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

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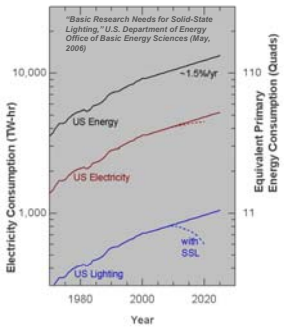

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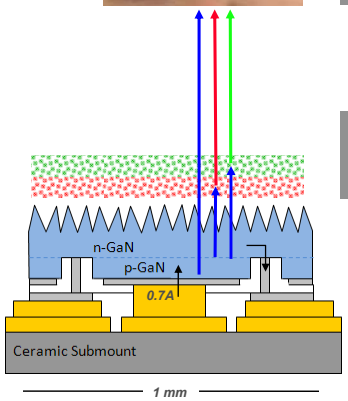
Anatomy of State-of-Art Commercial SSL

ε	= 16%
η_φ	= 66 lm/W
CRI	= 85
CCT	= 3,100K

Spectral	78%

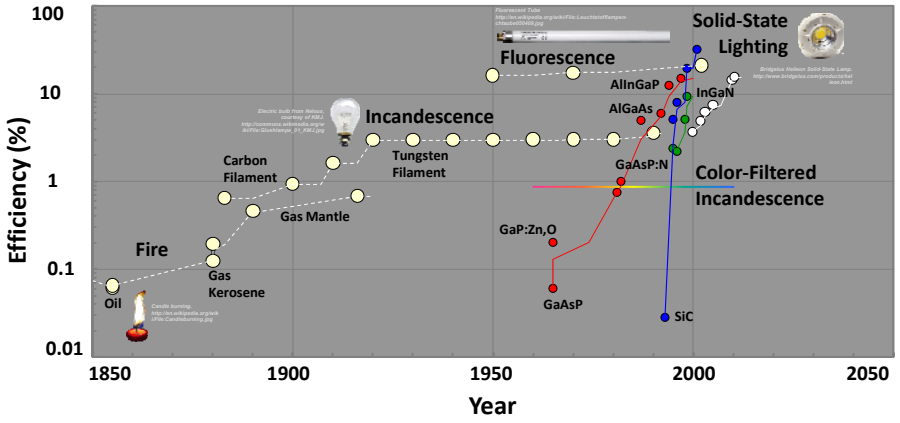
Phosphor/Package	54%
Internal quantum effic	90%
Stokes deficit	76%
Scattering/absorption	80%



Blue LED	38%
Joule	90%
IQE at low power	75%
Droop at high power	70%
Light extraction	80%

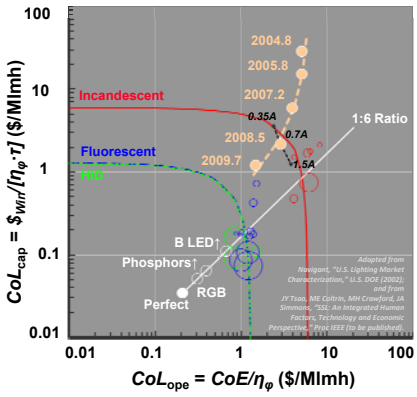
Thin-Film Flip Chip (TFFC) schematic courtesy of Jon Wierer

200 Years of Lighting Technology Efficiency

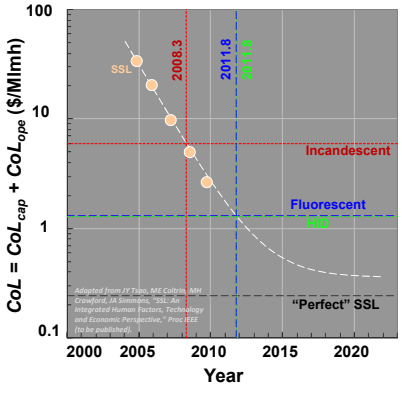


What about Cost of Light?

CoL_{cap} is already ~CoL_{ope}/6, so η_φ is the key



2012 may be the beginning of "the transition"



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

HP calculator. http://www.hpmuseum.org/32.jpg

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

Traffic light. http://mksurf8.blogspot.com/2009/11/relasyon.html

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

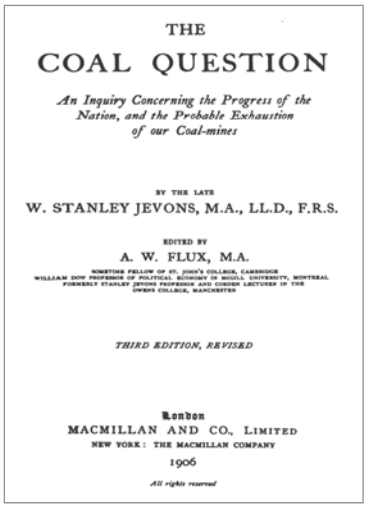
Surefire U2 flashlight. http://en.wikipedia.org/wiki/File:SurefireU2JPG.jpg

