Eco Design Notes

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Energy and Carbon Benefits of Pico-powered Lighting

This Eco Design Note reviews current research on the life cycle analysis of pico-powered lighting products and the reduction in climate warming emissions that occur when consumers switch from fuel-based to electronic lighting. The results show substantial energy savings and significant reductions in climate warming emissions associated with solar-powered lighting products.

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Introduction

How much energy is required to manufacture and use a pico-powered lighting product, and how does this compare to the kerosene lamps that these products replace? Do solar products actually reduce climate-warming emissions by displacing kerosene consumption or are the reductions cancelled out by the manufacturing emissions of these new technologies? These questions are at the heart of scientific and policy debates about the energy and climate benefits of solar powered products.

Studies conducted by Lighting Global researchers and others in the scientific energy community conclude that **there are substantial energy and carbon benefits associated with pico-powered lighting products**. Energy payback periods are short and overall greenhouse gas and aerosol emissions are reduced when fuel-based light sources are replaced with rechargeable electronic lights. These environmental benefits can now be added to any discussion of the many social, economic, and health benefits also associated with this class of products. Replacing kerosene lights with modern alternatives thus represents a local solution that has significant positive global implications.

The information presented in this Eco Design Note is a summary of findings from several recent technical papers concerned with energy consumption and climate warming emissions associated with pico-powered solar lighting products and kerosene-fueled lamps. This complex topic is global in scope and interested readers are strongly encouraged to seek additional supporting information from the source papers listed in the References section below.

Embodied energy of kerosene and solar lighting[1]

The energy needed to produce a consumer product can be estimated based on the components and processes used in its production. This is a type of "life-cycle-analysis" and includes energy used for the extraction of raw materials, manufacturing, assembly, and transportation. Adding any energy consumed during use of the product (e.g., from recharging using grid-based electricity) leads to a total energy consumption figure over the projected lifetime of that product.

Fuel-based lamps require a small amount of energy to manufacture, but they then consume a larger amount of energy through burning fuel during daily use. A solar-powered electric light is just the opposite - a larger energy investment is required to manufacture the lamp, but no fuel energy is consumed in use because it generates its own power from the sun (Figure 1).

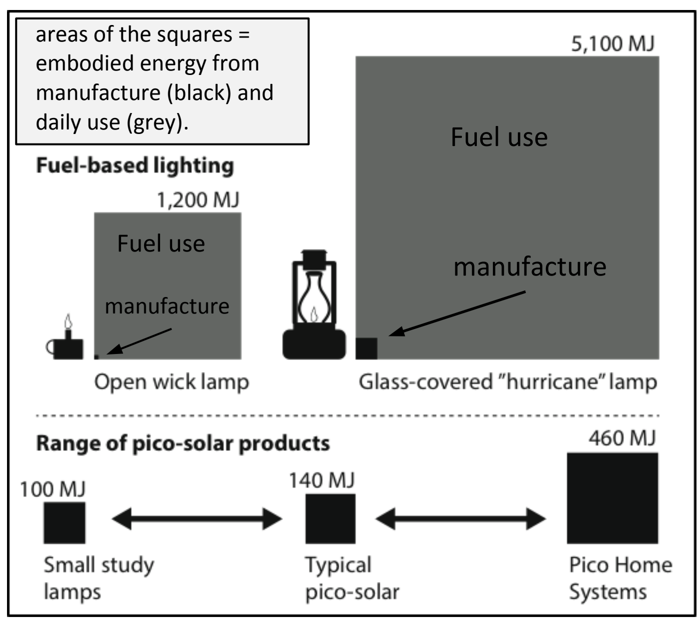

Figure 1. Life-cycle embodied and use-phase energy of pico-solar and kerosene lighting products. All squares drawn to scale. Data taken from Alstone, et. al., 2014.

Tracking Progress from Technology Transitions

The goal of energy life-cycle-analysis is to understand whether technology transitions (in this case, from fuel-based to modern lighting) make sense in global energy terms. Two related metrics can be used to make the assessment: energy payback and energy return on investment (EROI).

A key part of this analysis requires knowledge of the displacement rate of kerosene as consumers substitute electronic light sources for fuel-based lamps. Some consumers will stop using fuel-based lamps altogether, while others might simply add a solar light and keep using their fuel-based sources as well. A third case will see a reduction, but not elimination, of kerosene use. Research collected for this Note suggests a 50%-100% reduction in kerosene used for lighting when a consumer adopts an electronic alternative, depending on the context.

