The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents

Jeffrey Y. Tsao* and Paul Waide**

* Principal Member of Technical Staff, Physical, Chemical and Nano Sciences Center, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0601, USA. E-mail: *jytsao@sandia.gov*

** Senior Policy Analyst, Energy Efficiency and Environment Division, International Energy Agency, 9 Rue de la Federation, 75739 Paris Cedex 15, France. E-mail: Paul.WAIDE@iea.org

We have collected and self-consistently analyzed data for per-capita consumption of artificial light, per-capita gross domestic product and cost of light. The data span a wide range (three centuries, six continents, five lighting technologies, and five orders of magnitude), and are consistent with a linear variation of per-capita consumption of light with the ratio between per-capita gross domestic product and cost of light. No empirical evidence is found for a saturation in per-capita consumption of light, even in contemporary developed nations, and we review some reasons why such a saturation might or might not occur in the future. Finally, we extrapolate to the world in 2005, and find that 0.72% of gross domestic product and 6.5% of primary energy was expended to purchase 130 Plmh/yr of artificial light at a primary energy cost of 457 Quads/yr.

Table of Contents

1 INTRODUCTION

Artificial light has long been a significant factor contributing to the quality and productivity of human life. It expands the productive day into the non-sunlit hours of the evening and night, and during the day it expands productive spaces into the non-sunlit areas of enclosed dwellings, offices and buildings (Bowers 1998; Boyce 2003; Schivelbusch 1988).

Because we value artificial light so highly, we consume huge amounts of energy to produce it. As estimated later in this paper, the production of artificial light consumed roughly 6.5% of total global primary energy in 2005. This percentage is large and, coupled with increasing concern over energy consumption, has inspired a number of projections of light and associated-energy consumption into the future (Kendall and Scholand 2001; Tsao 2002; Navigant 2006). Such projections are of special interest at this point in history when lighting technologies are evolving rapidly. Filament-based incandescent technology is giving way to gas-plasma-based fluorescent and high-intensity-discharge (HID) technology; and over the coming 10-30 years both may give way to solid-state-lighting (SSL) technology (Tsao 2004; Krames et al. 2007; Schubert et al. 2006; Shur and Zukauskas 2005; Krames et al. 2007).

Projections of the consumption of light and associated power are difficult, however, because there is no consensus regarding the factors that underlie the demand for light. Hence, relatively arbitrary assumptions must be made, the most common of which is that demand for light is independent of the efficiency (and hence cost) with which it is produced and delivered. If true, then technology evolution leading to efficiency improvement would not lead to an increase in light consumption, but rather to a decrease in energy consumption. If not true, however, there might instead be an increase in light consumption, a type of "rebound" effect (Khazzoom 1980; Brookes 1990) that would lessen the decrease in energy consumption.

Indeed, the possibility of rebound effects are of intense current interest (UKERC 2007) not just for lighting, but for all the energy services (e.g., transport of people and goods, heating and cooling of spaces, and process machinery and appliances). These services are the dominant consumers of energy in our modern economy, and whether (and by how much) improvements in their energy efficiencies increase or decrease energy consumption has important ramifications on public policies aimed at reducing energy consumption and risk of human-induced climate change.

Because of the importance of possible rebound effects, much work has been expended trying to understand and quantify them, both theoretically (Saunders 1992) and empirically (Greening et al. 2000). For any particular energy service, however, its magnitude has been difficult to quantify, especially over longer time periods for which its magnitude can be anticipated to be largest. Nearly all empirical studies of which we are aware focus on relatively short (months to years) time periods during which societal-use paradigms for an energy service are relatively static. It is only over longer (decades to centuries) time periods that radically new societal-use paradigms may be expected to emerge, with associated radical changes in consumption of that service. It is in fact these radically new societal-use paradigms that were envisaged in the first formulation of the rebound effect (Jevons 1906; Alcott 2005).

Recently, a number of careful estimates have been made of the consumption of light in various nations over diverse geographic, economic and temporal circumstances. In this work, we have built on these estimates -- filling in gaps in the datasets, estimating demand factors auxiliary to the datasets, and self-consistently integrating across the datasets -- to create a quantitative picture of the consumption of light and associated energy. These estimates span a wide enough (over five orders of magnitude) dynamic range to enable accurate correlations between the consumption of light and its underlying demand factors. They also span a long enough (decades to centuries) time period to enable quantitative conclusions to be drawn about the rebound effect in this important energy service over historically significant time scales.

Indeed, lighting appears to be uniquely well suited amongst the various energy services for such a quantitative study. Its output (light), is more easily defined and estimated than the outputs (e.g., weight times distance traveled, or change in temperature times volume or heat capacity of space) of other energy services. Though it has had a long history of technology innovation, each major lighting technology has had a reasonably well-defined historical period of maturity or dominance, without the accounting difficulties associated with a massive proliferation of subtechnology variants, each with a different energy efficiency, market penetration and cost structure.

The remainder of this paper is organized as follows. In Section 2, we discuss how the estimates, taken from a number of sources, were self-consistently analyzed and interpreted. In Section 3, we discuss the primary empirical trend: that consumption of light varies linearly with the ratio between gross domestic product and cost of light. In Section 4, we discuss some of the secondary (non-income and non-price) factors that might underlie consumption of light at a higher level of detail. Some of these factors might also become more important, and hence may cause a deviation from the primary empirical trend, in the future. In Section 5, we extrapolate and aggregate these trends to estimate world consumption of light and associated energy.

2 DATA, ESTIMATES AND ASSUMPTIONS

In this Section, we discuss estimates of the consumption of light, along with how we have built on these estimates -- filling in gaps in the datasets, estimating demand factors auxiliary to the datasets, and self-consistently integrating across the datasets -- to create a quantitative picture of the consumption of light and associated power. We organize our discussion according to the quantity being estimated: consumption of light, luminous efficacy, cost of energy and light, consumption of associated energy, and finally gross domestic product and population. Before we begin, though, we make a few comments regarding scope, nomenclature and units.

Monetary units. Wherever monetary units are used, we use year 2005 US$, using exchange rate conversions across nations from the XE Interactive Currency Table (XE 2007) and deflation conversions across years from Measuring Worth (MW 2007).

Light and associated energy units. We choose as our units for light and associated energy: petalumen-hours (Plmh) and petawatt-hours (PWh). These units are large, but appropriate for nation-scale quantitites. As the usual unit for time scale of consumption is the year, we then choose as our units for the rates of consumption of light and associated energy: petalumen-hours per year (Plmh/yr), denoted by the symbol Φ, and petawatt-hours per year (PWh/yr), denoted by the symbol $\dot{E}_{\Phi}$. We will often refer to these simply as consumption of light or energy, though precisely speaking they are *rates* of consumption of light or energy. Also, we choose as our unit of population billions of persons (Gper), so that our units for per capita rates of consumption of light and associated energy become: megalumen-hours per person-year (Mlmh/(per-yr)), denoted by the symbol φ, and megawatt-hours per person-year (MWh/(per-yr)), denoted by the symbol $\dot{e}_{\varphi}$. Analogously, we denote gross domestic product *GDP*, with units of billions of dollars per year G$/yr, and we denote per capita gross domestic product *gdp*, with units of $/(per-yr).

Illumination vs. signaling. Our focus throughout is on consumption of light in those applications in which light is used to illuminate (and hence is viewed indirectly, after it scatters from an object or scene) but not those in which light is used to signal or display information (and hence is viewed directly). We note here that the energy economics of these two broad classes of applications for light are quite different. For illumination, the cost of light is mostly the cost of the energy that is converted into light;[1] while for signaling or information display, the cost of light is mostly the cost of the capital equipment used to convert energy into light.[2] Hence, by including illumination but not signaling or information display, we are focusing on those applications for light which are most energy-intensive.

Vehicle, grid-electricity and fuel-based energy-source sectors. Within the broad class of illumination applications, our intent is to be comprehensive, and hence to include consumption of light produced from all types of energy sources: from electricity in those populations with access to the electrical grid, from chemical fuel in those populations without access to grid electricity, and from electricity produced *in situ* from chemical fuel in vehicles. We think of these as defining three energy-source sectors and, for simplicity, refer to them as the vehicle, grid-electricity, and fuel-based energy-source sectors. We note that, even in modern times, the fuel-based sector is not insubstantial. It has been estimated that, as recently as 1999, 2 billion persons did not have access to grid electricity, and were largely dependent on kerosene lamps for their lighting (Mills 2005).

Electricity vs. chemical fuels. We keep track of the different "natural" units of energy associated with these different energy-source sectors by using subscripts ("e" for electricity and "c" for chemical), then convert between units by assuming efficiencies for the conversion of chemical fuel to electricity followed by transport of the electricity to point-of-use. For grid electricity, we use an efficiency of σ_{grid} = 0.316 W_e/W_c (DOE 2007, Chap. 6). For vehicle electricity, we use an efficiency of σ_{veh} = 0.15 W_e/W_c, which is basically the product of engine (assuming a mix of gas and diesel) and alternator efficiencies (Navigant 2003). Thus, luminous efficacies (denoted by the symbol η_{φ}) in units of lm/W_c are equivalent to those in units of lm/W_e multiplied by one of these efficiency factors: the luminous efficacy of an incandescent lamp powered by grid electricity could either be written as 14 lm/W_e or

[1] A typical 30W compact fluorescent light bulb (equivalent to a 100-150W incandescent light bulb) had, in early 2008, a retail capital cost of about $3, but, powered by electricity at $0.08/kWh, will use about $19 worth of electricity over a typical 8,000-hour operating life (http://www.bulbs.com/eSpec.aspx?ID=13178&Ref=Compact+Fluorescent+Screw-in&RefId=20&Ref2=Light+Bulbs).

[2] A typical 48W 22" liquid-crystal display television had, in early 2008, a retail capital cost of about $400, but, powered by electricity at $0.08/kWh, will only use about $200 worth of electricity if used over its product life of 50,000 hours (6 hours per day for 23 years), less if used for less than its product life, as is typical for advanced consumer electronics (http://www.viewsonic.com/products/lcdtv/NX2232w/).

4.4 lm/W_c, depending on whether one chooses units of wall-plug grid electricity or units of the primary chemical energy used to produce that wall-plug electricity. Similarly, per capita consumption of energy in units of MW_ch/(per-yr) is equivalent to that in units of MW_eh/(per-yr) divided by one of these efficiency factors; and costs of energy (*CoE*) in units of \$/MW_ch are equivalent to those in units of \$/MW_eh multiplied by one of these efficiency factors.

