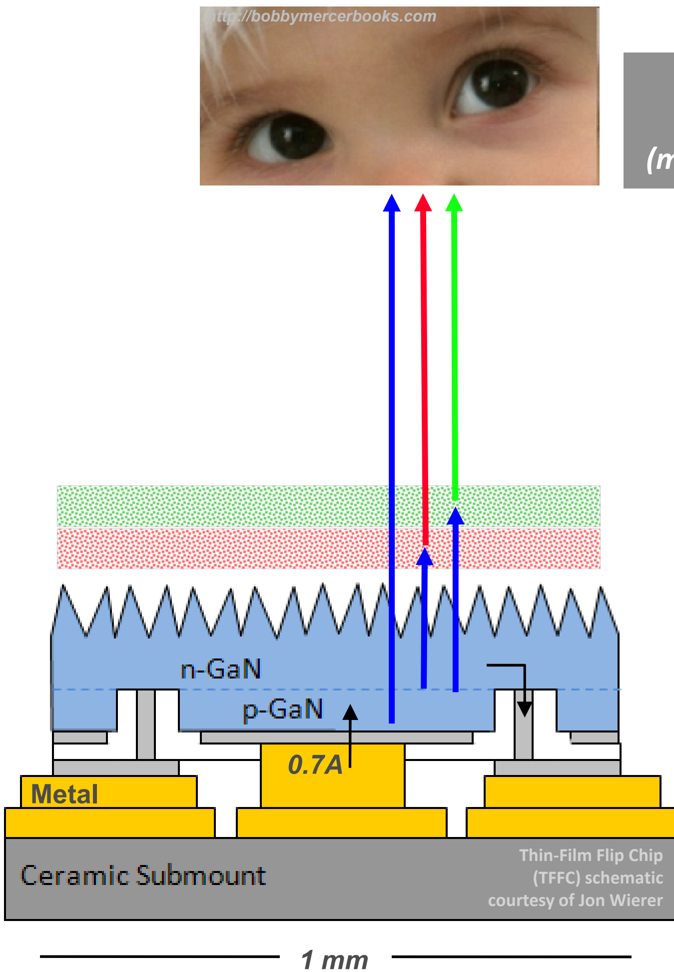
Surefire U2 flashlight. http://en.wikipedia.org/wiki/File:SurefireU2JPG.jpg

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

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

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

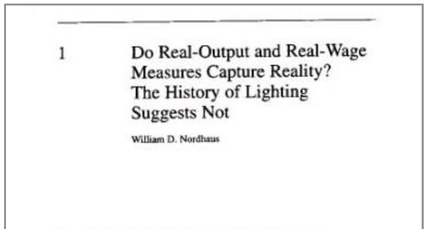
Thin-Film Flip-Chip Architecture

16%
Overall efficiency
(luminous efficacy η_φ = 66 lm/W)

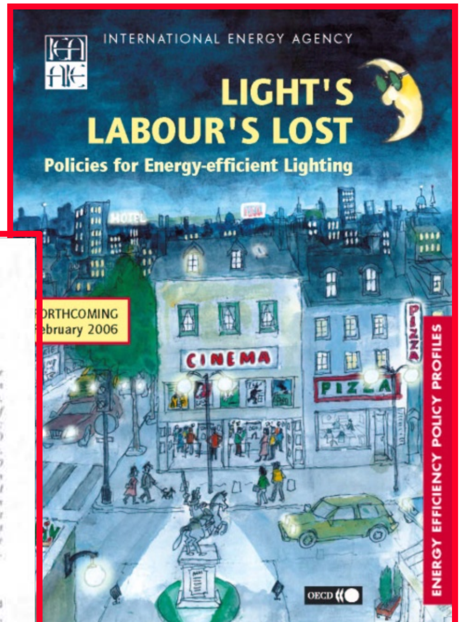
@
Color rendering index (CRI) 85
Color temperature (CCT) 3,100 K
Current density 70 A/cm^2

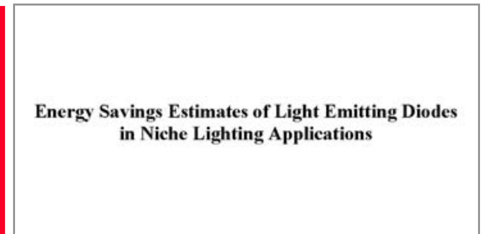
Estimates of Light Consumption, spanning:

- *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




Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications


GUAN FU MIN
EVAN MILLS
QIN ZHANG

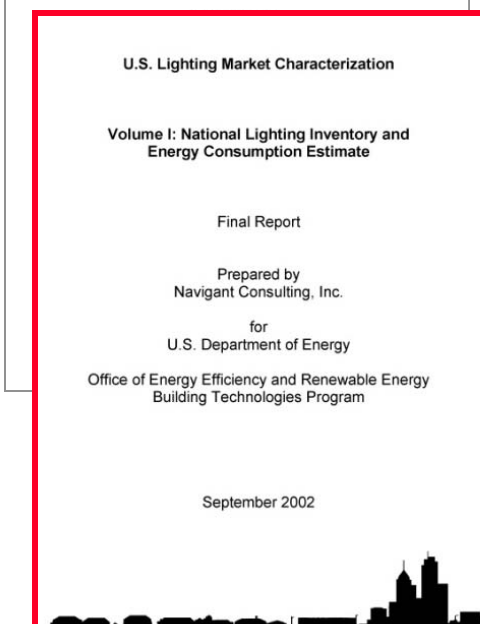
April 1995

ENERGY-EFFICIENT LIGHTING IN CHINA: PROBLEMS AND PROSPECTS*


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

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

1. INTRODUCTION


U.S. Lighting Market Characterization

Volume I: National Lighting Inventory and Energy Consumption Estimate

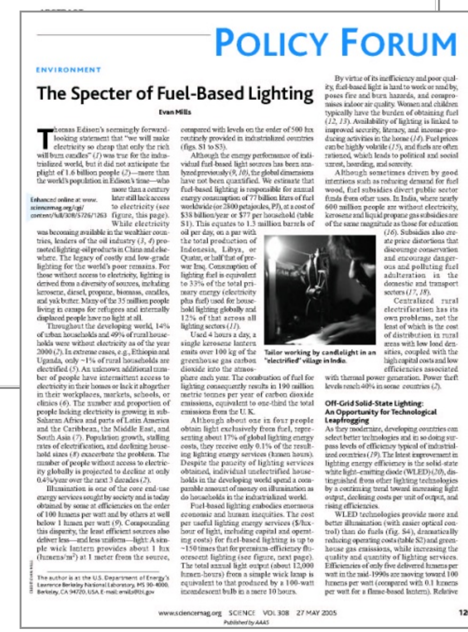
Final Report

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

SSLS EFRC

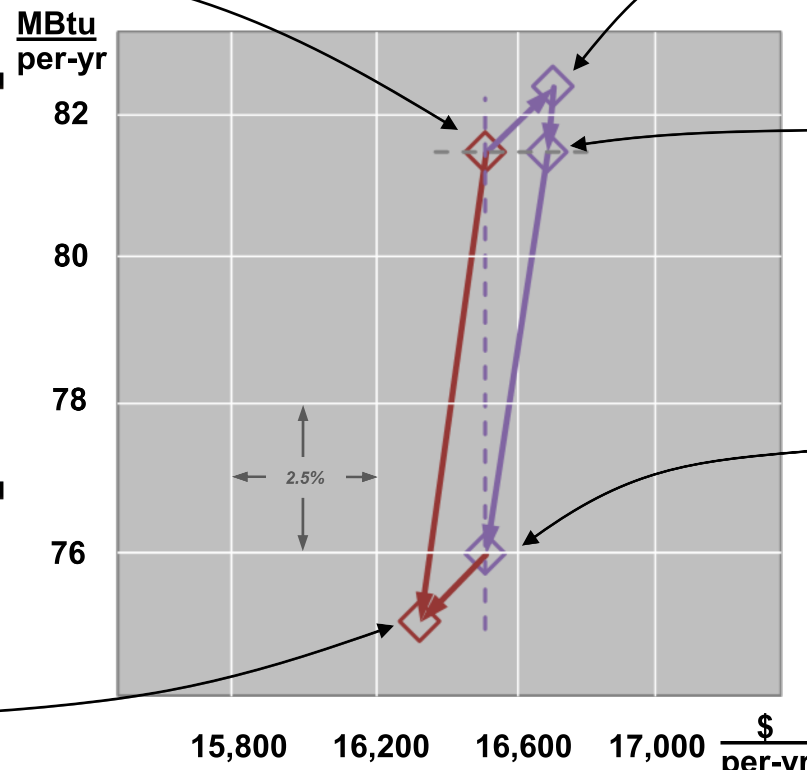
Sandia National Laboratories

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)

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)



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

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

FLU-H
η_φ 87 lm/W_e
CoE_φ 369\$/MW_eh
(Fluorescent lighting dominant with high increase in energy cost for lighting)

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