Another important factor is the useful lifetime of the pico-powered lighting product. The longer the product lasts, the more kerosene is offset. The analysis shown in Figure 1 compares the expected lifetime embodied and use-phase energy in several different *solar lighting products* to *simple wick lamps* and *hurricane lanterns* that use kerosene.

Product lifetime and energy payback

At some point a solar product will reach energy payback as the energy consumed in the manufacture and transportation of the device equals the energy offset by a reduction in kerosene consumption. The results show that the energy used to manufacture and use a pico-powered lighting product is small compared to the energy used by a kerosene lamp. **The simple energy payback from adopting pico solar is fast, with parity reached in only 1-3 months for products included in the study.**

Energy Return on Investment (EROI)

EROI builds on energy payback and is the ratio of energy saved to energy invested in new technology over the full lifetime. An EROI of 1 represents a product that saves exactly as much energy as the embodied energy it consumes. EROI over 1 means that, on net, less energy was used globally. The EROI ratios for pico-solar can be quite high, on the order of 15-45 (depending on the kerosene replacement scenario) for products with a 2-year lifespan, meaning that these products pay for themselves many times over from an energy perspective (Figure 2). Products that have useful lifetimes exceeding two years will have even higher EROI ratios. This underscores the considerable energy benefits associated with longer lifetime products.

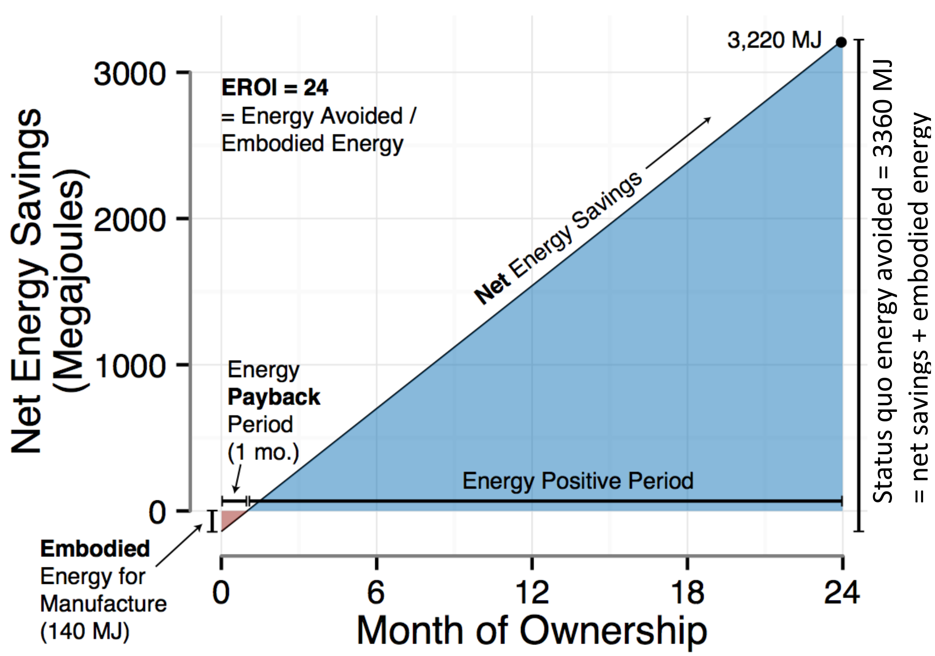

Figure 2: Illustration of a prototypical use-case for replacing a kerosene lamp with pico solar. This illustrates a 2-year period of use but in practice the real lifetime for pico solar can be longer. Initially 140 MJ are "invested" as embodied energy in month 0, followed by energy savings in every month after from avoided fuel use. The total energy avoided over the period can be compared to the embodied energy for EROI. The net savings are the net effect on global fossil fuel consumption. The energy payback period in this case is 1 month, meaning the status quo use pattern that was avoided was 140 MJ per month.