Comparing and aggregating across energy-source sectors. Of primary interest in this paper are the consumption and cost of light, neither of which depend on the choice of energy units (W_e or W_c) just discussed. However, because important intermediate quantities such as consumption of energy, luminous efficacy and cost of energy *do* depend on the choice of energy units, and because we wish to compare and aggregate these intermediate quantities (see Table 1), we must choose a common energy unit. The most natural choice is W_c, since chemical fuel is the starting point of the vast majority of energy for lighting, past and present. However, that choice is unnatural and confusing for quantities such as the luminous efficacy of today's grid-electricity-powered lamps (e.g., the 4.4 lm/W_c calculated above for an incandescent lamp). Therefore, we choose instead W_e, which makes natural and intuitive those quantities associated with the (currently much larger) grid-electricity energy-source sector, though making somewhat unnatural and non-intuitive those associated with the (currently much smaller) vehicle and fuel-based energy-source sectors.

Time-series vs. cross-sectional data. As discussed in the Introduction, we are purposefully interested in changes in consumption of light over the longer (decades to centuries) time periods required for radically new societal-use paradigms to emerge. Over such long time periods, we assume light consumption to have reached a near-steady-state response to these new societal-use paradigms, so that we can combine and treat on the same footing historical time-series (in one country over time) data with contemporary cross-sectional (across many countries at the same time) data. The degree to which steady-state has been achieved may vary from time period to time period and from country to country, however, and is a potential source of error in our analysis.[3]

2.1 Consumption of Light

The starting point for our estimates of the consumption of light is the five datasets summarized in Table 1. The first dataset (in brown) we refer to as the "Fouquet-Pearson" dataset: it represents estimates from the monumental work by Fouquet and Pearson on consumption of light in the United Kingdom over a 300-year time span (Fouquet and Pearson 2006). The second dataset (in dark grey) we refer to as the "IEA" dataset: it represents estimates from the recent comprehensive study by the International Energy Agency on consumption of light in various nations or groups of nations for which grid electricity is available, mostly in the year 2005 (IEA 2006). The third dataset (in blue) we refer to as the "Navigant" dataset: it represents an estimate from the extremely thorough bottoms-up survey by Navigant of consumption of light in the United States in 2001 (Navigant 2002). The fourth dataset (in green) we refer to as the "Mills" dataset: it represents estimates by Mills and co-workers of the consumption of light in China in 1993 (Min et al. 1997) and in

[3] For example, the lower-than-expected consumption of light for the data points associated with China (1993, 2005, 2006) seen in Figure 2 may be due to a lag time associated with consumption of light keeping pace with the extremely rapid rate at which *gdp* has grown in that nation.

populations in 1999 for which grid electricity was not available (Mills 2005). The fifth dataset (in red) we refer to as the "Li" dataset: it represents an estimate of consumption of light in China in 2006 (Li 2007a).

Of the estimates in these datasets, we consider those of contemporary consumption of light to be much more accurate than those for historical consumption of light. Despite the care with which the historical estimates were made, such estimates are fraught with difficulties, not the least of which are assumptions on the mix of lighting technologies used during periods when the efficiencies (or luminous efficacies) of these technologies were evolving rapidly. And of the estimates of contemporary consumption of light, we consider that of the United States in 2001 to be the most accurate, and those for China in 1993 and 2006 to be the least accurate.

All five of the datasets provide estimates of consumption of light for two of the energy-source sectors (grid electricity and fuel-based). Although it is a small (of order 1%) contribution, for completeness we have added to the contemporary (post 1950) data estimates of consumption of light for the third energy-source sector (vehicles). To do this, in anticipation of the result for all energy-source sectors discussed in Section 3, we assume that per-capita consumption of light associated with vehicles is simply proportional to the ratio of the *gdp* ($/(per-yr)) of a nation (or group of nations) to the cost of light (*CoL*, in $/Mlmh) in that nation (or group of nations):

$$\varphi_{veh} = \beta_{veh} \cdot \frac{gdp}{CoL_{veh}}. \quad (2.1)$$

For the proportionality constant we use β_{veh} = 0.000485, deduced from Navigant's study of consumption of light in vehicles (autos, buses and trucks) in the United States in 2002 (Navigant 2003), where we have summed over only those lamps (high- and low-beam headlamps, parking lamps, license plate lamps and fog lamps) used for illumination (rather than signaling) purposes. For *gdp* we use the estimates discussed in Subsection 2.6. For cost of light we use the expression discussed in Subsection 2.4, but particularized for vehicles: $CoL_{veh} \approx (1+\kappa_\varphi)\cdot CoE_{veh}/\eta_{\varphi,veh}$.

Finally, for each nation or group of nations, we sum the estimates of consumption of light from the three energy-source sectors to get an aggregate consumption of light across those sectors.

2.2 Luminous Efficacy

Luminous efficacy represents the efficiency with which energy is used to produce visible light. As has been discussed recently, there is a limiting luminous efficacy for the production of high quality white light which renders well the colors of typical environments: 408 lm/W_e (Phillips et al. 2007). In practice, the luminous efficacies of various lighting technologies are far less than this limiting value, and have evolved considerably throughout history. Indeed, as discussed first by Nordhaus (Nordhaus 1997), they have evolved spectacularly -- a key insight in the development of "hedonic" indices based on the price of consumed services or features rather than of the inputs to those services or features.[4]

[4] See, e.g., U.S. Department of Labor discussions of hedonic adjustments to the U.S. consumer price index (http://www.bls.gov/cpi/home.htm).

			per capita Consumption of Light (φ)				per capita Consumption of Energy ($\dot{e}_\varphi$)				Luminous Efficacy (η_φ)				Cost of Energy (*CoE*)				Cost of Light (*CoL*)				Population, *GDP*, *gdp*		
Nation or Nations	Year	Predominant Energy Source or Lighting Technology	Vehicle	Grid	Fuel-Based	All	Vehicle*	Grid	Fuel-Based*	All	Vehicle*	Grid	Fuel-Based*	φ-Weighted Inverse Average	Vehicle*	Grid	Fuel-Based*	All	Vehicle	Grid	Fuel-Based	All	Population (N)	Gross Domestic Product (*GDP*)	per capita gross domestic product (*gdp*)
			Mlmh/(per-yr)				MW_eh/(per-yr)				lm/W_e				\$/MW_eh				\$/Mlmh				Gper	G\$/yr	\$/(per-yr)
UK	1700	Can			0.00058	0.00058			0.0068	0.0068			0.085	0.085			2,188	2,188			29,253	29,253.1	0.0086	16	1,863
UK	1750	Can			0.00060	0.00060			0.0065	0.0065			0.092	0.092			2,360	2,360			29,386	29,385.8	0.0125	27	2,120
UK	1800	Can+Oil			0.00274	0.00274			0.0247	0.0247			0.111	0.111			1,439	1,439			14,846	14,846.5	0.0183	44	2,414
UK	1850	Gas+Can			0.01288	0.01288			0.0271	0.0271			0.475	0.475			576	576			1,386	1,385.7	0.0272	94	3,472
UK	1900	Gas+Ker			0.26728	0.26728			0.3519	0.3519			0.759	0.759			345	345			520	519.6	0.0412	275	6,693
UK	1950	Inc		4.99		4.98733		0.43		0.4299		12		11.600		182		182		20.9		20.9	0.0501	518	10,340
UK	2000	Inc+Flu+HID	0.32	46.09		46.40813	0.0146	0.85		0.8681	22	54		53.462	748	73		84	45	1.8		2.1	0.0595	1,788	30,037
US	2001	Inc+Flu+HID	1.22	134.89		136.10225	0.0552	2.75		2.8029	22	49		48.558	278	72		76	17	2.0		2.1	0.2850	12,039	42,237
China	2006	Inc+Flu+HID	0.13	16.25		16.38264	0.0074	0.28		0.2876	18	58		56.964	441	79		88	33	1.8		2.1	1.3108	11,842	9,034
FSU	2000	Inc+Flu+HID	0.18	38.52		38.70621	0.0103	0.90		0.9061	18	43		42.717	235	49		51	17	1.5		1.6	0.2891	1,918	6,636
OECD Eur	2005	Inc+Flu+HID	0.24	45.68		45.92144	0.0109	0.85		0.8569	22	54		53.591	944	138		149	57	3.4		3.7	0.4859	13,800	28,404
JP+KR	2005	Inc+Flu+HID	0.31	71.62		71.93434	0.0141	1.10		1.1160	22	65		64.457	799	142		150	48	2.9		3.1	0.1761	5,452	30,967
China	2005	Inc+Flu+HID	0.14	13.22		13.36237	0.0080	0.23		0.2359	18	58		56.644	374	78		88	28	1.8		2.1	1.3032	10,717	8,224
AU+NZ	2005	Inc+Flu+HID	0.49	62.96		63.45005	0.0222	1.28		1.3071	22	49		48.541	568	98		106	34	2.7		2.9	0.0241	836	34,671
Wrld Grid	2005	Inc+Flu+HID	0.18	32.70		32.87727	0.0082	0.65		0.6584	22	50		49.933	600	110		116	36	2.9		3.1	4.0767	54,821	13,447
China	1993	Inc	0.13	2.57		2.70515	0.0074	0.10		0.1108	18	25		24.415	168	104		109	12	5.6		5.9	1.1784	4,059	3,445
Wrld Non-Grid	1999	Ker			0.04275	0.04275			0.1228	0.1228			0.348	0.348			183	183			600	600.2	2.0000	4,404	2,202
Wrld	2005	Ker+Inc+Flu+HID												47.527				119				3.3	6.4234	60,670	9,445

Table 1. Per-capita consumption of light (φ) and associated energy ($\dot{e}_\varphi$), luminous efficacies (η_φ), costs of energy (*CoE*) and light (*CoL*), population (N), gross domestic product (*GDP*) and per capita gross domestic product (*gdp*), for the five datasets (in brown, blue, pink, grey and green) discussed in Section 2. Estimates are also given for aggregate luminous efficacy and costs of light and associated energy for the World 2005. Monetary units are all year 2005 US\$. The various nation abbreviations are: UK = United Kingdom; FSU = Former Soviet Union; OECD Eur = Organization for Economic Development Europe = Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, UK, Ireland, Greece, Portugal, Spain, Hungary, Poland, Czech Republic, Slovak Republic, Turkey, Iceland, Luxembourg; JP+KR = Japan + South Korea; AU+NZ = Australia + New Zealand; Wrld = World. The various lighting technology abbreviations are: Can = candle; Oil = oil; Gas = gas; Ker = kerosene; Inc = incandescence; Flu = fluorescence; HID = high-intensity discharge. The various energy-source sectors are vehicle, grid electricity and fuel-based.

*As discussed in the text, in order to more easily compare and aggregate the various energy-source sectors, we use for the energy consumption units of the vehicle and fuel-based energy-source sectors Watts (W_e) of electrical power that would have been available had the Watts (W_c) of primary chemical power been converted and transported to point of use. Note that cost of light (\$/Mlmh), which is proportional to the ratio between cost of energy (\$/MW_eh) and luminous efficacy (lm/W_e), is independent of energy consumption unit.

