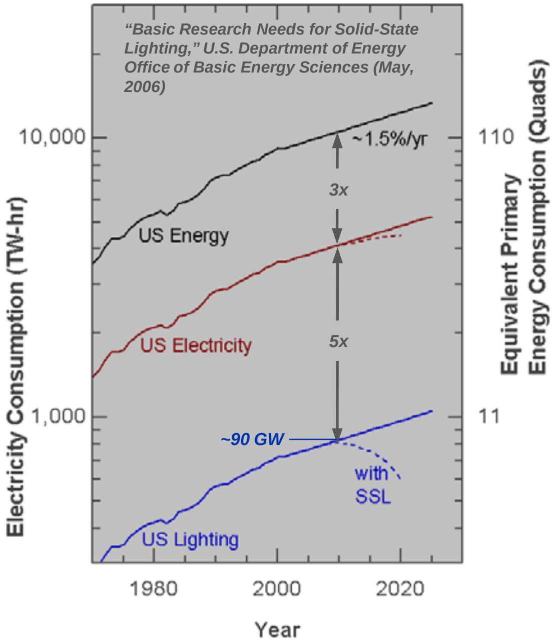
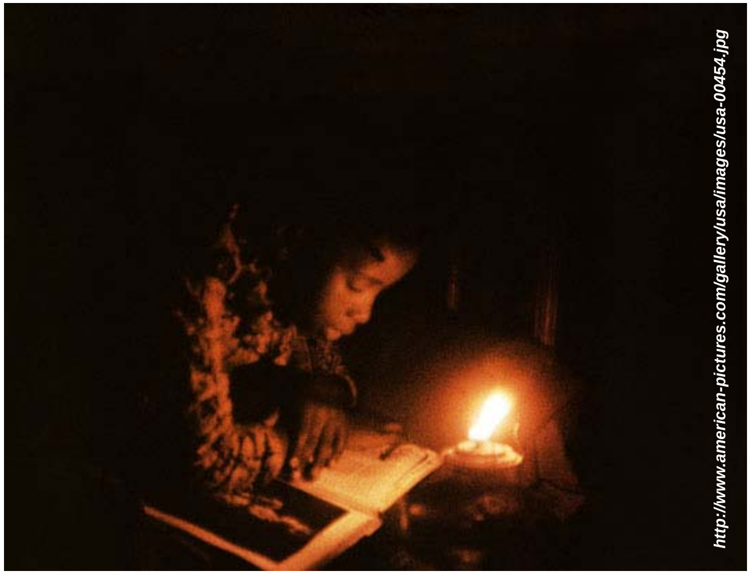
Lighting Technologies, Costs & Energy Demand: Global Developments to 2030

Sandia National Laboratories
Jeff Tsao, Harry Saunders, Randy Creighton, Mike Coltrin, Jerry Simmons
Decision Processes Incorporated





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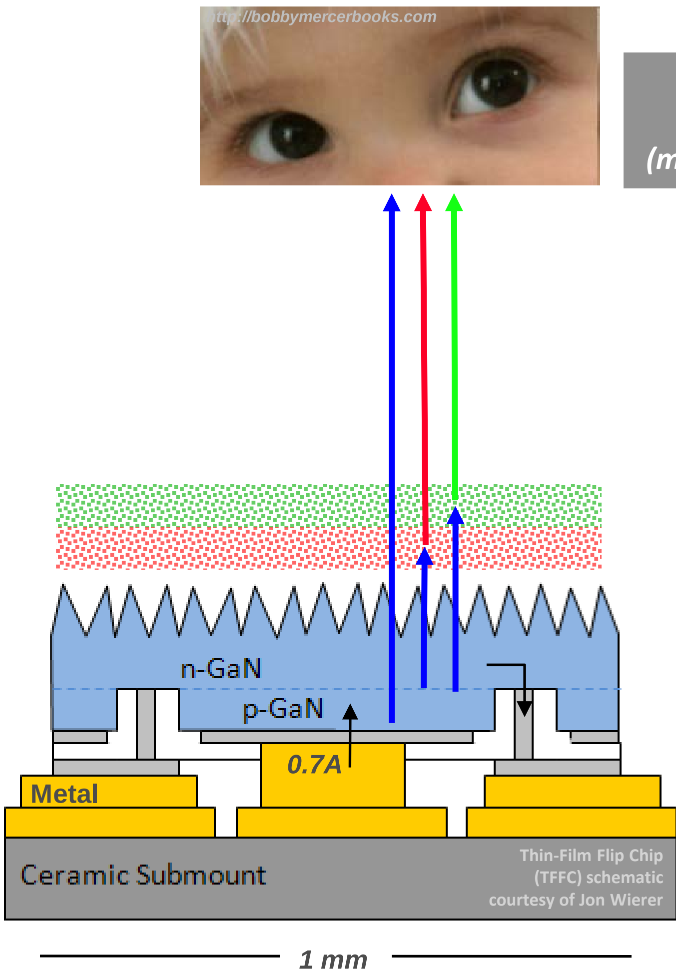
State-of-Art Commercial Solid-State Lighting Lamp