Climate change and fuel-based lighting[2]

From a simple energy perspective, the lower net energy embodied in pico-solar lighting products results in a net reduction of CO_2 emissions when these products replace kerosene-fueled lamps. The United Nations Environment Programme (UNEP) estimates that replacing all fuel-based lamps with modern energy efficient lighting would save 90 million tonnes of CO_2 annually. This situation is complex, of course, and emissions other than CO_2 occur during the manufacture and use of these lighting technologies. One type of emission in particular has been under-represented in the discussion concerning climate change and lighting. This emission is black carbon (BC).

Black Carbon (BC)[3,4]

Black carbon is a fine particulate released by the inefficient combustion of kerosene, including notably from kerosene wick lamps. BC particles that escape the household (where the particles are associated with indoor air quality issues) remain airborne for only a few days, but during this time they are highly efficient absorbers of solar heat energy and thus have a fast and local atmospheric warming effect. Preventing these emissions can therefore very quickly remove this source of climate forcing, suggesting that pico-powered lighting solutions can play a meaningful role in climate warming mitigation efforts beyond what is suggested by previous studies and the positive EROI described above.

Photo credit: Ajay Pillarisetti

Figure 3. A simple wick lamp emits light, heat, CO_2, and soot in the form of black carbon.[5]

Light from kerosene requires inefficiency

When burning fuel for cooking, the best way to get the most heat is to burn the fuel as completely as possible. This means a blue flame where most of the fuel's hydrocarbon chains are combined with oxygen (oxidized), releasing CO_2, water, and heat energy as byproducts of the reaction. The blue light of the flame comes from the plasma gases in the combustion as electrons transition from one quantum state to another.

Cooking with high efficiency combustion makes good use of the energy in the fuel but it does not generate much usable light. To get 'white' visible light with a broad spectrum from red to blue, the combustion must be constrained so that solid carbon particulate matter is released. These soot particles literally glow as they are carried upward in convective hot air currents, and it is this incandescent light that we see as the yellow flame in a simple wick lamp, hurricane lantern, or candle. Some of these particles will continue to oxidize (and be converted to CO_2 and water) and some will cool rapidly and be emitted as BC. Simple wick lamps in particular emit a large percentage of spent fuel as BC.

Simple wick lamps emit 7-9% of the kerosene they burn as BC and are the worst offenders among kerosene-fueled lighting products. Due to better burner design, wick geometries, and protected flame columns, hurricane lamps burn their fuel more completely and emit less BC as a fraction of spent fuel (~1%). The particulate emissions, however, are still primarily heat-absorbing black carbon particles.

Kerosene consumption and BC emission

Attempts to calculate worldwide BC emissions from kerosene lighting rely on estimates of global kerosene fuel consumption. Country specific consumption rates and household survey data result in estimates ranging from 4 to 25 billion liters of kerosene consumed annually for lighting. In India, 25% of residential kerosene is used for lighting. In Africa the number is slightly higher at 29%. Approximately half of this consumption is used to fuel simple wick lamps.

An estimated 270,000 tonnes of BC are emitted annually as a result of these lighting-based emissions. This represents 20-25% of global diesel emissions or 10-15% of emissions from solid fuels used for residential cooking.

Black carbon and radiative climate forcing

Radiative forcing, a common measure of climate impact, describes changes in the Earth's net energy balance as solar radiation is absorbed or reflected in the atmosphere. Carbon dioxide (CO_2) is one of many gases that affect this balance. Solid aerosol particulates are another category, and among these black carbon stands out as one of the few that absorbs solar radiation and has a *positive* (warming) forcing effect on the climate. Other aerosols co-emitted from BC sources, including a significant portion of the particulate emissions from solid fuel cooking and diesel engines, are organic carbon compounds (OC) that reflect sunlight and therefore have a *negative* (cooling) climate forcing effect.

The aerosols emitted by simple wick lamps and hurricane lanterns are composed primarily of warming BC particles and have a very low fraction of cooling OC particles. These BC particles are typically emitted indoors and then carried outside by air currents (an estimated 90% escape outdoors), where they stay airborne for a few days before they settle to the ground. During this time they absorb sunlight and heat the atmosphere at a much higher rate than CO_2. One gram of BC warms the atmosphere several hundred times more in its short lifetime than one gram of CO_2 warms the atmosphere in 100 years.

The local nature of BC emissions also means that BC climate forcing is regionally concentrated. Warming will be higher where the emissions are produced and this can be displayed as watts/m^2 of direct radiative forcing (Figure 4).