For most of the datasets, because of the relationship between luminous efficacy (η_φ, in lm/W), per-capita consumption of light (φ, in Mlmh/(per-yr)) and associated energy ($\dot{e}_\varphi$, in MWh/(per-yr)),

$$\frac{\varphi}{\eta_\varphi} = \dot{e}_\varphi , \tag{2.2}$$

two of the quantities were estimated and the third inferred. For example, in the Fouquet-Pearson dataset consumption of energy and luminous efficacy were estimated and consumption of light was inferred. Or, for example, in the Navigant dataset consumption of light and luminous efficacy were estimated and consumption of energy was inferred.

For the most part, we have used "as is" the estimates of luminous efficacy in the original datasets. The only exception was in the Fouquet and Pearson dataset, for which luminous efficacies were based on an evolved weighting of the proportions of old and new lighting technologies, with the underlying luminous efficacies of the various technologies based on estimates from Nordhaus' classic study (Nordhaus 1997). In this dataset, the luminous efficacy for 2000 appeared to be biased towards incandescent technology rather than reflecting a more accurate modern mix of incandescent, fluorescent and high-intensity discharge (HID) technology. Hence, instead of Fouquet and Pearson's estimate of 25 lm/W_e (based on Nordhaus' original estimate), we substituted the 2005 OECD Europe aggregate average of 54 lm/W_e from the IEA dataset.

Note that luminous efficacy relies on an assumption regarding the source of energy that is used to produce light, and these in turn differ according to the energy-source sectors (vehicle, grid electricity, and fuel-based) discussed in the introduction to Section 2. To compare across these sectors, and because electricity is now and likely in the future the dominant source of energy for lighting, we list in Table 1 luminous efficacies in units of lm/W_e, calculated as if electricity were the initial energy source.

For the grid electricity and vehicle energy-source sectors, the most common units for luminous efficacy are lm/W_e, calculated as if electricity were the initial energy source, and so these are listed "as is" in Table 1. Note that for the vehicle sector the range of luminous efficacies is not very great, varying from the $\eta_{\varphi,veh}$ = 18 lm/W_e typical of tungsten incandescent bulbs to the $\eta_{\varphi,veh}$ = 24 lm/W_e of tungsten-halogen incandescent bulbs (Denton 2004, p. 292). In newer vehicles, the latter is more common, and so we have assumed luminous efficacies for the various nations and groups of nations closer to the latter for recent years in more developed nations, and closer to the former for less recent years in less developed nations.

For the fuel-based energy-source sector, the starting point is the luminous efficacy in units of lm/W_c calculated as if chemical fuel were the initial energy source. Then, we divide by the σ_{grid} = 0.316 W_e/W_c efficiency of conversion-and-transport-to-point-of-use factor to get the effective luminous efficacy in units of lm/W_e as if grid electricity were the initial energy source.

Finally, given the luminous efficacies and per-capita consumptions of light of the various sectors for a particular nation or group of nations, an aggregate luminous efficacy for all the sectors combined is calculated by averaging the inverse luminous efficacies of each sector weighted by the fraction of light consumed per capita by that sector,

$$\frac{\varphi}{\eta_\varphi} = \frac{\varphi_{grid}}{\eta_{\varphi,grid}} + \frac{\varphi_{fuel}}{\eta_{\varphi,fuel}} + \frac{\varphi_{veh}}{\eta_{\varphi,veh}}, \qquad (2.3)$$

where $\varphi = \varphi_{grid} + \varphi_{fuel} + \varphi_{veh}$ is the per-capita consumption of light for all three sectors. This weighting allows Equation 2.2 to be valid for each sector individually as well as for the sum over all sectors.

2.3 Cost of Energy

By cost of energy (*CoE*), we mean the point-of-use cost to the consumer who is converting the energy into light. Just as for luminous efficacy, however, the initial energy source is important to keep in mind. And, just as for luminous efficacy, to compare across these sectors, and because electricity is now and likely in the future the dominant source of energy for lighting, we list in Table 1 cost of energy in units of \$/MW$_e$h calculated as if electricity were the initial energy source.

For the Fouquet and Pearson historical UK dataset, we used their estimates of the cost of energy "as is," but assumed that for 1900 and earlier the dominant energy source was chemical fuel, while for 1950 and later it was grid electricity. For the IEA and Navigant datasets (except for China), we used international residential and industrial electricity prices compiled (EIA 2007b) by the U.S. Energy Information Administration.[5] For China, estimates were spliced together from a number of sources (Li 2007b).

For the Mills non-grid world, we used his estimate[6] of \$0.5/liter for kerosene (in year 1999 US\$), divided by the energy content of kerosene (36.5 MJ/liter), then multiplied by 60·60 s/h (number of seconds in an hour) and a year 1999 to year 2005 exchange rate conversion, to derive a *CoE* of 58 \$/MW$_c$h. Then, we divide by the σ_{grid} = 0.316 W$_e$/W$_c$ efficiency-of-conversion-and-transport-to-point-of-use factor to get an effective *CoE* of 183 \$/MW$_e$h as if grid electricity were the initial energy source.

For the vehicle sector, we use international gasoline costs per unit volume (\$/gallon) taken from a compilation by the German Federal Ministry for Economic Cooperation and Development (GTZ 2007), divided by the σ_{veh} = 0.15 W$_e$/W$_c$ efficiency factor, then divided by the energy content of gasoline (38.3 kW$_c$h/gallon), to get the cost of energy in \$/MW$_e$h as if electricity were the initial energy source.

In all cases, for groups of nations, we used *GDP*-weighted averages.

---

[5] Since the cost and use of energy for lighting varies across the residential, commercial and industrial sectors, the aggregate cost of energy for lighting across these sectors can be written as: $CoE = (CoE_{Res}\cdot\dot{E}_{Res}+CoE_{Com}\cdot\dot{E}_{Com}+CoE_{Ind}\cdot\dot{E}_{Ind})/\dot{E}$, where $\dot{E} = \dot{E}_{Res}+\dot{E}_{Com}+\dot{E}_{Ind}$ is the energy consumed for lighting. In the U.S., the cost of energy in the form of electricity for the commercial sector is, very roughly (EIA 2007a), $CoE_{Com} \approx (2/3)\cdot CoE_{Res}+(1/3)\cdot CoE_{Ind}$, and the fractions of energy for lighting consumed by the various sectors are roughly (Navigant 2002) $\dot{E}_{Res}/\dot{E} \approx 4/9$, $\dot{E}_{Com}/\dot{E} \approx 3/9$ and $\dot{E}_{Ind}/\dot{E} \approx 2/9$. Hence, we can deduce, after some algebra, that $CoE \approx (2/3)\cdot CoE_{Res}+(1/3)\cdot CoE_{Ind}$. Though this formula is strictly valid only for the U.S., we use it, in the absence of similarly detailed inventories, for all other nations (except China) as well.

[6] Note that this cost for kerosene is an estimate averaged over many different countries and continents, and could be the source of some error.

2.4 Cost of Light

By cost of light (*CoL*, in units of $/Mlmh), we mean the ownership cost of light, which includes (Rea 2000): the cost of the energy that is converted into light, the purchase and maintenance cost of the lamp (or bulb) that converts the energy into light, and the purchase cost of the luminaire and lighting system that directs and controls the light. The first cost is an operating cost, the second and third costs are capital costs.

The operating cost is the dominant of these, and is just the cost of energy divided by luminous efficacy, CoE/η_φ, with luminous efficacy and cost of energy as discussed in Subsections 2.2 and 2.3.

The purchase and maintenance cost of the lamp is smaller, and can be thought of as a fraction of the operating cost. For modern incandescent, fluorescent and high-intensity-discharge (HID) lamps, the fraction is approximately 1/6 (Navigant 2002). For the replaceable parts of modern kerosene lamps (the wick and mantle) such as those used for fuel-based lighting, the fraction has been estimated to be very similar, approximately 1/7 (Mills 2005). For solid-state lighting (sometimes considered the next generation of lighting technology), the fraction estimated from industry targets (EERE 2008, p. 65) for high-color-rendering white light in the years 2012-2015 is also similar, in the range 1/5 to 1/12. We have not attempted to estimate whether these fractions also hold for past generations of more primitive lighting technologies. However, even in primitive lighting technologies, fuels appear to dominate the container for the fuels (e.g., firewood in a hearth), and it is not unreasonable to assume (as did Nordhaus (1997) and Fouquet and Pearson (2006) in their classic historical studies of the economics of lighting) that the fractions are similarly small.

The purchase cost of the luminaire and lighting system is more difficult to estimate, though it has been characterized as being of the same order of magnitude as the purchase cost of the lamp (IEA 2006). In the absence of accurate historical and contemporary data across nations, we simply assume here that these costs are a similar fraction, 1/6 to 1/7, of the operating cost. This is an assumption, however, that would benefit from more detailed examination.

Taken together, we write the cost of light as:

$$CoL = \frac{CoE}{\eta_\varphi} \cdot (1 + \kappa_\varphi), \tag{2.4}$$

where κ_φ = 1/3 is the ratio of the capital to operating costs of light. The operating fraction of the cost of light is then $1/(1+\kappa_\varphi) \sim 3/4$ and the capital fraction of the cost of light is $\kappa_\varphi/(1+\kappa_\varphi) \sim 1/4$.

To see the variation in cost of light over the various datasets, and how that variation is determined by variations in luminous efficacy and cost of energy, Figure 1 shows a scatterplot of the datasets on an η_φ versus *CoE* plot. The dashed diagonal lines are contours of constant CoL calculated according to Equation 2.4.

One sees that the cost of light varies across the datasets by ~4.3 orders of magnitude. The greater part of that variation is due to a ~2.8 order-of-magnitude variation in luminous efficacy; the lesser part is due to a ~1.5 order-of-magnitude variation in cost of energy. Note that in general the more recent data points have higher luminous efficacies and lower costs of energy. The glaring exception is the WRLD-NONGRID 1999 data point, which represents the world population in 1999 without access to grid electricity. Because of this population's reliance on relatively primitive kerosene lamp technology, its luminous efficacy is comparable to, though

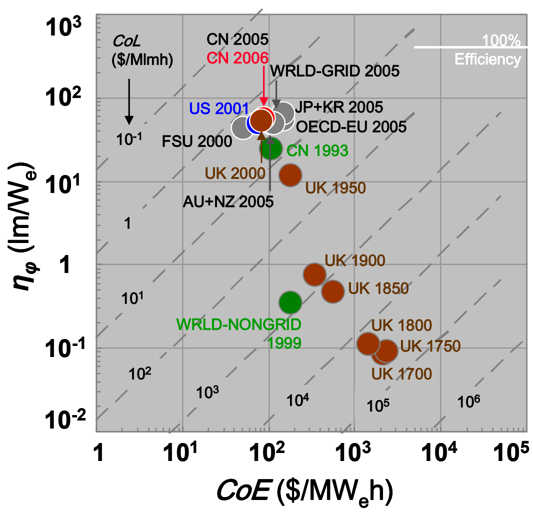

Figure 1. Scatterplot of the luminous efficacies (η_φ) and costs of energy (CoE) associated with the five datasets discussed in Section 2. Country abbreviations are given in the caption to Table 1. The dashed diaganol lines are contours of constant cost of light. The horizontal white line at the upper right indicates the luminous efficacy associated with 100% efficient conversion of energy into a high quality (color rendering index = 90) white light.

its cost of energy is somewhat lower than, that of the United Kingdom in the 1850's. Also note that even amongst the most contemporary (2000-2005) data points, there is a surprisingly large variation in cost of energy, with the FSU 2000 data point at the low end, and JP+KR 2005 at the high end. There is much less variation, however, in their luminous efficacies.