78%
Spectral efficiency
(match to human eye)

54%
Phosphor
(and package)
efficiency

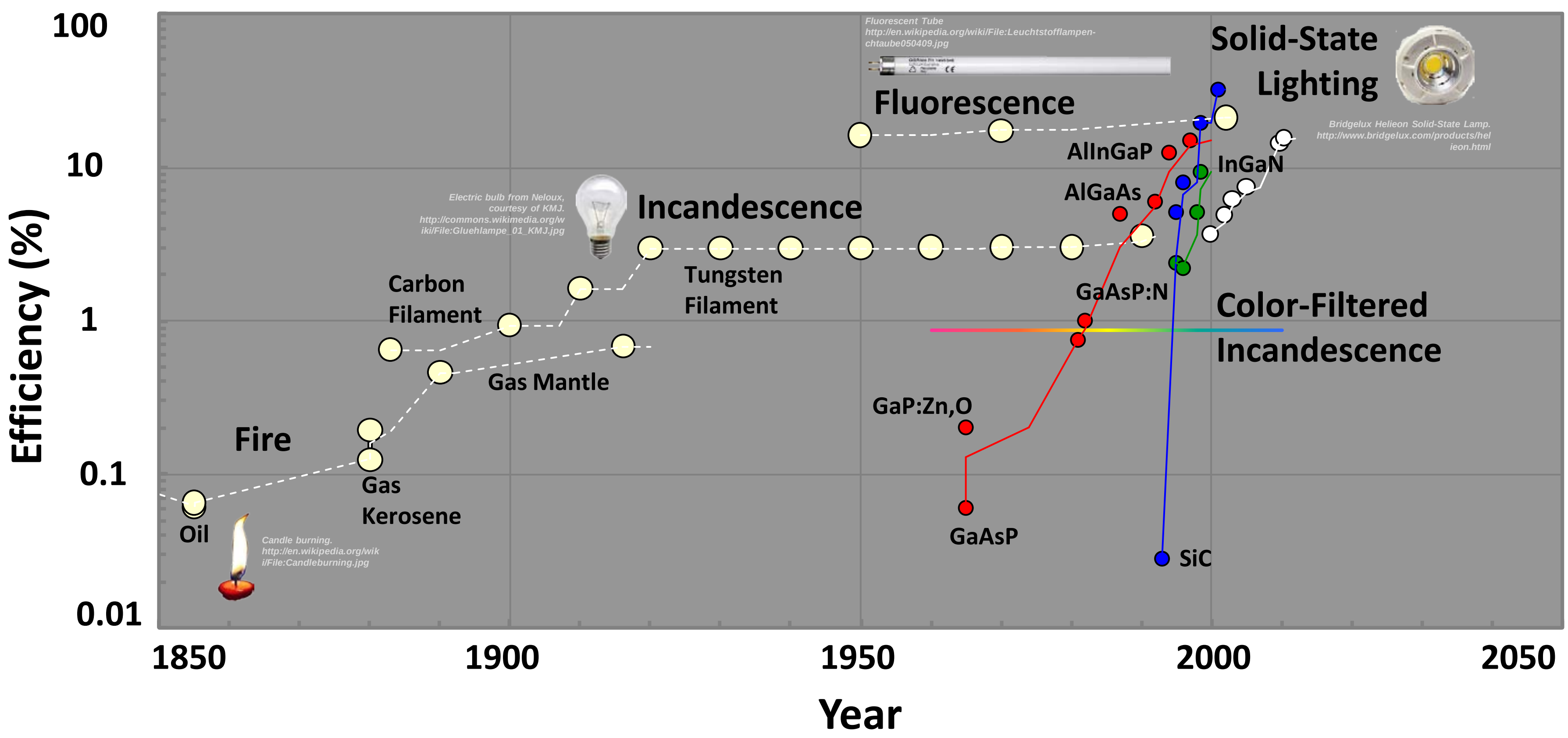
38%
Blue LED
efficiency

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

200 Years of Lighting Technology Efficiency



