Doubling the Global Pace of Progress for Energy Efficiency

Applying the "Moore's Law" of Energy Efficiency to Technology Innovation for Off-grid Applications

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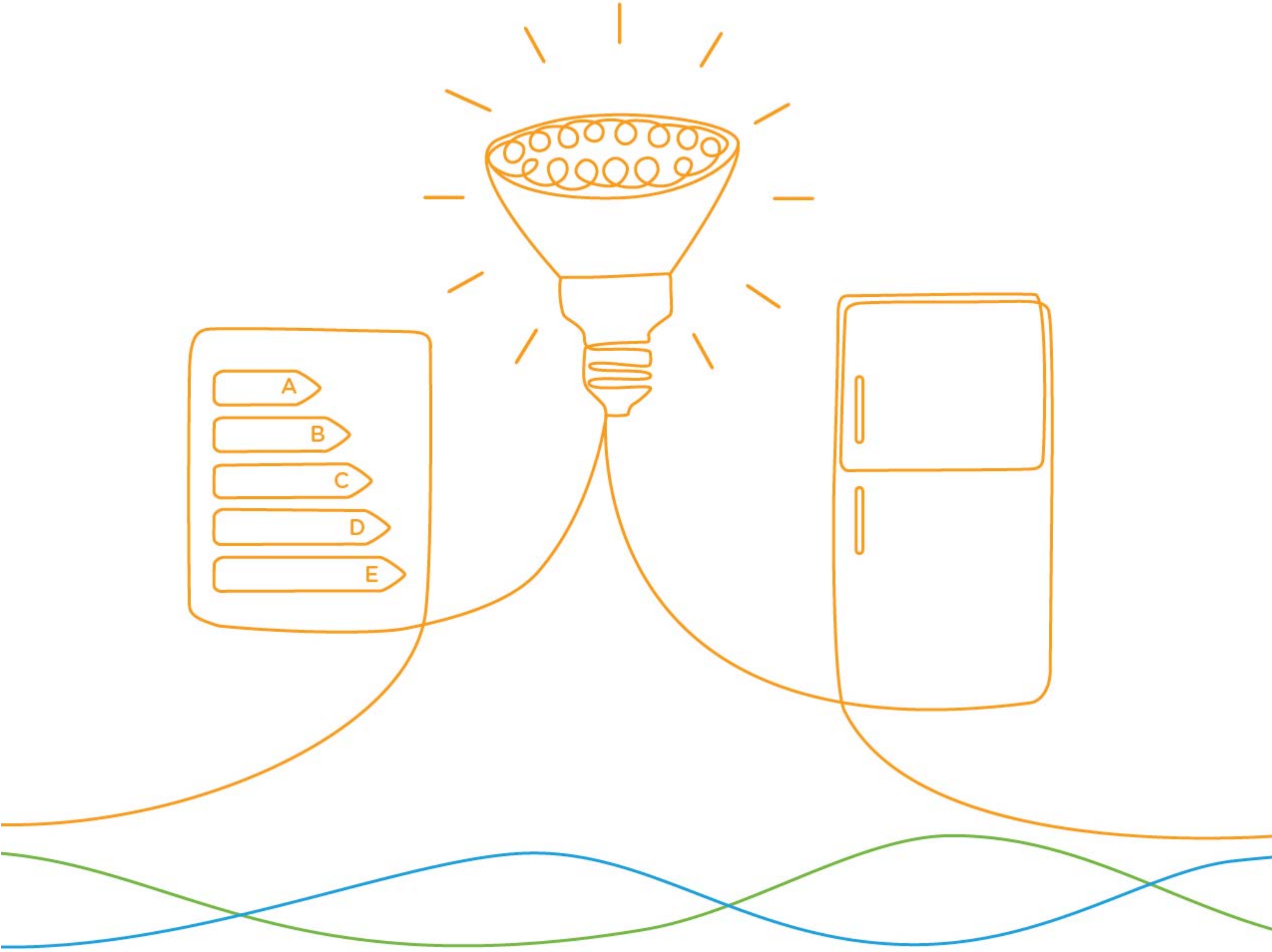

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Executive Summary

How might the pace of progress in energy efficiency improvement be accelerated to help provide increased modern electricity access for the global poor?