2.5 Consumption of Associated Energy

By consumption of energy associated with the consumption of light we should in principle include two contributions: consumption of energy associated with the operating cost of light, and consumption of energy "embodied" in the capital cost of light.

The first contribution is given by Equation 2.2: $\dot{e}_{\varphi,op} = \varphi/\eta_\varphi$. The second contribution can be written as: $\dot{e}_{\varphi,cap} = (\varphi \cdot \kappa_\varphi \cdot CoE/\eta_\varphi)/\eta_\mu$, where $\varphi \cdot \kappa_\varphi \cdot CoE/\eta_\varphi$ is the cost of the capital equipment used to produce, direct and control light (the capital cost-of-light part of Equation 2.4 multiplied by φ), and $1/\eta_\mu$ is the energy intensity for manufacturing that capital equipment. The ratio between the two contributions is $\dot{e}_{\varphi,cap}/\dot{e}_{\varphi,op} = \kappa_\varphi \cdot CoE/\eta_\mu$., and contains three terms.

The first two terms we can estimate easily. The capital equipment fraction of the cost of light we estimated in Subsection 2.4 to be $\kappa_\varphi \sim 1/3$. The cost of electricity in the U.S. in 1994, per unit of chemical fuel source energy, has been estimated to be CoE ~ 28 \$/MW$_c$h (EIA 2006, Table 8.10).

The third term, the energy intensity for manufacturing the capital equipment for lighting, is more difficult to estimate but can be reasonably bounded. An upper bound would be that associated with the most energy intensive manufactured product group, which in the U.S. in 1994 was stone, clay and glass products, with $1/\eta_\mu \sim$ 15.09 kBtu/\$ ~ 1/226 MW$_c$h/\$ (EIA 1998). A lower bound would be that associated with the least energy intensive manufactured product group, which in the U.S. in 1994 was apparel and other textile products, with $1/\eta_\mu \sim$ 0.47 kBtu/\$ ~ 1/7,260 MW$_c$h/\$ (EIA 1998).

Using these estimates for the first two terms and the bounds for the third term, the ratio, $\dot{e}_{\varphi,cap}/\dot{e}_{\varphi,op}$, between the energy embodied in the capital cost of light to the energy associated with the operating cost of light can then be bounded between 1/24 and 1/778. These bounds are consistent with ratios of 1/90 and 1/400 found in a study (Gydesen and Maimann 1991) in which 15W compact fluorescent and 60W incandescent lamps, respectively, were dissected into their material contents and embodied energies, and the embodied energies compared to their lifetime energies of operation.

We conclude that the energy embodied in the capital cost of light is negligible, and for the remainder of this paper we assume that Equation 2.2 holds for the relationship between consumption of light and consumption of associated energy, both for the U.S. in 1994 as well as for all other nations in all other years.

2.6 Gross Domestic Product and Population

As we shall see, gross domestic product (*GDP*) and population (*N*) are key factors underlying consumption of light, so we have gathered together various estimates for these.

For individual nations our primary sources for historical and contemporary gross domestic products and populations were the comprehensive databases compiled by Angus Maddison (Maddison 2007) and the University of Groningen (GGDC 2007). Importantly, the GDPs in these databases were derived using purchase-power-parity, rather than exchange-rate, methods. Although we do not pursue this issue further in this paper, we did find that consumption of light had a significantly stronger correlation with such purchase-power-parity *GDP*s than with exchange-rate *GDP*s.

For most of the groups of nations, we simply summed the *GDP*s or populations of the individual nations. In the few cases where *GDP* or *N* for a particular year was not in the database, simple geometric interpolation between years was done.

To estimate GDPs and populations of those with (WRLD-GRID 2005) and those without (WRLD-NONGRID) access to grid electricity, we approximate the first to be those nations classified by the World Bank (WB 2007) as middle or high income, and the second to be those classified as low income. Doing so for the first in 2005 yields a population of 4.1 Gper and a GDP of 54.8 G$/yr, numbers we associate with the estimates in the IEA dataset of world consumption of light from grid electricity in 2005. Doing so for the second in 1999 yields a population of 2.1 Gper and a *GDP* of 4.6 G$/yr. We note that this population is very close to the estimate in the Mills dataset of 2.0 Gper without access to grid electricity in 1999. Since the deviation is small, and since we would like to use without modification Mills' associated estimates of the consumption of light, for our purpose we accept his estimate of 2.0 Gper and simply scale *GDP* proportionately down to (2.0/2.1) · 4.6 G$/yr = 4.4 G$/yr.

3 RELATIONSHIP BETWEEN CONSUMPTION OF LIGHT, INCOME AND PRICE

In this Section, we describe what we have found to be the primary relationship governing consumption of light: that per-capita consumption of light varies linearly with the ratio between per capita gross domestic product and cost of light. We then discuss how this primary relationship can be improved slightly through higher-order non-linear relationships with per capita gross domestic product and cost of light, though the introduction of such relationships is not yet believed warranted by the accuracy of the underlying data.

3.1 Relationship between φ and *gdp*/*CoL*

The central result of this paper is that per-capita consumption of light is, to a very good approximation, linearly proportional to the ratio between per capita gross domestic product and cost of light, obeying the expression:

$$\varphi = \beta \cdot \frac{gdp}{CoL}. \quad (3.1)$$

The surprising descriptive power of this expression is illustrated[7] in Figure 2. The vertical axis of the Figure is per-capita consumption of light, φ, in units of Mlmh/(per-yr). The horizontal axis of the Figure is β, a dimensionless proportionality constant, times per capita gross domestic product, *gdp*, in units of \$/(per-yr), divided by cost of light, *CoL*, in units of \$/Mlmh. Because the two axes have the same units, Mlmh/(per-yr), Figure 1 basically plots direct estimates of per-capita consumption of light in a number of nations or groups of nations (vertical axis) against indirect predictions of per-capita consumption of light based on independent estimates of *gdp* and *CoL* in those same nations or groups of nations (horizontal axis).

As illustrated in Figure 2, per-capita consumption of light is predicted remarkably well by Equation 3.1, despite a span of data over: 3 centuries (1700-2006), 6 continents (Africa, Asia, Australia, Europe, North America, South America), 5 types of fuel (tallow, whale oil, gas, petroleum, electricity), 5 overall families of lighting technologies (candles, oil lamps, gas lamps, electric incandescent bulbs, electric gas-discharge bulbs or tubes), 1.4 orders of magnitude in per capita gross domestic product, 4.3 orders of magnitude in cost of light, and 5.4 orders of magnitude in per-capita consumption of light.

That per-capita consumption of light varies so simply with the ratio between *gdp* and *CoL* seems fortuitous, but allows for the following interpretation. People expend a fixed fraction (β) of their *gdp* on light, and per-capita consumption of light is simply this expenditure ($\beta \cdot gdp$) divided by the cost of light (*CoL*). The fixed fraction can be determined, by a least squares fit of $log(\varphi)$ to $log(\beta \cdot gdp/CoL)$, to be β = 0.0072.[8] More precisely, logarithmic regression gives $log(\beta)$ = -2.15±0.26 FWHM, with an adjusted coefficient of determination $R^2 = 0.986$.[9] Note that on an absolute scale the confidence interval for β is not small: its lower end is $\beta = 10^{-2.15-0.26} = 0.0039$ and its upper end is $\beta = 10^{-2.15+0.26} = 0.0130$. This range of $10^{2 \cdot 0.26} = 3.3$ is infinitesimal, however, compared to the dynamic range of $10^{5.36}$ = 230,000 for per-capita consumption of light itself.

Indeed, it is the wide dynamic range of the data that enables us to have confidence in the observed empirical trend in per-capita consumption of light. As discussed in Section 2, the various estimates of per-capita consumption of light, per-capita gross domestic product and cost of light are fraught with difficulty. Nevertheless, even errors at the high end of likelihood (factors of 2-3x for any individual data point) are small compared to the dynamic range of 230,000 of the entire data set.

---

[7] Note that, since the axes of Figure 2 are logarithmic, we have effectively plotted the logarithmic form of Equation 3.1: $\log(\varphi) = \log(\beta) + \log(gdp) - \log(CoL)$.

[8] This procedure gives a β which is essentially the mean of the values for $\varphi \cdot CoL/gdp$ for all of the data points (see Table 1 in Section 5), weighted equally. We could instead have taken β to be the value of $\varphi \cdot CoL/gdp$ associated with the data point considered most accurate: the comprehensive Navigant study of the 2001 U.S. lighting market (Navigant 2002), which self-consistently aggregated bottom-up surveys, audits and inventories from a large number of independent sources. Doing so would give an β which is slightly lower, 0.0067 rather than 0.0072.

[9] The adjusted and non-adjusted coefficients of determination are virtually the same, due to the large number (seventeen) of samples compared to the number (one) of fitting parameters.

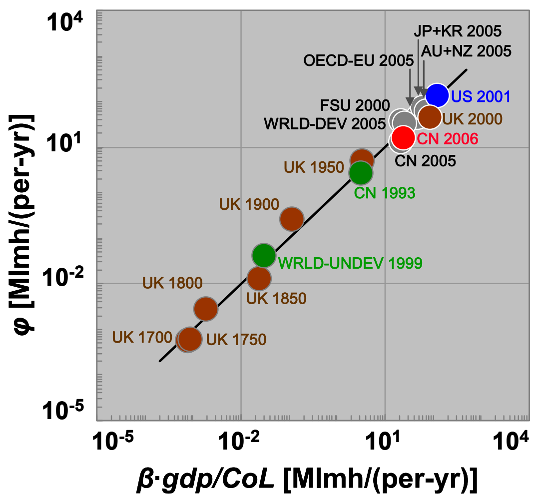

Figure 2. Data for per-capita consumption of light (φ) plotted against the product of a constant factor (β) and per capita gross domestic product (*gdp*), divided by the cost of light (*CoL*). Country abbreviations are given in the caption to Table 1. The diagonal black line has slope unity and zero offset.

We conclude that, to a very good approximation, people in nations over diverse temporal, geographic, technological and economic circumstances [10] have expended 0.39% to 1.30% (with a best fit value of 0.72%) of their *gdp* on light.[11] We also conclude that the income elasticity (at constant price) and the price elasticity (at constant income) of the demand for light are both unity or nearly unity.