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

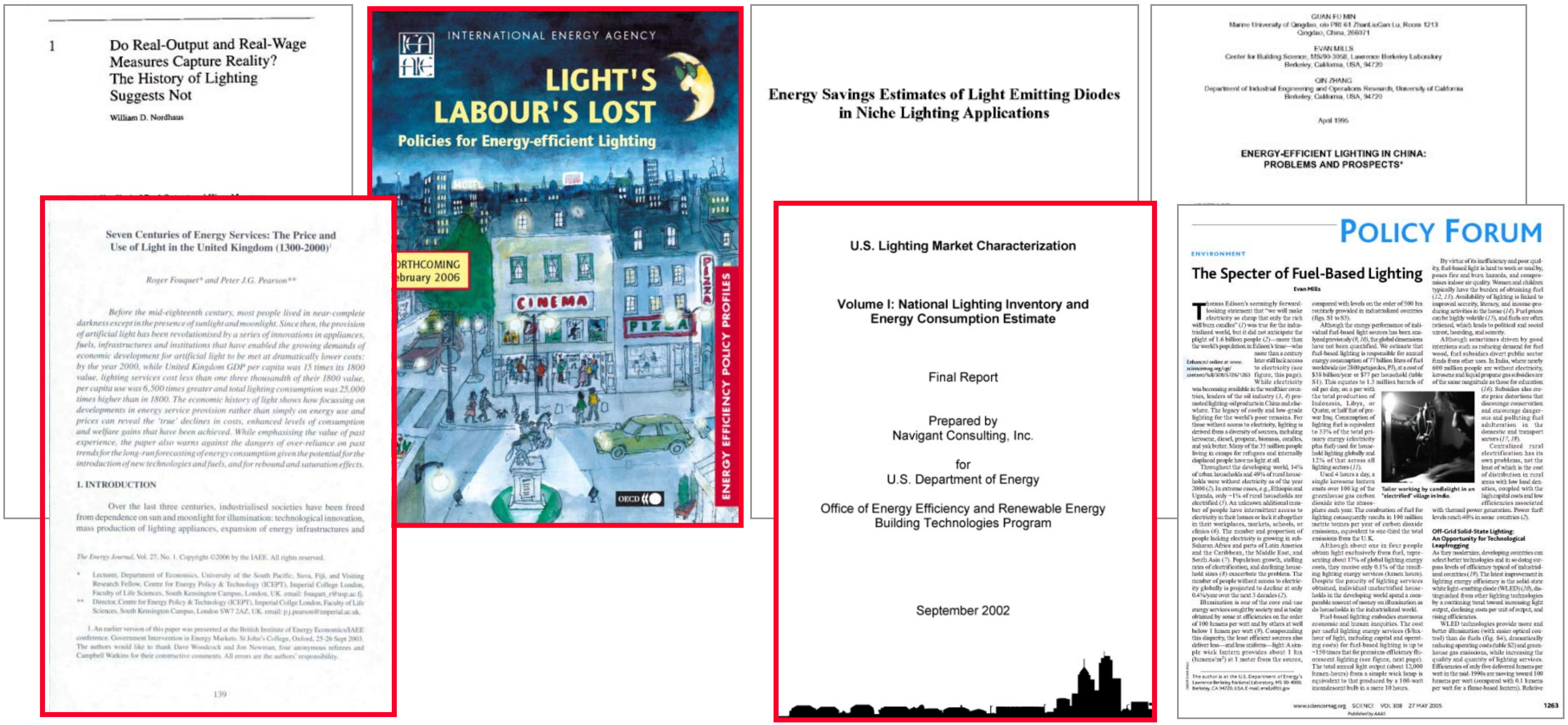
Nokia camera phone with LED flash. http://www.itechnews.net/wp-content/uploads/2009/07/Nokia-3720-Classic-the-most-rugged-mobile-phone.jpg