Black carbon warming and CO_2 equivalencies

Conservative estimates conclude that the annual greenhouse warming contribution of BC emissions from simple wick lamps and hurricane lanterns is equivalent to 240 million tonnes of CO_2. To clarify what this means, the warming effect from fuel-based lighting is equal to the warming effect of 4.5% of annual United States CO_2 emissions or 12% of annual CO_2 emissions from India. *This is much larger than previous estimates that consider CO_2 emissions alone* and indicates the substantial contribution that fuel-based lighting makes to human induced climate warming.

Reducing lighting-based BC emissions by 50% (as suggested by estimates for kerosene displacement from electronic lighting) would be equivalent to a 2.5-gigaton reduction in CO_2 over the next 20 years and could contribute significantly to climate change mitigation.

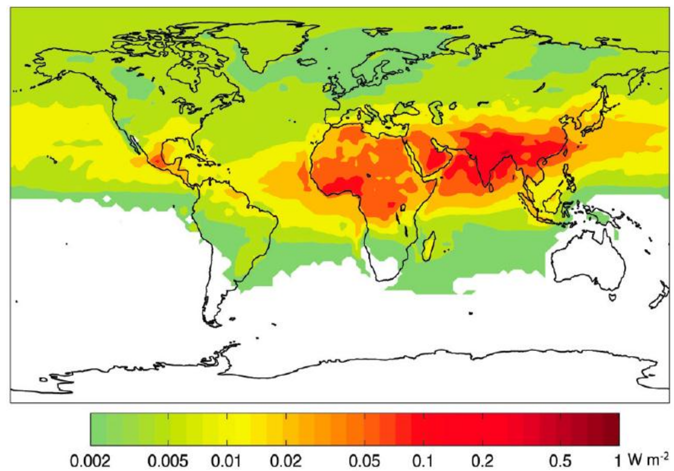

Fig 4. Direct BC radiative forcing from residential kerosene lighting (W/m2). [5]

Summary

The analysis presented here shows that pico-powered lighting products require less energy to manufacture and operate than the kersosene-fueled lamps that they have the potential to replace. The energy input is shifted from the daily use of the lamp (burnt kerosene) to the manufacturing processes involved in the electronics industry. On an absolute scale, these energy inputs are at least an order of magnitude smaller for solar products and can occur in controlled manufacturing environments where human health and environmental considerations are both possible and more likely to occur.

This shift in energy use would also have a meaningful climate benefit that goes beyond the typical savings in conventional greenhouse gases from energy conservation alone. Conservative estimates of black carbon aerosol emissions from simple wick lamps are shown to be much higher than previously understood, high enough to represent a small but significant fraction of total global emissions related to climate warming. Replacing kerosene-fueled lighting with electronic alternatives would almost instantly remove this source of climate forcing – equal in scale to nearly 5% of US emissions or 12% of Indian emissions.

Perhaps the most compelling aspect of the energy and carbon story for pico-powered lighting is the shared set of benefits that consumers experience when adopting electronic lights to replace their existing fuel-based predecessors. Many social, economic, and health benefits are experienced on the local level, and now it is increasingly apparent that these coexist with energy and climate benefits on a regional and global scale. This synergy can and should serve as inspiration to those working to deliver pico-powered lighting products to the market, place them into off-grid communities, and secure a spot for this technology in the toolset of global energy access solutions.

References

1) Alstone, P., P. Lai, E. Mills, and A. Jacobson. (2014), High Life Cycle Efficacy Explains Fast Energy Payback for Improved Off-Grid Lighting Systems. *Journal of Industrial Ecology*. doi: 10.1111/jiec.12117

2) United Nations Environment Programme (UNEP) – Global Environment Facility (GEF) en.lighten initiative. http://www.enlighten-initiative.org/ResourcesTools/CountryLightingAssessments.aspx

3) Jacobson, A., N. Lam, T. Bond, N. Hultman. (2013) Black Carbon and Kerosene Lighting: An Opportunity for Rapid Action on Climate Change and Clean Energy for Development. Global Views Series #41, The Brookings Institution, April 2013. http://www.brookings.edu/research/papers/2013/04/climate-change-clean-energy-development-hultman

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5) Reproduced with permission from Lam, et. al., 2012. Copyright 2012 American Chemical Society.