At first blush, such high elasticities are surprising, given the widely made assumption that demand for light is independent of efficiency (and hence cost), and the also widely made corollary assumption that energy consumption will decrease as technology evolution leads to improvement in lighting efficiency (Kendall and Scholand 2001; Tsao 2002; BES 2006; Navigant 2006).

At second blush, however, such high elasticities for lighting, over decades-to-centuries time periods, are perhaps not so surprising. The human visual system is among the most complex and developed of our sensory systems, and is key to how we experience the world around us. Humans are not indifferent to ways of enhancing this experience, including through use of artificial light. One can only speculate how altered the architecture of enclosed spaces and buildings would need to be if only natural sun- and moon-light were available to be exploited, and how expensive it would be to substitute enough capital, labor and materials to compensate.

Moreover, though an expenditure of 0.72% of *gdp* on any single good or service seems like a significant fraction, on an absolute scale it is relatively small. Hence, one can anticipate that it would be relatively painless in economic terms to maintain its magnitude under diverse temporal, geographic, technological, and economic circumstances, particularly if the consumption of light confers significant benefit to the productivity and quality of human life.

Finally, we point out that the empirical relationship between φ, *gdp* and *CoL* is not intended to be interpreted as a dependency of φ as a dependent variable on *gdp*

---

[10] We especially call attention to the WRLD-UNDEV 1999 data point, which corresponds to the fuel-based lighting consumed by those in the modern world without access to grid electricity. This data point falls very closely on the straight line drawn in Figure 2, indicating that the poor (whether in modern or historical times) do *not* spend a disproportionately larger (or smaller) fraction of income on light than do the wealthy.

[11] Note that while the confidence interval encompasses the percentage, 1.2%, found in the recent International Energy Agency study (IEA 2006), the best-fit value, 0.72%, is somewhat lower. The reasons are twofold: the IEA's use of exchange-rate based, but our use of purchase-power-parity based, *gdps*; and the IEA's estimates of $\varphi \cdot CoL/gdp$ being slightly high relative to those of the other datasets.

and *CoL* as independent variables. More likely, the three are self-consistently interdependent: if *CoL* were to decrease, φ might increase; as φ increases, human productivity associated with the consumption of light might increase; as human productivity increases, *gdp* might increase; and as *gdp* increases, investment in technology development might lead to further decreases in *CoL*.

3.2 Other Possible Relationships between φ on *gdp* and *CoL*

Though the simple linear variation of per-capita consumption of light on the ratio between *gdp* and *CoL* is striking, it is interesting to explore other possible variations.

φ varies solely with either *gdp* or *CoL*

The simplest of these would be a variation of φ solely with either *gdp* or *CoL*. After all, over historical time, *gdp* has generally increased while *CoL* has generally decreased, and one might anticipate that consumption of light could be predicted using either variable alone.

To see how, we show the two variations in Figures 3a and 3b. If we assume simple power-law variations, then logarithmic regressions give two two-parameter fits: $log(\varphi) = -13.64+log(gdp^{3.52})$ and $log(\varphi) = 2.01+log(CoL^{-1.15})$. Because the 5.4 orders-of-magnitude variation in φ is larger than either the 1.3 orders-of-magnitude variation in *gdp* or the 4.3 orders-of-magnitude variation in *CoL*, the magnitudes of the power-law exponents must both be larger than unity: 3.52 for the variation with *gdp* and -1.15 for the variation with *CoL*. The adjusted coefficients of determination are $R^2 = 0.766$ for the variation with *gdp*, and $R^2 = 0.958$ for the variation with *CoL*. Though these adjusted coefficients of determination for the two *two*-parameter fits are in a reasonable range, neither is as high as the $R^2 = 0.986$ found for the *one*-parameter fit to a linear variation with *gdp/CoL*.

Moreover, closer inspection of Figures 3a and 3b indicates plausible explanations for the lower adjusted coefficients of determination. Consider Figure 3a, which plots φ against *gdp*. Per-capita consumption of light has a larger apparent variation with *gdp* for the *CoL*>$10/Mlmh (mostly fuel-based) data points than for the *CoL*<$10/Mlmh (mostly grid-electricity) data points. A plausible explanation is that, for the former but not for the latter, the variation in *gdp* is augmented by a large but hidden variation in *CoL*.[12] Likewise, consider Figure 3b, which plots φ against *CoL*. Here, the situation is reversed. Consumption of light has a larger apparent variation with *CoL* for the *CoL*<$10/Mlmh (mostly grid-electricity) data points than for the *CoL*>$10/Mlmh (mostly fuel-based) data points. A plausible explanation is that, for the former, *CoL* varies hardly at all, hence most of its variation in consumption of light is due to the large (but hidden) variation in *gdp*.

Of course, it is still *possible* that consumption of light varies either solely with *gdp* or with *CoL*, but that the variations are piecewise, with different power-law exponents for *CoL*<$10/Mlmh than for *CoL*>$10/Mlmh. For example, all that would be necessary for consistency with Figure 3a would be for the magnitude of the power-law exponent with respect to *gdp* to be relatively large (~4.7) for *CoL*>$10/Mlmh, then to become relatively small (~1.5) for *CoL*<$10/Mlmh.

[12] Note that if only the grid electricity datapoints are used, *gdp* is at least an *approximate* predictor for consumption of light. But *CoL* still plays a role, as can be seen from a compilation of data from 33 countries by Mills (Mills 2002) in which Norway is an outlier, most likely because of its low hydroelectricity cost and hence low *CoL*.

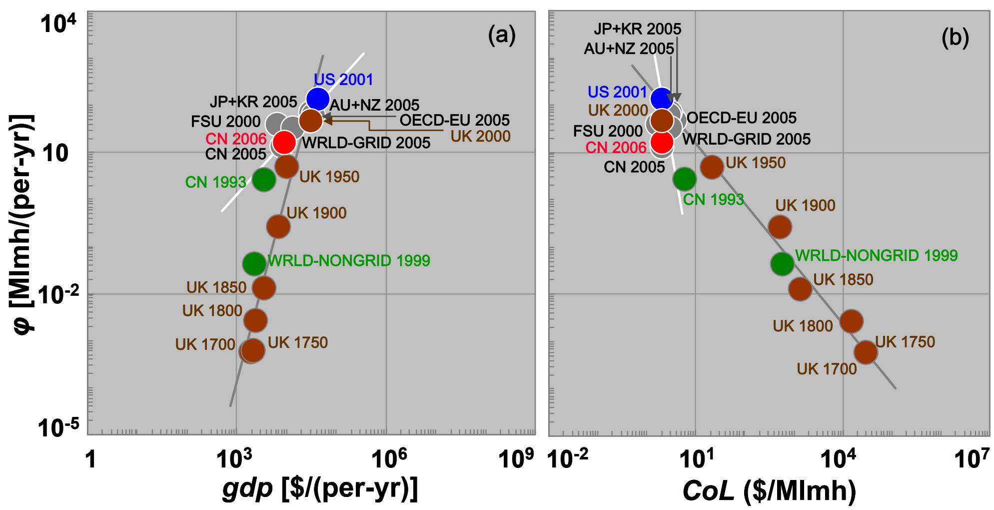

Figure 3. Data for per-capita consumption of light (φ) versus (a) per capita gross domestic product (*gdp*) and (b) cost of light (*CoL*). Country abbreviations are given in the caption to Table 1. The black and white diagonal lines are independent power-law fits to the *CoL*>$10/Mlmh (outlined in white) and *CoL*<$10/Mlmh (outlined in dark grey) data points, respectively, and are intended to visually illustrate the different dependences on *gdp* and *CoL* of these data points.

Likewise, all that would be necessary for consistency with Figure 3b would be for the magnitude of the power-law exponent with respect to *CoL* to be relatively small (~-1.3) for *CoL*>$10/Mlmh, then to become relatively large (~-6) for *CoL*<$10/Mlmh.

Although neither larger-than-unity nor piecewise changes in power-law exponents can be ruled out, we do not find any reason to invoke them. Instead, Occam's Razor suggests that it is more likely that per-capita consumption of light varies similarly with the ratio between *gdp and CoL* for all *CoL* values, energy sources and data sets. The 5.4 orders-of-magnitude variation in φ would thus not be due to non-linear (power-law) variations with either the 1.4 orders-of-magnitude variation in *gdp* or the 4.3 orders-of-magnitude variation in *CoL*, but rather to linear power-law variations with the ratio of the two.

Non-unit elasticities

Another possible variation is one in which the variations of φ on *gdp* and *CoL* are power law but not with unit elasticities. The dependence that is most consistent with the data is one in which consumption of light varies with *gdp* and *CoL* as

$$\varphi = \frac{0.0025 \cdot gdp^{1.08}}{CoL^{0.90}}, \qquad (3.2)$$

with a (logarithmic) adjusted regression coefficient of determination that is increased (very slightly) to $R^2 = 0.989$. The implication would be that the income elasticity (at constant price) of light consumption is slightly (8%) greater than unity, while the price elasticity (at constant income) of light consumption is slightly (10%) less than unity.

We note, however, that these deviations from non-unity elasticities of demand are small and, in our judgment, give insignificant improvement in consistency with the data compared to the likely errors in the data points themselves. As was discussed in in Section 2, each data point is associated with estimates of *three* quantities (φ, *gdp*, *CoL*). These estimates, made over diverse temporal, geographic, technological, and economic circumstances, are fraught with potential for error, particularly for the data points going back furthest in time, when the mixes of fuel and lamp technologies were undergoing radical changes.

Variation of β with *gdp*

A third possible variation might be one in which the proportionality factor β itself depends on per-capita gross domestic product. If we assume an exponential form to that dependence, then we find that $\beta = 0.0056 + 0.0109 \cdot e^{gdp/gdpo}$, where $gdpo$ = 6,300 \$/(per-yr). The "fit" to the data improves, but because there are more fitting parameters, the adjusted (logarithmic) regression coefficient of determination does not improve, but stays the same at $R^2 = 0.986$. We find no reason to invoke this more complex variation, but cannot rule out the notion that β, the fraction of *gdp* spent on lighting, decreases slightly with *gdp*.[13]

4 POSSIBLE DEPENDENCES OF CONSUMPTION OF LIGHT ON NON-INCOME AND NON-PRICE FACTORS

From Figure 2 it seems apparent that per-capita consumption of light has a *primary* dependence on per-capita gross domestic product and cost of light. At a higher level of detail, however, we can anticipate that per-capita consumption of light might also have secondary dependences on other factors.

In this Section, we discuss some of the most important of these possible secondary dependences on other factors. We do so even though it does not appear currently possible to quantify them, due both to the uncertainties associated with the estimates of the consumption of light and to the incompleteness of the data associated with the other factors. Our reasons are twofold. First, some of these possible secondary dependences seem a priori more likely to have been primary dependences, and it is interesting to speculate on why they do not seem to have been in the past. Second, some of these secondary dependences may become more important (perhaps even primary) in the future, and it is of interest to speculate in what ways this may happen.