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

WHITE

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*



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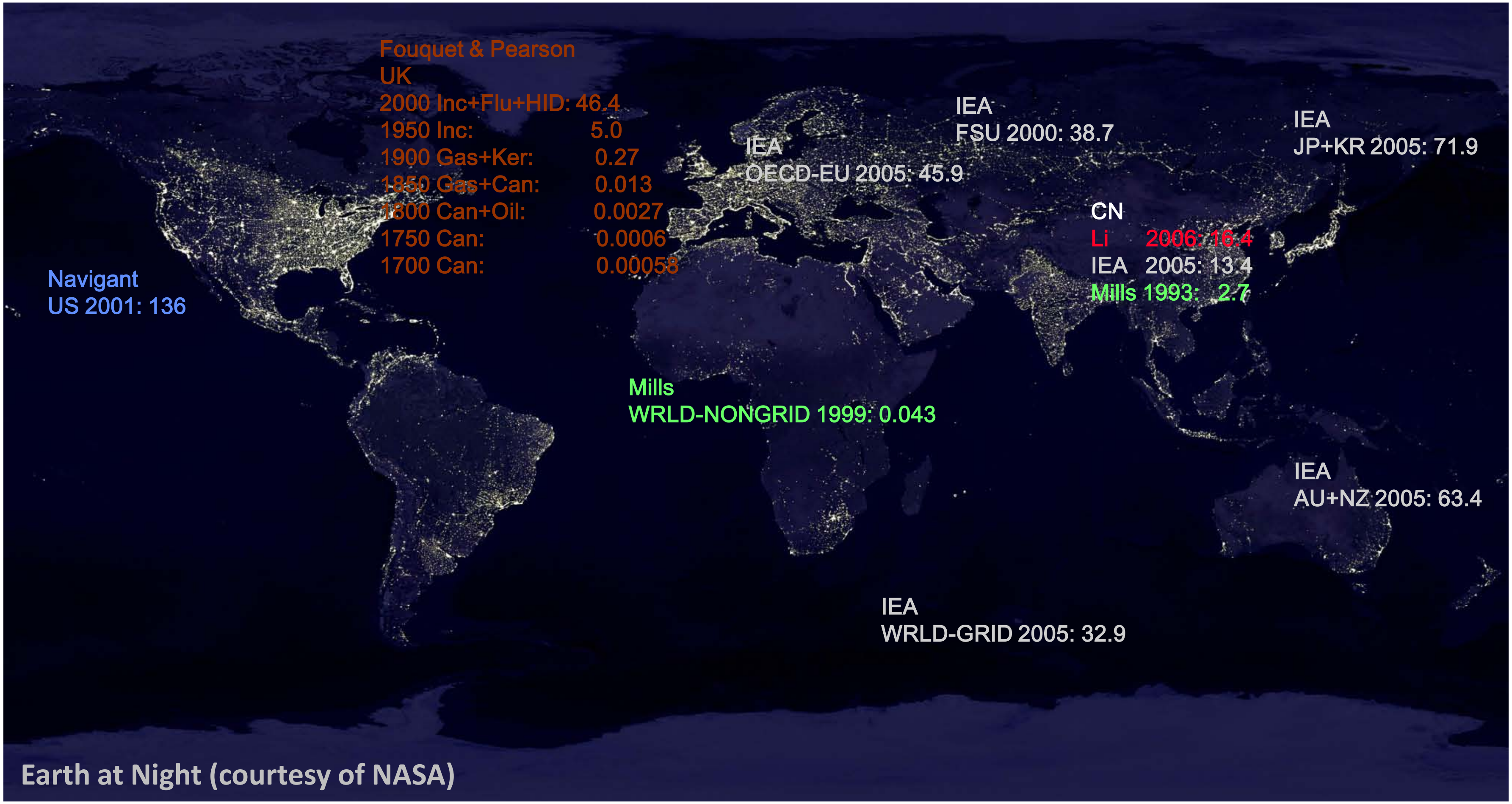
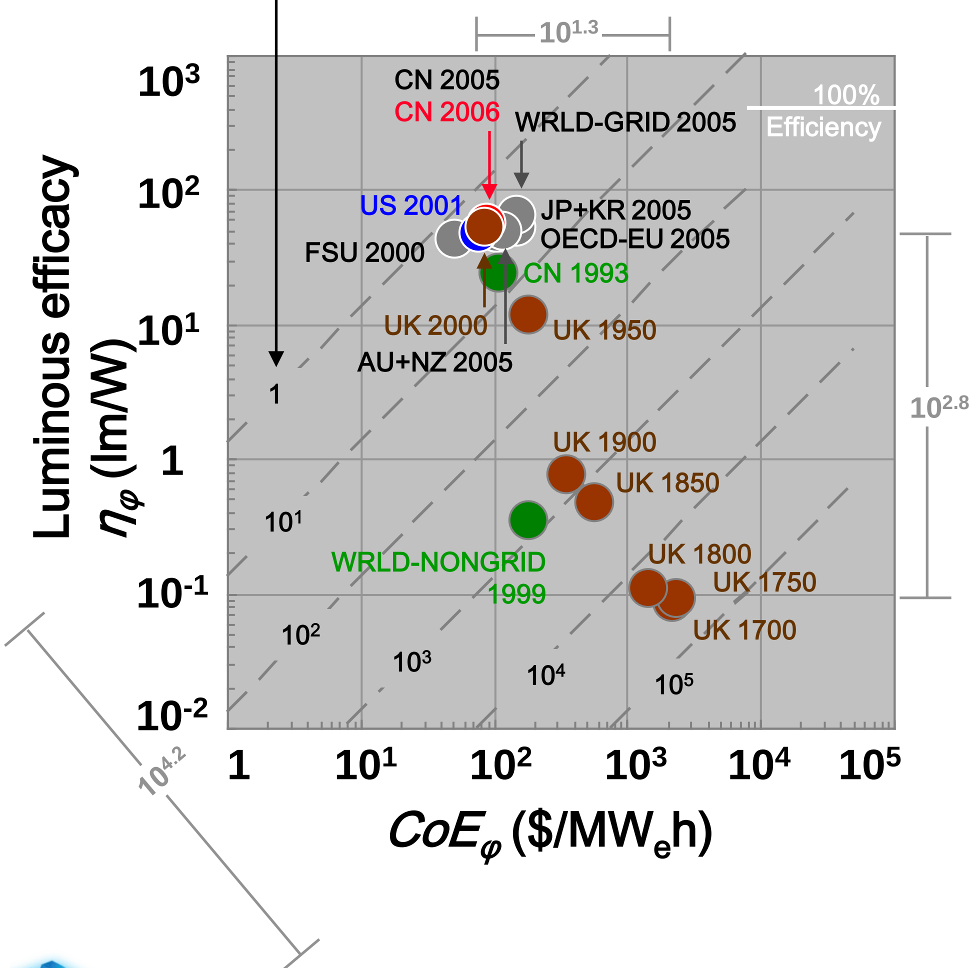
per capita Consumption of Light: φ, in Mlmh/(person-yr)



