Sustainable Lighting: Nano-enabled Lighting and the Rebound Effect

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Artificial Lighting

• Accounts for 19% of electricity consumed in US

• Since 1950, cost reduced 3-fold, but per capita consumption increased 2-fold

• Policy trends favor conversion to more efficient forms of light

• Productivity gains (safety, light surroundings, new jobs and products)

• Undergoing a “nano-enabled” evolution to SSL (~2 times efficiency of CFL, lasts ~ 3 times longer than CFL, promises much greater functionality)
Some predicted nano-enabled efficiency improvements

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>Energy Savings (quads/year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building technology</td>
<td>10</td>
<td>GTF 2007</td>
</tr>
<tr>
<td>Lightweight materials in transportation</td>
<td>6.2</td>
<td>EIA, 2005</td>
</tr>
<tr>
<td>Solid State Lighting</td>
<td>3.5</td>
<td>DOE, 2013</td>
</tr>
<tr>
<td>Self-optimizing motor systems (sensors)</td>
<td>1.2</td>
<td>Brown, 2005</td>
</tr>
<tr>
<td>Catalyst efficiency, coatings, membrane technology</td>
<td>0.70</td>
<td>LANL 2006</td>
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<tr>
<td>Transmission line conductance</td>
<td>0.2</td>
<td>Brown, 2005</td>
</tr>
</tbody>
</table>
Projections for Energy Consumption for Lighting Through 2027 (US)

Ownership Cost =

\[ \frac{\text{Capital Cost} + (\text{lifetime lumens} \times (\text{Cost/lumen}))}{\text{lifetime lumens}} \]

(Nordhaus, 1996; Bardsley Consulting et.al, 2011)
Figure 1. Consumption of Energy Services in the United Kingdom, Index 1900=100, 1700-2000
“Jevon’s Paradox”, named after the 19th century British economist Stanley Jevons, who first described it:

An increase in the technological efficiency of a process that uses a resource tends to increase the rate of consumption of that resource in excess of simple engineering calculations.

How come? Efficiency gains look very much to consumers like price reductions, thereby stimulating more consumption than before,

i.e. real reductions in price for the same level of utility, or increases in utility at constant or in some cases higher prices.
Rebound Lexicon

• $R = 1 + \eta^E_{\tau_E}$

• $\eta^E_{\tau_E} = \frac{\tau_E}{E} \frac{\partial E}{\partial \tau_E}$ (elasticity of energy use changes with respect to a technology gain)

• $R > 1$ Backfire
• $R = 1$ Full Rebound
• $0 < R < 1$ Partial Rebound
• $R = 0$ Zero Rebound
• $R < 0$ Super-conservation
Artificial Lighting Displays the “Rebound” Effect

Over 300 years, 6 continents, and 5 technologies, and over data spanning several orders of magnitude, lighting has historically been observed to exhibit ~100% rebound


Question: Will this continue with the transition to SSL?
Integrative Approach

Social: Ask consumers what their preferences are
Economic: Translate social preferences into economic demands
Technological: Project economic demands forward to environmental life cycle impacts
Policy: Explore policy options (LCA speak = improvement analysis)
Life Cycle Integrated Within the Product Chain

Focus on just this part of the product chain
Methods—Survey/Agent-based Modeling

Survey: If it is cheaper will you use more light?
*Answer: ~50% affirmative (depends on how much)*

Survey: Rank order the factors that affect your decision (price, quality of light, failure rate, productivity, etc.)
*Result: Decision “typologies”*

Agent-Based Modeling:
Models the behavior of agents in space and time
Agents—decision-making entities
Bottom-up (from micro to macro)
Most useful for illustrating emergent properties of complex systems
Decision is Expressed Through Agent Utility Subject to a Probable Course of Action

- \( U_i = \prod_{i=1}^{n} F_i^{w_i} \) (Cobb-Douglas)
  where \( F \) is a factor in a decision, \( w \) is the weighting

- \( P_T = 1 = \sum_{i=1}^{L} P_i = \frac{e^{U_i}}{e^{U_i} + e^{U_{i+1}} + e^{U_{i+2}} + \ldots + e^{U_L}} \)

  \( P \) is the probability of a course of action,
  \( L \) is the number of possible actions
Agent Based Simulation Cellular Automata
Projections for Energy Consumption for Lighting Through 2027 (US)

Assumes $R = 0$

A Few Scenarios

Scenario 1
- % better: 50
- Productivity > 1
- Subsidy: 0

Scenario 2
- % better: 0
- Productivity < 1
- Subsidy: 0

Scenario 3
- % better: 50
- Productivity > 1
- Subsidy: 25

Scenario 4
- % better: 50
- Productivity > 1
- Subsidy: 50

Scenario 5
- % better: 25
- Productivity > 1
- Subsidy: 25

“Better” if:
- Ownership cost goes down
- Efficiency is greater
- “Greenness” is greater
- Neighbors are adopters
Outcomes are non-obvious

Average Household Energy Consumption for Transition to LED Lighting

<table>
<thead>
<tr>
<th>Year</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
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<tbody>
<tr>
<td>2010</td>
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<tr>
<td>2015</td>
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<td>2020</td>
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<td>2030</td>
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These results point to three general directions for sustainable product-chain research:

(1) **Stronger interdisciplinary effort** to understand the complex factors emergent across the complete product chain (including human behavior) that contribute to resource consumption, environmental degradation, and human health risk, while recognizing benefits to society,

(2) Expansion of “green” design for the environment, and organizational eco-design principles beyond their traditional focus on increasing efficiency and lowering pollutant loads per unit product to include economic and behavioral factors, and

(3) Investigation of the impacts of more highly integrated policies, based on the sustainability paradigm, that are able to meet human needs while capturing economic excesses and decoupling environmental degradation that have their roots in over-consumption.
What Do People Think About Artificial Light?

• A commodity that has improved the general well-being of society in numerous ways through empowering humans to control the use, productivity, and safety of spaces on a near-continuous basis

• A cultural symbol of enlightenment, modernity, urbanity, and security, with its symbolism as important as the achievements it has enabled