The answer to this question lies in an understanding of the forces that drive rates of technological progress. This memorandum argues that long-term technology planning and roadmaps, which set expectations of progress and define a set of technical performance and cost milestones over a period of one to several decades, can be forceful drivers of technological improvement and change. The development of technology roadmaps has been used to drive technology progress in computer technologies, solid-state lighting, solar photovoltaic modules, and batteries. This memorandum asserts that applying a similar process to a wide range of other energy end-use technologies—with a specific focus on off-grid applications—can also be used to drive technology progress in energy efficiency, potentially doubling the global pace of progress of energy efficiency improvement. This memorandum argues that such accelerated progress in energy efficiency will be critical to providing affordable access to modern energy services for the more than one billion people who currently lack access to electricity.

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Empirical descriptions and forecasts of technology improvement trends, notably Moore's Law,[1] tend to show only a weak dependence on purely economic drivers. In some sense, rates of technology improvement are "exogenous" to the evolution of the economy: while technological improvement strongly influences the evolution of relative prices[2] in the economy, prices in the economy sometimes only weakly influence the long-term rate of technological progress.[3] In other words, technology performance improvement rates may be malleable under the influence of changing expectations for technological progress or changing policy influences.[4]

To support the creation of efficiency technology roadmaps similar to those applied to computers, solid-state lighting, and other technologies, and to aid in setting long-term technology expectations for the efficiency of a variety of appliances and equipment, this memorandum presents a Moore's Law of Energy Efficiency (MLEE). MLEE provides an estimate of technology learning rates as a function of trends in the cost of energy versus trends in the cost of energy efficient products. This memorandum argues that a key implication of MLEE is that significant investment in the development of super-efficient appliances for off-grid applications should lead to a major acceleration of energy efficiency improvement rates globally.

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[1] Moore's Law refers to a statement made by Gordon Moore in the 1970's, asserting that the density of transistors in an Integrated Circuit (IC) chip produced by the computer industry would double every 18 months. For more detail on Moore's law and similar knowledge industry technology trends, see for example: (Schaller, 1997) and (Chang, Lee & Jung, 2012).

[2] See: (Baumol, 1967)

[3] See: (Van Buskirk, et.al., 2014).

[4] See: (Stewart, 2010).

This claim is predicated on analysis providing a quantitative estimate of essential efficiency improvement milestones for achieving the Sustainable Energy for All (SE4All)[5] goal of ensuring "universal access to modern energy services" in the most cost-effective manner within the next decade. This analysis finds that meeting these milestones will require the complementary SE4All goal of "doubling the global rate of improvement in energy efficiency" to also be satisfied or exceeded. Experience with other technology innovation processes indicates that the pursuit of such accelerated and ambitious energy efficiency-improvement goals will need to be guided by long-term technology planning and roadmaps, specifically focused on the efficiency needs of off-grid appliances and equipment. These roadmaps will require policymakers, technologists, financial institutions, manufacturers, and suppliers to set expectations for efficiency milestones in different off-grid products, and then to create robust R&D programs to achieve these targets.

Significant investment in the development of super-efficient appliances for off-grid applications should lead to a major acceleration of energy efficiency improvement rates globally.

For energy efficient lighting, the historical pace of progress of energy efficiency has approximately doubled with the creation of robust technology R&D programs and long-term technology development roadmaps for solid state lighting. Undertaking similar initiatives for other energy-using technologies—including air conditioning, heating, ventilation, refrigeration, pumping, and electronics—can also help drive the innovation cycle faster for these products. Such initiatives, with focus on the more stringent efficiency targets demanded by off-grid applications, have the potential to double the global rate of energy efficiency improvement, and in so doing help accelerate and expand the benefits of technology innovation for billions of new consumers and a wide range of energy-using products. Such initiatives would also help transform the market for highly-efficient appliances and equipment overall, to the benefit of communities in both off-grid and grid-connected settings

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[5] See: http://www.se4all.org/our-vision/our-objectives/energy-efficiency/, Accessed January 4, 2015.