We start by discussing the demand for raw lumens – the aspect of light that enables us to see and that is presumably the principal motivation for its purchase. Then, we discuss the demand for other features beyond lumens – safety, reliability, quality, mood enhancement, convenience, etc. – that together comprise the lighting "experience."

4.1 Desire for Lumens

First and foremost, of course, we use light to illuminate our environment so that we can see. Because the dynamic range of the human visual system is large but ultimately still limited, one might anticipate a saturation in how brightly we would like our environment to be illuminated, and consequently a saturation in our appetite for light. If we let φ_{sat} represent a hypothetical saturation value for per-capita consumption of light, then we might anticipate a dependence for per-capita consumption of light along the lines of[14]:

---

[13] We acknowledge Peter Dempster for prompting us to examine dependences of β on *gdp*.

[14] This particular function was chosen for simplicity and illustrative purposes only. Many other functions could be imagined with a similar variation. We deliberately exclude, however,

$$\varphi = \left(1 - e^{-\frac{\beta \cdot gdp / CoL}{\varphi_{sat}}}\right) \cdot \varphi_{sat} \,. \tag{4.1}$$

If so, consumption of light would increase linearly with *gdp/CoL* for small *gdp/CoL*, then saturate at φ_{sat} for large *gdp/CoL*.

At current levels of per-capita consumption of light, a central result of this paper is that there has been no evidence for such a saturation in the past. It is nevertheless an open question whether we will approach such a saturation in the future, or whether per-capita consumption of light will continue to scale linearly with *gdp/CoL*. To understand this question more quantitatively, we decompose per-capita consumption of light into the product of three factors: I_N, the average illuminance[15] (or light per unit area, in units of lm/m^2) that a person is surrounded by during his or her waking hours; $\tau_{on}/(\tau_{on}+\tau_{off})$, a dimensionless illumination duty factor that accounts for how many hours per year the area around a person is actually illuminated; and $a_N/(1+a_N\rho_N)$, the average unshared illuminated area (in units of m^2) that a person is surrounded by.[16] In other words,

$$\varphi = I_N \cdot \left(\frac{\tau_{on}}{\tau_{on} + \tau_{off}}\right) \cdot \left(\frac{a_N}{1 + a_N \rho_N}\right). \tag{4.2}$$

It is possible that, in developed countries, each of these factors is nearing saturation. As we discuss in the remainder of this section, however, plausible arguments can be made that, even in developed countries, the first and third factors may yet be 10x or more from saturation.

Illuminance: I_N

The first term in Equation 4.2 is I_N, the average illuminance (or light per unit area, in units of lm/m^2) that a person is surrounded by during his or her waking hours.

Illuminances have gradually increased over the centuries and, for modern indoor office or living spaces, are now on the order of $I_N \approx 500\ lm/m^2$. Such illuminances are, from a purely visual acuity point of view, clearly enough for most people for most tasks, and might be anticipated to be near a saturation level.

Furthermore, over the last decade many countries have introduced energy efficiency regulations that effectively constrain the degree to which interior light levels can be increased (IEA 2006, Chapter 5) by limiting the maximum permissible energy consumption, either within a building on a per-unit-floor-area basis, or for whole buildings of which lighting is a key piece. The scope of these requirements is increasingly being extended to apply to substantive interior refurbishments involving lighting systems, and not just to new construction.

---

sigmoidal (e.g., Gompertz or logistic) functions which would increase nonlinearly with *gdp/CoL* for small *gdp/CoL*.

[15] We use the symbol *I* rather than the usual symbol for illuminance, *E*, as in this paper *E* refers to energy. The subscript "*N*" refers to local illuminance from the perspective of an average person, as opposed to global illuminance from the perspective of an average area of land.

[16] Just as for the symbol *I*, for the symbols *a* and *ρ* the subscript "*N*" refers to local illuminated area and local population density from the perspective of an average person, as opposed to from the perspective of an average area of land.

Moreover, we do not always wish to be surrounded by illuminances suitable for tasks requiring high visual acuity. Ambient illuminances for enhancing particular moods or emotional states of mind can be much lower than 500 lm/m^2. And even when high visual acuity is desired, not all illuminance must be supplied artificially – artful use of sunlight can be an important supplement.

Nevertheless, arguments can be made that we have not yet approached saturation levels for illuminance. Considerable uncertainty exists regarding what constitutes optimal lighting -- despite over a century of research, recommended levels for comparable spaces still vary by a factor of up to 20. It is now recognized that optimal lighting conditions are contingent on numerous factors other than just average horizontal illuminance levels and include visual contrast and light distribution parameters.

And, even if one considers only horizontal illuminance, the evidence regarding the levels that humans would choose were affordability not a factor is far from complete. Humans might well choose higher illuminances than they do today, particularly to help mitigate losses in visual acuity in an aging world population, but perhaps also to function as neuropsychological modifiers (helping, e.g., to synchronize Circadian rhythms, to reduce seasonal affective disorder, and to enhance mood).

Indeed, the generally comfortable outdoor illuminance characteristic of an overcast or cloudy day is of the order 5,000 lm/m^2 – 10x higher than the 500 lm/m^2 mentioned above as typical of modern indoor office or living spaces. And the outdoor illuminance characteristic of a bright sunny day is of the order 30,000 lm/m^2, 60x higher than today's 500 lm/m^2. Though this latter illuminance is uncomfortable viewed from a close distance (requiring the use of sunglasses), it may well be desirable viewed from a farther distance (e.g., viewing scenery).

We conclude that it is possible that the developed countries are nearing a saturation point in average illuminance, but plausible arguments can be made that the saturation point may yet be a factor 10x or greater away.[17]

Illumination duty factor: $\tau_{on}/(\tau_{on}+\tau_{off})$

The second term in Equation 4.2 is $\tau_{on}/(\tau_{on}+\tau_{off})$, a dimensionless illumination duty factor that accounts for how many hours per year the area around a person is actually illuminated. The duty factor for a person who spends most of his or her time indoors, either at work or at home, is roughly the number of waking hours per year, or about $\tau_{on}/(\tau_{on}+\tau_{off}) \approx (16\ h/day)\cdot(365\ days/yr) = 5{,}840\ h/yr$.

This is the term that is most clearly nearing saturation. Most people need on the order of 8 h of sleep each day. And most people need darkness to sleep, and even apart from sleep, to rest their human Circadian rhythms (IEA 2006, Chapter 2).

---

[17] We note in passing that, whatever its saturation value, average illuminance might be expected to vary with geography. In countries further from the equator, illuminance from the sun is lower, and illuminance from artificial sources might be expected to increase to compensate. The limited data which is available appears not to support this, however. For example, Japan consumes significantly more light per capita than Northern Europe despite being nearer the equator and despite a similar standard of living. A proximate explanation for this, via Equation 3.1, is the greater penetration of higher luminous efficacy fluorescence lighting technology, hence lower cost of light, in Japan than in Northern Europe. But an ultimate explanation for the greater penetration of fluorescence technology itself may be a desire for higher artificial illuminance levels so as not to provide too stark a contrast with outdoor illuminance levels.

Unshared illuminated area: $a_N/(1+a_N\rho_N)$

The third term in Equation 4.2 is $a_N/(1+a_N\rho_N)$, the average unshared illuminated area (in units of m^2) that a person is surrounded by. This area is a_N, the average illuminated area (in units of m^2) that a person is surrounded by (regardless of how many other persons share that area), divided by $1+a_N\rho_N$, the number of persons that share that area. Here, ρ_N (in units of per/m^2) is the density of people within the illuminated area that a person is surrounded by. When ρ_N is small, light is not shared, and $a_N/(1+a_N\rho_N)$ approaches a_N; when ρ_N is large, light *is* shared, and $a_N/(1+a_N\rho_N)$ approaches $1/\rho_N$.

The order of magnitude of a_N can be estimated as follows. As indicated in Table 1, per-capita consumption of light in the U.S., representative of the high end in the world, was about $\varphi \approx 136$ Mlmh/(per-yr) in 2001. As discussed above, the average illuminance in modern indoor office or living spaces is roughly $I_N \approx 500$ lm/m^2, and the illumination duty factor is roughly $\tau_{on}/(\tau_{on}+\tau_{off}) \approx 5{,}840$ h/yr. In the absence of light sharing ($\rho_N \approx 0$), the illuminated area that the average person is surrounded by is thus, using Equation 4.2, roughly $a_N \approx \varphi(\tau_{on}+\tau_{off})/(I_N \cdot \tau_{on}) \approx 46\ m^2$. This area is plausible: larger than a typical one-person office area, but smaller than a typical one-person residential area.

Regarding how this term might evolve in the future, it is, just as for illuminance, possible that it be approaching a saturation level. Humans, often characterized as den animals, find comfort in enclosed areas, and to be surrounded by a $(46\ m^2/\pi)^{1/2} = 3.8$ m $\approx$ 12.5 ft radius of illuminated area is surely sufficient for most people most of the time. Indeed, an increasing trend in modern buildings is the use of motion sensors to turn lights on and off when a person enters or exits a space, with typical coverage areas comparable to 46 m^2. With new technologies such as solid-state lighting, such opportunities for sensor-based intelligent control will only increase in the future.

Moreover, humans are not only den animals, they are social animals, and tend to cluster in groups. Indeed, local population density[18] can, in a typical office building or urban public space, easily be on the order of $\rho_N \approx 0.1/m^2$. Hence, for $a_N \approx 46\ m^2$ and $\rho_N \approx 0.1/m^2$, we have $1/(1+a_N\rho_N) \approx 1/5$, and for these environments the unshared illuminated area is reduced by a factor 5.

However, den and social animals though they may be, humans also like space. Environments in which local population density is so high, and space is shared so heavily, are not necessarily the desired norm. Even the most densely populated city in the U.S. (New York) only has an average population density of about $0.009/m^2$ (Gibson 1998), implying that its average resident has plenty of less-dense areas to "escape" to. Moreover, as nations develop, the densities of their cities tend to decrease, as transportation costs decrease relative to income (Tobler 1969; Stephan and Tedrow 1977). Clearly, humans do not *prefer* to share space to an extreme.

Indeed, if the average size of residences is an indication of the preferred size of spaces that humans prefer, it is clear that these can be rather large. The average area per person in new single-family homes in the U.S. increased from 27 m^2 in 1950 to 45 m^2 in 1970 to 78 m^2 in 2000, and can easily be 2-5x larger still in "upper-end" homes. Hence, the saturation illuminated area surrounding each person could be more than 5-10x larger than the current 46 m^2 estimated above.

---

[18] By local population density, we mean that seen from the perspective of a person, which includes the tendency towards clustering. As seen from the perspective of the land, median world population density is much lower, on the order of $4\cdot10^{-6}/m^2$ (Cohen and Small 1998).