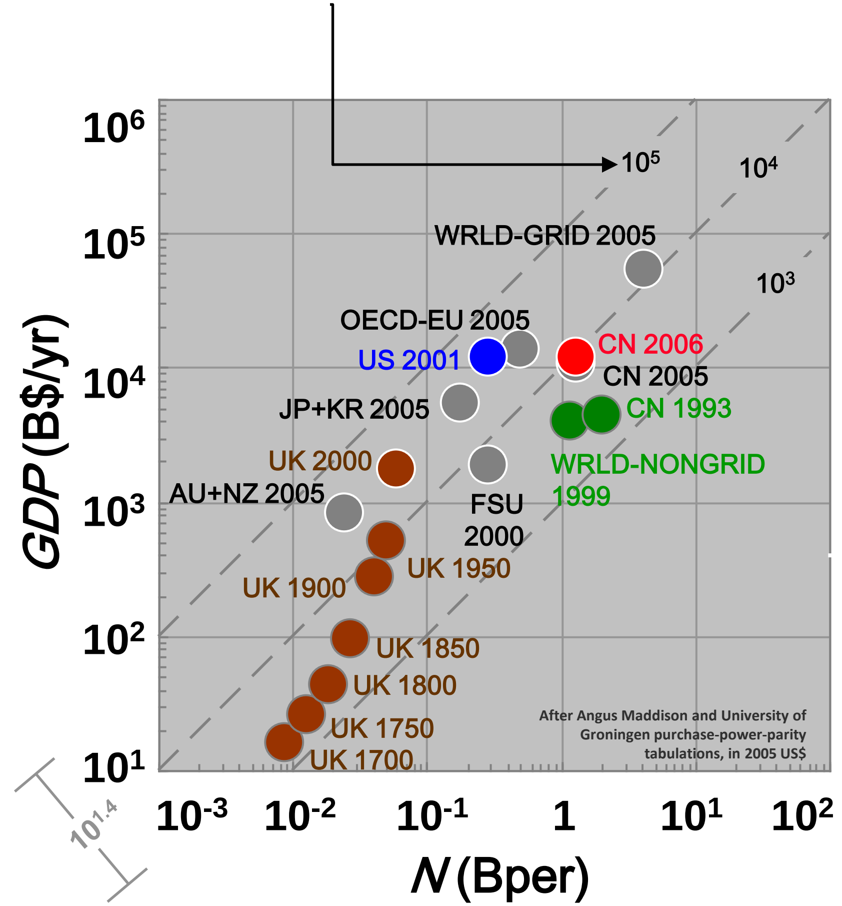
Cost of Light:

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

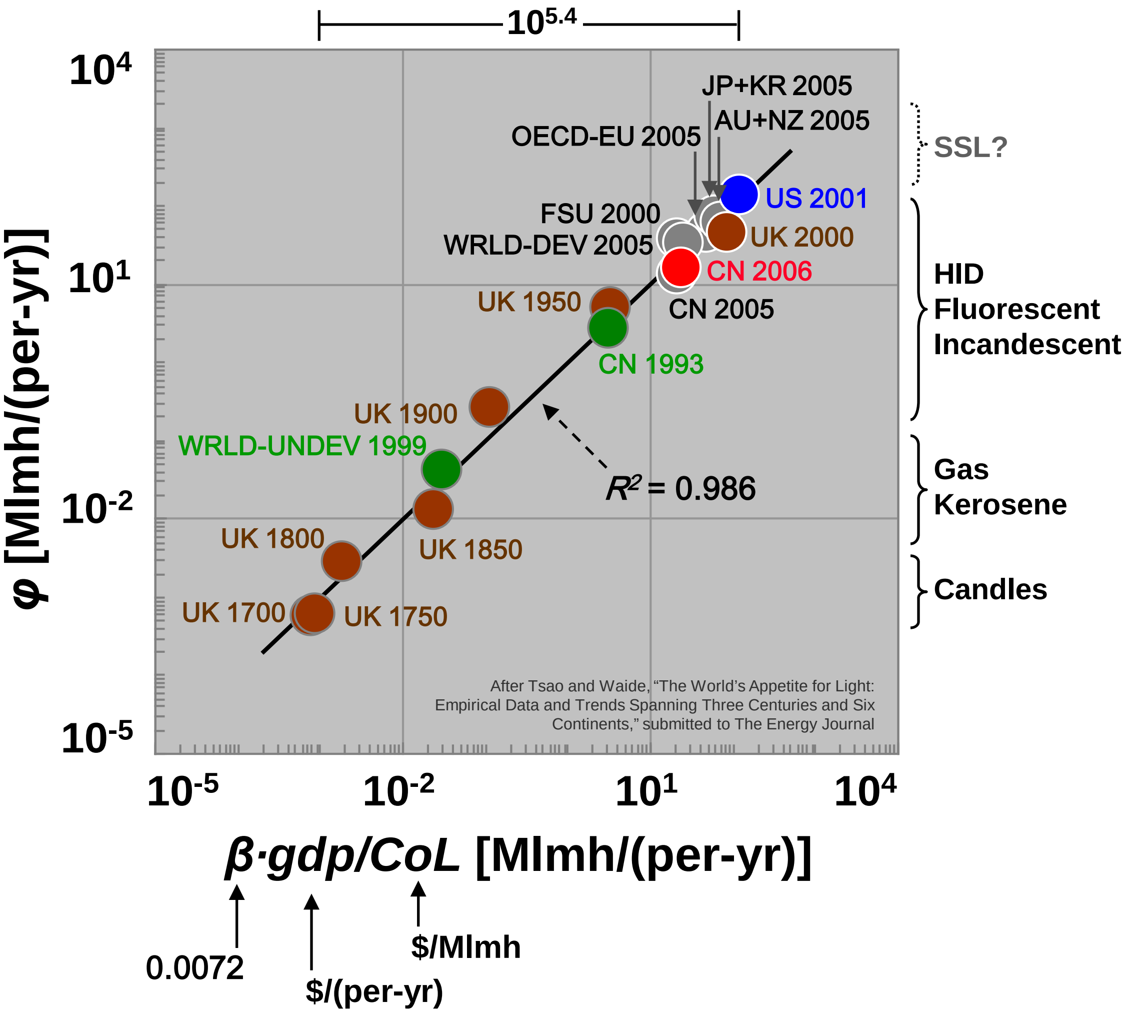


per capita gross domestic product:

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



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



<u>Implication 1</u>:
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

<u>Implication 2</u>:
Price and income elasticity of consumption of light is ~unity

Are we treading water or not?

Profit maximization in a two-factor economy

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

per capita consumption of everything else (χ)

per capita consumption of light (φ)

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

Labor component (0.7)

Cost of everything else (χ) (CoX)

Cost of Light (φ) (CoL)