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

Sharp QuadPixel RGBY LED-backlit LCD Display. http://www.macworld.com/article/145541/2010/01/sharp_quadpixel.html

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

Rebound and the Undeveloped World



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COAL QUESTION

An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-mines

BY THE LATE

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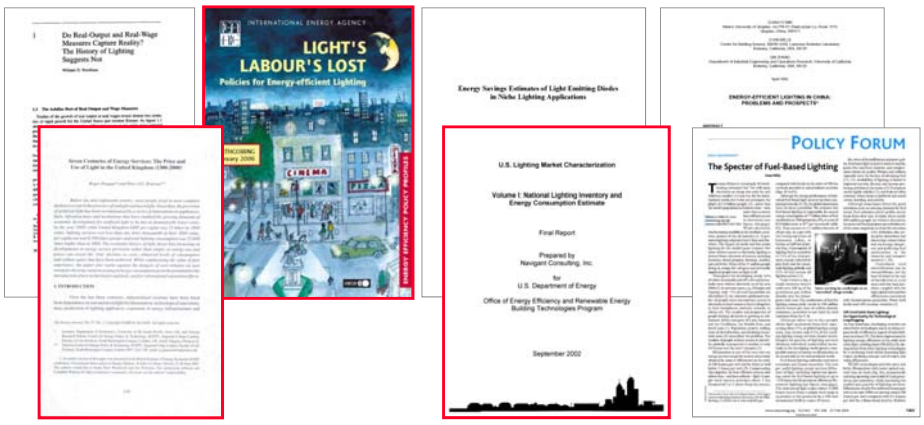
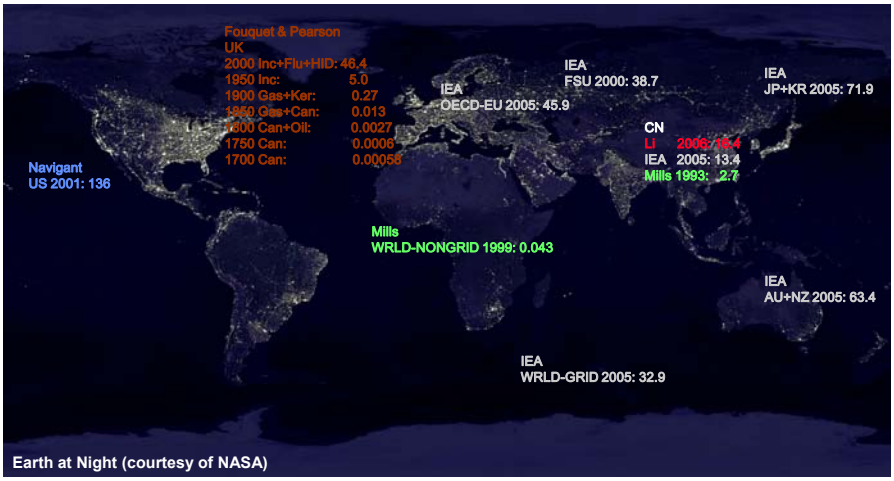
Estimates of Light Consumption, spanning:

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

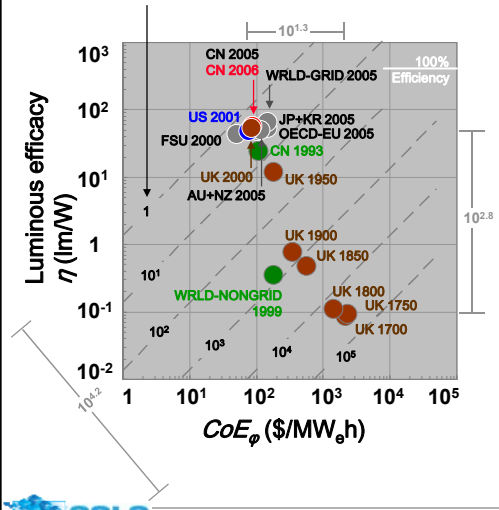


per capita Consumption of Light: φ, in Mlmh/(person-yr)



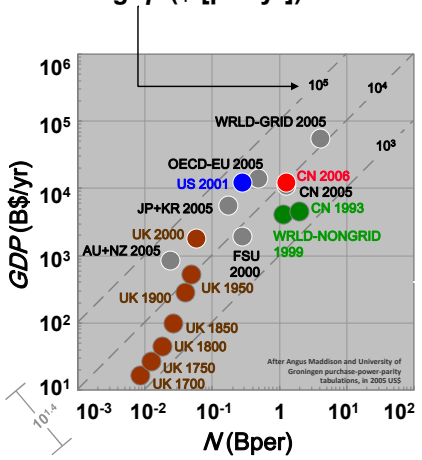
Cost of Light:

CoL ($/Mlmh) ≃ CoE_φ/η

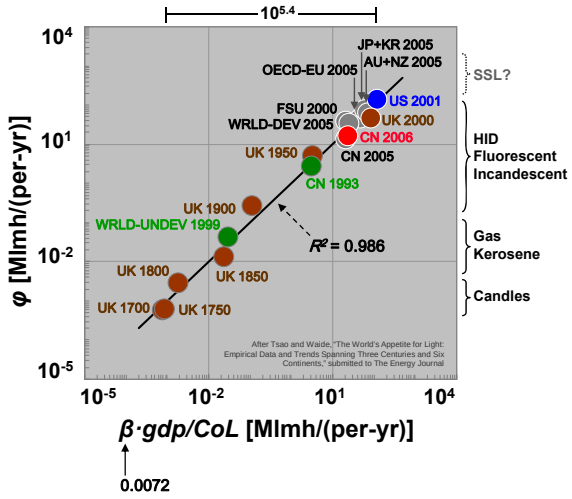


per capita gross domestic product:

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

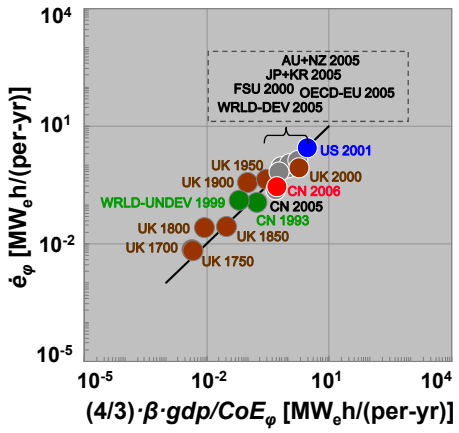


$\varphi = \beta \cdot (gdp/CoL)$



- φ has unit elasticity with respect to gdp and CoL
- over empirical data spanning many orders of magnitude
  - 5.4 in φ
  - 4.3 in CoL
  - 1.4 in gdp
- and a broad swath of history and humanity
  - 3 centuries
  - 6 continents
  - 5 technologies

$\dot{e}_\varphi \approx (4/3)\cdot\beta\cdot(gdp/CoE_\varphi)$



$$\underbrace{\eta_\varphi \cdot \dot{e}_\varphi}_{lm/W \quad MW_e h/(per\text{-}yr)} \rightarrow \underbrace{\varphi}_{\frac{Mlmh}{per\text{-}yr}} = \beta \cdot \frac{\overbrace{gdp}^{\$/(per\text{-}yr)}}{\underbrace{CoL}_{\$/Mlmh}} \leftarrow (4/3)\cdot\frac{\overbrace{CoE_\varphi}^{\$/MW_e h}}{\underbrace{\eta_\varphi}_{lm/W}}$$

- $\dot{e}_\varphi$ has been
  - proportional to *gdp*
  - inversely proportional to CoE_φ
  - independent of η_φ

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 ($1 = \alpha + \beta + 0.71$)

Labor component

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

$$\chi = \underbrace{\alpha}_{0.2928}\frac{gdp}{CoX}$$

$$\varphi = \underbrace{\beta}_{0.0072}\frac{gdp}{CoL}$$

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

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

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

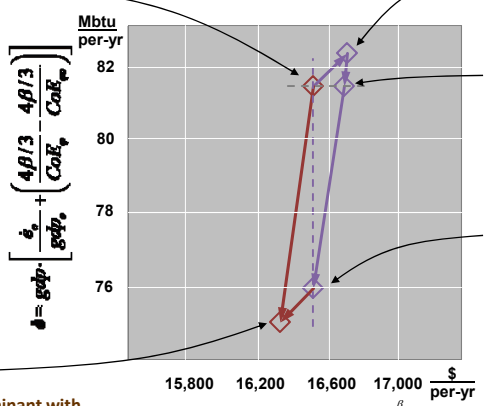
$$= \frac{\alpha\cdot gdp}{CoX\cdot\eta_\chi} + \frac{\beta\cdot gdp}{CoL\cdot\eta_\varphi}$$

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)



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)

$$\dot{d} = gdp_o \left[\frac{\dot{e}_e}{gdp_e} + \left(\frac{4\beta/3}{CoE_\varphi} - \frac{4\beta/3}{CoE_{\varphi\infty}} \right) \right]$$

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

Main Points

- **Past 300 years: β = 0.0072**
  - Consumption of artificial light has increased with *gdp*/*CoL*
  - Consumption of energy for artificial light has increased with *gdp*/CoE_φ
  - *gdp* has increased as consumption of artificial light and human productivity have increased
- **Coming 20 years scenario 1: β = 0.0072 continues**
  - Likely in undeveloped world as usage patterns from developed world are borrowed
  - Possible in developed world as new uses are developed (e.g., outdoor evening illumination, integration of illumination with displays)
  - Massive potential for continued increases in consumption of light and human productivity
  - SSL won't by itself contribute to decreasing C emissions
- **Coming 20 years scenario 2: β = 0.0072 does not continue**
  - Maybe consumption of light will saturate
  - Maybe demand for secondary "human factors" associated with light will saturate
  - Maybe governments will mandate consumption of light to saturate
  - SSL would contribute to decreasing C emissions