Moreover, even if the enclosed indoor areas in which we work and live might ultimately saturate, the unenclosed outdoor areas which we either occupy for short periods during the day or evening, or which are visible from enclosed indoor areas, may be less prone to saturation. Such unenclosed outdoor areas (e.g., streets, parks, and other recreation and public spaces) could all be rendered more useful if better illuminated in the evening hours (albeit at the cost of reducing the contrast of the night sky due to light pollution (Boyce 2003, pp. 504-512)). And there is a natural human tendency to gaze out (we value windows, not just because they are a portal for incoming light, but because of the view they afford (Boyce 2003, pp. 234, 256)) of faraway spaces, even if we do not directly occupy them.

We conclude that it is possible that the average unshared illuminated area is nearing a saturation point, but plausible arguments can be made that the saturation point may yet be a factor 10x or greater away.

4.2 Desire for Features Beyond Lumens

Although the primary demand for light is for raw lumens to illuminate our environment, there are many other features of light that are important to the consumer of light. Arguably, these features were just as important as cost in the historical transitions from one lighting technology to the next. It therefore comes somewhat as a surprise that these features do not seem to be reflected as significant breaks at various points in history, and it is interesting to speculate on whether such a break may occur at the current point in history, with the emergence of solid-state lighting technology.

On the one hand, the coming transition from incandescent, fluorescent and HID lighting to solid-state lighting will bring a significantly new set of performance attributes (Schubert and Kim 2005), including compactness, ruggedness, and the potential for real-time IP-addressable control of local illuminance, hue, saturation, color rendering, color temperature and perhaps even luminous efficacy itself. Their easy compatibility with video displays, either as back lights or as active pixels, even suggest the potential for integrated applications involving simultaneous illumination and information transfer. These new performance attributes at least have the *potential* to unleash new and unforeseen ways of consuming light, and to lead to greater-than-unity elasticities. They also, of course, have the potential to unleash new ways of consuming *less* light, through sensor-based control of light flux and directionality, and to lead to less-than-unity elasticities.

On the other hand, the transitions within chemical-fuel-based lighting (e.g., from candles to oil lamps to gas lamps), and the final transition from chemical-fuel-based to electricity-based lighting, also brimmed over with new performance attributes (Schivelbusch 1988), including increased cleanliness, faster turn-on and turn-off, greatly decreased concomitant room heating, and reduced fire hazard. These new performance attributes had similar tremendous potential, ultimately realized, to unleash new and unforeseen ways of consuming light. They also, of course, had a similar potential, ultimately not realized, to unleash new ways of consuming less light, through instant turn-on and turn-off, and through the increased ability to focus light sources with smaller spatial extent.

In other words, each transition from one technology to the next apparently brought with it similar potential for new ways to consume light, and these potentials are reflected in the historical constancy, at least back to 1700, of β, the fraction of *GDP* spent on lighting. It is difficult to guess whether the coming transition to solid-state lighting will be quantitatively similar, but plausible arguments can be made that it will be.

We mention here in particular one important feature of solid-state lighting: its potential to fill the visible spectrum with light of a precisely tailored mix of wavelengths and intensities. This potential would enable a tailoring of the rendering of the colors of natural objects in the environment, either to be as accurate as possible (as measured, e.g., by the color rendering index, or CRI), or to deliberately create subjective emotional responses (by mimicking, e.g., daylight, moonlight, candelight, etc.).

People might easily consume more of such high quality light, preferring it even at a higher price to light of lesser quality. And different use-sectors (residential, commercial, industrial, outdoor stationary, and vehicle) might have different preferences for light qualities, with the residential sector emphasizing subjective emotional response, and the commercial sector emphasizing raw human productivity. To some extent, such sector preferences are evident even with current lighting technology: the residential sector prefers higher CRI but also higher *CoL* incandescent over lower CRI but also lower *CoL* fluorescent and high-intensity-discharge technology, while the commercial sector prefers the opposite.

Indeed, given such sector preferences, it could well be that our datasets, which combine consumption of light across all sectors, reflect the cancelling of a slightly lower sensitivity to cost of light in the residential sector by a slightly higher sensitivity in the other sectors. Each sector could separately obey Equation (3.1), but with different values for β, the fraction of *gdp* spent on lighting. In fact, Equation (3.1) does appear to be separately consistent with a dataset (Waide 2007) of year 2000 residential light consumption for eleven international energy agency (IEA) nations, but with a fixed fraction β, of 0.0016. In other words, 0.16% of GDP is expended by the residential use-sector for light, roughly 0.0016/0.0072 ≈ 22% of that expended by all use-sectors for light.

5 IMPLICATIONS ON WORLD CONSUMPTION OF LIGHT AND ASSOCIATED ENERGY

In Section 3 we discussed how per-capita consumption of light depends on the ratio between per-capita gross domestic product and cost of light. In this Section, we discuss the implications of this dependence on world consumption of associated energy: for the past and present, and projected into the future.

5.1 Relation between Consumption of Light and Associated Energy

To start, note that, as discussed in Section 2, luminous efficacy connects two pairs of quantities. The first pair is per-capita consumption of light and per-capita consumption of associated energy, through Equation 2.2. The second pair is cost of light (*CoL*, in units of \$/Mlmh) and cost of associated energy (*CoE*, in units of \$/MW_eh), through Equation 2.4. Thus, we can rewrite Equation 3.1 as

$$\dot{e}_\varphi = \beta \cdot \frac{gdp}{(1+\kappa_\varphi)\cdot CoE}. \tag{5.1}$$

Likewise, we can replot the data of Figure 2 using the modified axes in Figure 4. Because Equation 5.1 is essentially equivalent to Equation 3.1, the data points in Figure 4 fall on a (logarithmic) unit-slope line just as did those in Figure 2. However, because luminous efficacy varies between time periods and between nations, the relative placements of the data points are not the same.

Also note that per-capita consumption of associated energy does not span as wide a dynamic range (2.6 orders of magnitude) as per-capita consumption of light (5.4 orders of magnitude). The reason is that, as discussed in Section 2, cost of energy does not span as wide a range as cost of light, due to the steady advancement, over the centuries, in luminous efficacy.[19]

5.2 World Consumption of Light and Associated Energy: Present

Up until now, we have dealt exclusively with per capita quantities for consumption of light and associated energy. It is also of interest to estimate *total* human consumption of light and associated energy, by multiplying by world population, *N*:

$$\Phi = N \cdot \varphi = \frac{\beta \cdot GDP}{CoL} \tag{5.2a}$$

$$\dot{E}_{\Phi} = N \cdot \dot{e}_{\varphi} = \frac{\beta \cdot GDP}{(1+\kappa_{\varphi}) \cdot CoE}. \tag{5.2b}$$

In particular, we can estimate, using Equations 5.2, world consumption of light and associated energy in 2005. As for all other estimates, we use estimates of *GDP* based on Maddison's work (GGDC 2007), EIA estimates for average price of energy, and light-consumption-weighted inverse luminous efficacies, all listed in Table 1. The result is an estimated world 2005 consumption of light and associated energy of 130 Plmh/yr and 2.7 $PW_e h$/yr, respectively. This represents about 16% of the world's total electrical energy generation of about 16.9 $PW_e h$/yr in 2005 (EIA 2007c). And, since 2.7 $PW_e h$/yr of electrical energy is equivalent to roughly 8.5 $PW_c h$/yr and 29.5 Quads/yr of primary chemical energy, this represents about 6.5% of the world's consumption of 457 Quads/yr of primary energy in 2005 (EIA 2007c).

Note that lighting therefore represents a much larger (6.5%) percentage of world energy consumption than of *GDP* (0.72%). This is an indication of the very high energy intensity of lighting relative to other goods and services, and hence the reasonableness of its classification, along with heat, power and transportation, as an "energy service."

5.3 World Consumption of Light and Associated Energy: Future

Also up until now, we have dealt exclusively with the *historical* variation of per-capita consumption of light. This variation represents a reasonable baseline assumption for the future variation of per-capita consumption of light. Whether history will be predictive of the future, however, cannot be known, and there are at least two ways in which the historical variation might be moderated in the future.

First, as discussed in Section 4, we may be approaching a saturation in the factors into which demand for light may be decomposed: the average illuminance that a person is surrounded by during his or her waking hours; the illumination duty factor that accounts for how many hours per year the area around a person is actually illuminated; and the average unshared illuminated area that a person is surrounded by.

[19] This steady advancement was first made quantitative in W.D. Nordhaus' classic study of the luminous efficacies of lighting technologies throughout history (Nordhaus 1997).

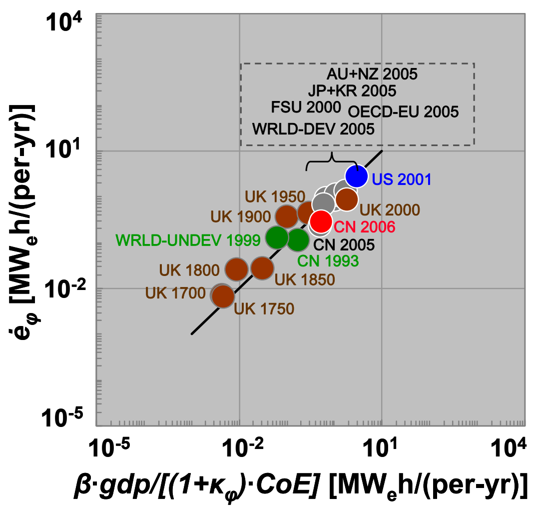

Figure 4: Data for per-capita consumption of energy associated with consumption of light, plotted against the product of a constant factor (β) and per capita gross domestic product (*gdp*), divided by a factor that accounts for operating and capital cost of light ($1+\kappa_\varphi$) and by cost of energy (*CoE*). Country abbreviations are given in the caption to Table 1. The diagonal black line has slope unity and zero offset.

As also discussed in that Section, however, plausible arguments can be made that, even in developed countries, the first and third factors may yet be 10x or more from saturation. Regarding the first factor: though 500 lm/m^2 is a common current office illuminance and is certainly adequate for most people for most tasks, the 5,000 lm/m^2 illuminance characteristic of an overcast or cloudy day is also generally quite comfortable. Regarding the third factor: though there may be a saturation in the enclosed indoor areas in which we work and live, the unenclosed outdoor areas which we either occupy for short periods during the day or evening, or which are visible from enclosed indoor areas, may be less prone to saturation.

Second, even we are not approaching a saturation in the intrinsic demand for light, guidelines and regulations aimed at efficient lighting system designs and light usage may nonetheless bring about such a saturation.

Non-legislated guidelines (standards and recommendations) on lighting and lighting system design have long been published by professional organizations in many industrialized and post-industrialized countries (Boyce 2003, Chapter 14). Examples are those of the Chartered Institution of Building Services Engineers in the United Kingdom (CIBSE 2002), and of the Illumination Engineering Society of North America (Rea 2000). Such guidelines cover recommended illuminance levels for spaces with various functional purposes and, though without formal legal status, could be a mechanism by which light usage might be curtailed or even reduced. Note, though, that the intent of these guidelines is not necessarily to reduce light usage, but to enhance the ways in which humans experience and use light. As discussed in Section 4, new ways in which humans experience and use light, particularly with the advent of new lighting technologies, could just as easily increase light usage.