Profit Maximization

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

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

Profit-maximizing φ and χ

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

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

α: 0.2928

β: 0.0072

Profit-maximizing *gdp* and *ė*

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

$\frac{\beta}{1-\alpha-\beta}$: 0.01

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

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

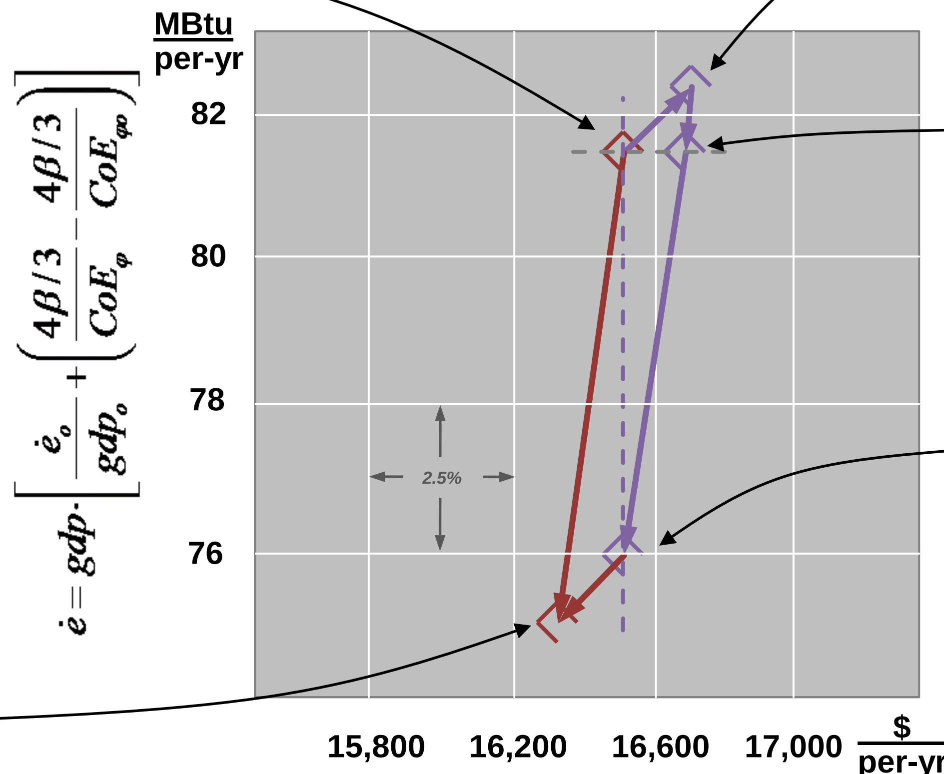
$CoL = CoE_{\varphi}/\eta_{\varphi}$

These cancel!

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)



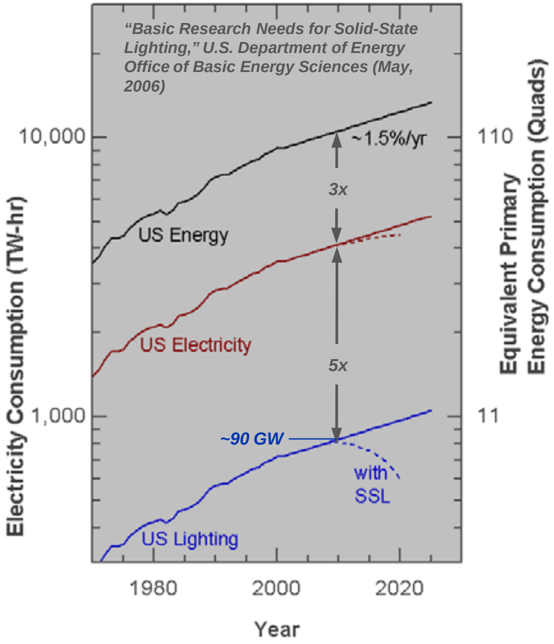
$$gdp = gdp_o \cdot \left(\frac{CoE_{\varphi o}}{CoE_\varphi} \cdot \frac{\eta_\varphi}{\eta_{\varphi o}} \right)^{\frac{\beta}{1-\alpha-\beta}}$$

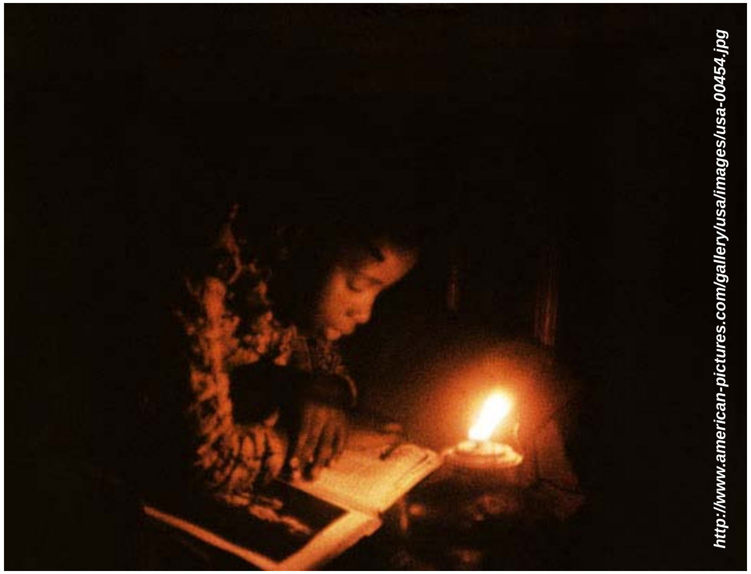
SSL-L
η_φ 268 lm/W_e
CoE_φ 119 \$/MW_eh
(SSL dominant)

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)


Courtesy,
Fred Schubert, RPI


"Basic Research Needs for Solid-State Lighting," U.S. Department of Energy Office of Basic Energy Sciences (May, 2006)
10,000
1,000
~1.5%/yr
3x
5x
US Energy
US Electricity
US Lighting
~90 GW
with SSL
110
11
1980
2000
2020
Year
Electricity Consumption (TW-hr)
Equivalent Primary Energy Consumption (Quads)


http://www.american-pictures.com/gallery/usa/images/usa-00454.jpg