Introduction: What drives technology improvement rates?

What drives trends in technology improvement? Is it economic incentives? Research and development investments? Engineering ingenuity? Or are inventors and engineers the analogue of technological mountain climbers, who make improvements in technology simply "because it is there!"?

While economic incentives undoubtedly play some role in motivating technological improvement, they do not appear to be the key determinant of the pace of change. Moore's Law is perhaps the best known example of a technological progress trend that defies a purely economic explanation. While there are clear economic incentives for technology improvement in information technologies, there does not appear any fundamental need or economic reason for transistor density or computing power to double every 12 to 18 months (Mack, 2011).

In the specific case of Moore's Law, there is a clear mechanism by which a theory became a largely self-fulfilling prophesy. The creator of the law, Gordon Moore, was also a co-founder of Intel, a company that played a pivotal role in realizing Moore's Law through its research and product development of central processing unit chips. Gordon Moore held key positions at Intel for 30 years, spending 12 of those years as CEO. The chips that his company made fueled the computer revolution that occurred between the 1970's and 1990's, and he was directly involved in managing this development.

As a historical example, Moore's Law indicates that it may be possible to change technology improvement rates through a combination of planning, foresight, research, and development. Given this precedent, one question that necessarily arises is whether such a process can be replicated to accelerate progress in other areas, such as energy efficiency technologies.

This memorandum discusses the possibility of facilitating modern energy access for the 1.3 billion people who currently lack access to electricity by accelerating energy efficiency technology improvement rates. Specifically, this memo argues that acceleration of energy efficiency technology improvement rates can be obtained by focusing the economics of energy efficiency technologies on off-grid applications. Off-grid applications represent a new, potentially fast-growing emerging market, encompassing more than one billion new electricity customers, including developing-country households and businesses utilizing off-grid electricity systems and micro-grids.

Relative energy/appliance price changes drive optimum efficiency

When customers have a very high unit cost of electricity, the efficiency that is cost-optimum for appliances used by these customers is correspondingly higher, and the corresponding energy consumption of the appliance much lower, than for comparable appliances in markets with low electricity costs. When electricity prices are high, the increased cost of a higher-efficiency appliance can be justified by the higher financial savings per unit energy savings, as demonstrated below.

Figure 1 illustrates the life-cycle cost (LCC) for a small refrigerator as a function of its energy use. The LCC is the sum of the purchase price of the appliance and the present value of the operating cost. In other words, it is the total cost of ownership of the appliance excluding maintenance costs and assuming that the discount rate reflects the cost of capital.[6] The example calculation in Figure 1 has the following three inputs: (1) the baseline price at a reference efficiency, which is assumed to be

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[6] See appendix A for details.

$300 for a refrigerator that consumes 400 kWh/year; (2) the elasticity of equipment price[7] with respect to energy use, assumed to be -0.6;[8] and (3) a lifetime (or investment period) of five years. The inputs to this calculation will change for different products in different markets, but the general impact of price on energy use will be qualitatively the same.