Legislated regulations have more recently (over the last decade) been introduced in many countries. These regulations effectively constrain the degree to which interior light levels can be increased (IEA 2006, Chapter 5) by limiting the maximum permissible energy consumption, either within a building on a per-unit-floor-area basis, or for whole buildings of which lighting is a key piece. Moreover, the applicability of these regulations is increasingly being extended to substantive interior refurbishments rather than just new construction. Note, though, that new lighting technologies with higher luminous efficacies can enable increased light usage within a building while satisfying an older generation of energy-consumption regulations. In addition, new lighting technologies can enable new uses not associated with buildings and hence not covered by such regulations.

We conclude that arguments can be made in both directions: human demand and/or guidelines/regulations might cause consumption of light to saturate (or not), and the historical variation of per-capita consumption of light therefore might not (or might) continue into the future.

6 SUMMARY AND FUTURE DIRECTIONS

We have self-consistently analyzed data for per-capita consumption of artificial light, per-capita gross domestic product, and cost of light. The data span a wide range: 3 centuries (1700-2006), 6 continents (Africa, Asia, Australia, Europe, North America, South America), 5 types of fuel (tallow, whale oil, gas, petroleum, electricity), 5 overall families of lighting technologies (candles, oil lamps, gas lamps, electric incandescent bulbs, electric gas-discharge bulbs or tubes), 1.4 orders of magnitude in per-capita gross domestic product, 4.3 orders of magnitude in cost of light, and 5.4 orders of magnitude in per-capita consumption of light.

We find that the data are consistent with a simple expression in which per-capita consumption of artificial light varies linearly with the ratio between per-capita gross domestic product and cost of light. The expression is plausible, but we make no serious attempt to explain its origin. Instead, we consider its explanation (both for developing and developed countries) an interesting direction for future work, and at present consider it to be simply an empirical result, though one with important implications.

A first implication of this empirical result is that, extrapolated and aggregated to the world in 2005, 0.72% of world gross domestic product and 6.5% of world primary energy was expended to purchase 130 Plmh of artificial light at a primary energy cost of 457 Quads.

A second implication of this empirical result is that it represents the historically consistent baseline assumption for constructing future scenarios for consumption of light and associated energy. In other words, there is a massive *potential* for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light. Indeed, this empirical result has powerful implications on the rebound effect discussed in the Introduction, and an important direction for future work will be to understand quantitatively these implications.

Whether the historical trend does indeed play out into the future cannot, of course, be known. Just as plausible arguments can be made that per-capita consumption of light will, as can be made that it will not, continue its past variation with the ratio between per-capita gross domestic product and cost of light. In view of the significant percentage of world primary energy used for the consumption of light, an interesting direction for future work could also be to try to understand better the factors that underly the human demand for light.

Finally, we believe another possible direction for future work would be to extend this empirical work on the consumption of artificial light to the consumption of other energy services (e.g., transportation). It would be especially interesting to combine, as has been done here, historical time-series with contemporary cross-sectional data. In this way, one could gain a broader understanding of the rebound effect not just on the relatively short (months to years) time periods during which societal-use paradigms for an energy service are relatively static, but over the longer (decades to centuries) time periods during which radically new societal-use paradigms emerge, with associated radical changes in consumption of that service.

7 ACKNOWLEDGMENTS

We acknowledge helpful comments and encouragement from colleagues: Lorna Greening, Jinmin Li, Roger Fouquet, Arnie Baker, Ellen Stechel, Tom Drennen, Mike Coltrin, Harry Saunders, Jerry Simmons, George Craford.

Work at Sandia National Laboratories was supported by the Division of Material Sciences and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC04-94AL85000.

8 REFERENCES

Alcott, B. (2005). "Jevons' paradox." Ecological Economics 54: 9-21.

BES (2006). *Basic Research Needs for Solid-State Lighting*. U.S. Department of Energy, Office of Basic Energy Sciences.

Bowers, B. (1998). Lengthening the day: a history of lighting technology. Oxford: Oxford University Press.

Boyce, P.B. (2003). Human Factors in Lighting, 2nd Ed. Taylor & Francis.

Brookes, L. (1990). "The greenhouse-effect - the fallacies in the energy efficiency solution." Energy Policy 18: 199-201.

CIBSE (2002). Code for Lighting. Butterworth-Heinemann (Chartered Institution of Building Services Engineers).

Cohen, J.E. and Small, C. (1998). "Hypsographic Demography: the Distribution of Human Population by Altitude." Proceedings of the National Academy of Sciences of the United States of America 95: 14009-14.

Denton, T. (2004). Automobile Electrical and Electronic Systems. Elsevier.

DOE (2007). *2007 Buildings Energy Data Book* . U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

EERE (2008). *Solid-State Lighting Multi-Year Program Plan FY'09-FY'14*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

EIA (1998). *Changes in Energy Intensity in the Manufacturing Sector 1985-1994*. Energy Information Administration .

________ (2006). *Annual Energy Review 2006 (http://www.eia.doe.gov/emeu/aer/pdf/aer.pdf)*. Energy Information Administration.

________ (2007a). *Annual Energy Outlook 2007 with Projections to 2030 (http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2007).pdf)*. Energy Information Administration.

________ (2007b). *Electricity Prices for Selected Countries, Recent Years (http://www.eia.doe.gov/emeu/international/electricityprice.html)*. Energy Information Administration .

________ (2007c). *International Energy Outlook 2007 (http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2007).pdf)*. Energy Information Administration.

Fouquet, R. and Pearson, P.J.G. (2006). "Seven Centuries of Energy Services: the Price and Use of Light in the United Kingdom (1300-2000)." Energy Journal 27: 139-77.

GGDC (2007). *Total Economy Database (http://www.ggdc.net/)* . Groningen Growth and Development Centre.

Gibson, C. (1998). *Population of the 100 Largest Cities and Other Urban Places in the United States: 1790 to 1990*. U.S. Bureau of the Census Population Division Working

Paper No. 27.

Greening, L.A., Greene, D.L., and Difiglio, C. (2000). "Energy Efficiency and Consumption - the Rebound Effect - a Survey." Energy Policy 28: 389-401.

GTZ (2007). *International Fuel Prices*. Federal Ministry for Economic Cooperation and Development (Germany).

Gydesen, A. and Maimann, D. (1991). "Life cycle analyses of integral compact fluorescent lamps versus incandescent lamps." Proceedings of Right Light 1: Policy and Planning Issues (Stockholm, Sweden).

IEA (2006). *Light's Labour's Lost: Policies for Energy-efficient Lighting*. International Energy Agency.

Jevons, W.S. (1906). The Coal Question: An Inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. Macmillan and Co.

Kendall, M. and Scholand, M. (2001). *Energy Savings Potential of Solid State Lighting in General Lighting Applications*. U.S. Department of Energy, Office of Building Technology, State and Community Programs.

Khazzoom, J.D. (1980). "Economic implications of mandated efficiency in standards for household appliances." Energy Journal 1: 21-40.

Krames, M.R., Shchekin, O.B., Mueller-Mach, R., Mueller, G.O., Zhou, L., Harbers, G., and Craford, M.G. (2007). "Status and future of high-power light-emitting diodes for solid-state lighting." Journal of Display Technology 3: 160-75.

Li, Jinmin (2007a). "Unpublished estimate of consumption of light and associated energy in China 2006."

Li, Jinmin (2007b). "Unpublished estimates of the cost of electricity in China 1993-2006."

Maddison, A. (2007). "World Population, GDP and Per Capita GDP, 1-2003 AD."

Mills, E. (2005). "Environment - the Specter of Fuel-Based Lighting." Science 308: 1263-64.

Mills, E. (2002). "Global Lighting Energy Savings Potential." Light and Engineering 10: 5-10.

Min, G.F., Mills, E., and Zhang, Q. (1997). "Energy Efficient Lighting in China - Problems and Prospects." Energy Policy 25: 77-83.

MW (2007). "Measuring Worth: A Service for Calculating Relative Worth over Time." [http://www.measuringworth.com/index.html]. Accessed 10 April 2007.

Navigant (2002). *U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

________ (2003). *Energy Savings Potential of Light Emitting Diodes in Niche Lighting Applications*. Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Navigant (2006). *Energy Savings Potential of Solid State Lighting in General Illumination Applications*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program.

Nordhaus, W.D. (1997.) "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," in The Economics of New Goods., Timothy F. Breshnahan and Robert J. Gordon, Ed., 29-70. Chicago: The University of Chicago Press.

Phillips, J.M., Coltrin, M.E., Crawford, M.H., Fischer, A.J., Krames, M.R., Mueller-Mach, R., Mueller, G.O., Ohno, Y., Rohwer, L.E.S., Simmons, J.A., and Tsao, J.Y. (2007). "Research challenges to ultra-efficient inorganic solid-state lighting." Laser and Photonics Reviews 1: 307-33.

Rea, M.S. (2000). The IESNA Lighting Handbook. New York: Illumination Engineering Society of North America.

Saunders, H.D. (1992). "The Khazzoom-Brookes postulate and neoclassical growth." The Energy Journal 13: 131-48.

Schivelbusch, W. (1988). Disenchanted Night: The Industrialization of Light in the Nineteenth Century. The University of California Press.

Schubert, E.F. and Kim, J.K. (2005). "Solid-state light sources getting smart." Science 308: 1274-78.

Schubert, E.F., Kim, J.K., Luo, H., and Xi, J.Q. (2006). "Solid-state lighting-a benevolent technology." Reports on Progress in Physics 69: 3069-99.

Shur, M.S. and Zukauskas, A. (2005). "Solid-state lighting: toward superior illumination." Proceedings of the IEEE 93: 1691-703.

Stephan, G.E. and Tedrow, L.M. (1977). "A Theory of Time-Minimization: The Relationship between Urban Area and Population." The Pacific Sociological Review 20: 105-12.

Tobler, W.R. (1969). "Satellite confirmation of Settlement Size Coefficients." Area 1: 31-34.

Tsao, J.Y. (2002). *Light Emitting Diodes (LEDs) for General Illumination Update 2002: Full Edition*. Optoelectronics Industry Development Association.

Tsao, J.Y. (2004). "Solid-state lighting: lamps, chips, and materials for tomorrow." IEEE Circuits and Devices Magazine 20: 28-37.

UKERC (2007). *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UK Energy Research Centre.

Waide, Paul (2007). "Unpublished estimates of year 2000 residential consumption of light in eleven IEA nations."

WB (2007). *World Bank List of Economies*. World Bank.

XE (2007). "XE Interactive Currency Table." [http://www.xe.com/ict/]. Accessed 10 April 2007.