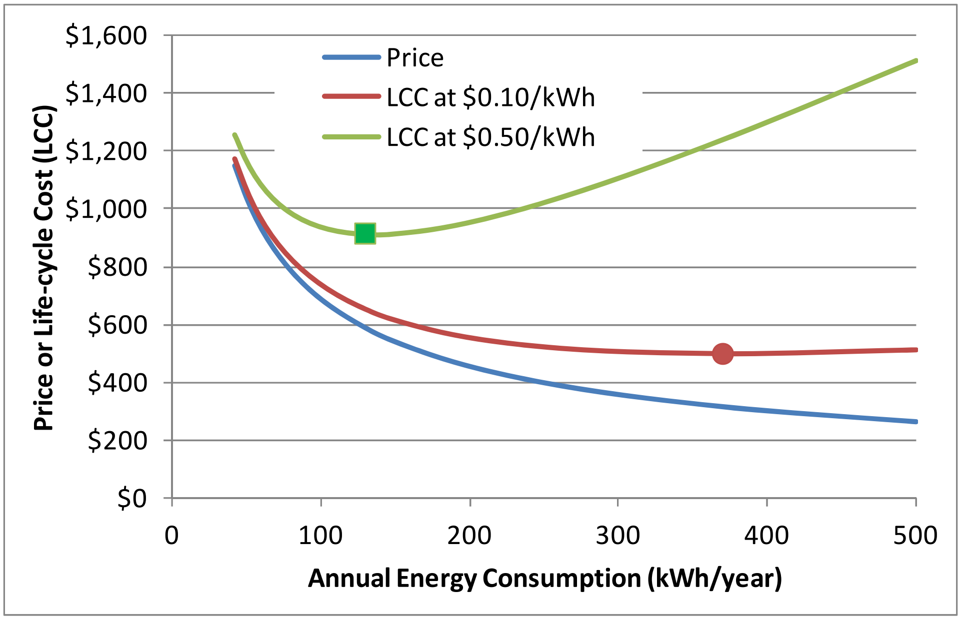

Figure 1: Life-cycle cost curves of a refrigerator for different prices of electricity, assuming an economic payback period of five years. The blue curve is the price of the refrigerator assuming an elasticity of price with respect to energy consumption of -0.6 and a refrigerator price of $300 for an energy consumption of 400 kWh/year.

Figure 1 illustrates the minimum LCC energy use (i.e. the energy use that minimizes the life-cycle cost of the appliance) for two cases: a low-electricity-price case of $0.10/kWh and a high-electricity-price case of $0.50/kWh. The refrigerator price vs. efficiency curve is the same in both calculations, but the minimum-cost energy use is very different. At $0.10/kWh, the minimum-cost energy use is 370 kWh/year, but at a price of $0.50/kWh, the minimum-LCC refrigerator uses 130 kWh/year, i.e. 65% less than the low-electricity-price case.

Appendix A provides detailed mathematical calculations of appliance LCC minimization as a function of elasticity, electricity price, and discount rate.

Electricity prices for households in developed countries—often subsidized—range between $0.10/kWh and $0.36/kWh.[9] However, for small scale off-grid solar applications, electricity costs are typically

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[7] Elasticity of price with respect to energy use is the quantity that indicates what percentage change in price occurs when there is a percentage change in energy use. When the elasticity is -0.6, this says that when energy use increases by 1%, price decreases 0.6%. Conversely when the elasticity is -0.6, then when energy use decreases 10%, the price increases by approximately 6%. This elasticity is approximately the elasticity seen in the European refrigerator market between 1995 and 2005.

[8] See the supplemental information of (Van Buskirk, et.al. 2014) for detailed calculations of the elasticity of price with respect to efficiency for refrigerators in the European market.

[9] According to IEA Statistic's Electricity Information 2012, Table 3.9, prices for household electricity range from $0.099 to $0.360 in purchasing power parity dollars in 2011.

substantially higher, e.g. between \$0.30/kWh and \$1/kWh.[10] This is because off-grid and micro-grid electricity tends to be supplied from either diesel generators or solar photovoltaic (PV) equipment (Brown, et.al., 2012), and generating such electricity is typically more expensive, in part because many applications are in developing countries where the cost of capital for electricity supply is high. Appliances and products that consume expensive, off-grid electricity would therefore benefit much more from greater energy efficiency than appliances and equipment utilizing much cheaper grid-connected, utility-based electricity.

Moore's Law of Energy Efficiency

If we consider a case where the relative prices of electricity and appliances change over time, then the relationship illustrated in Figure 1 can be described by a Moore's Law of Energy Efficiency (MLEE). MLEE says that the economically optimum (i.e. minimum consumer cost) annual energy consumption for an appliance (AEC_{MinLCC}) decreases with decreasing appliance cost and increasing electricity cost. MLEE also provides that the optimum rate of decrease of energy use for an appliance follows a power law relationship, where the optimum energy use scales with the ratio of the appliance price to the energy price. The exponent of this scaling law depends on a technical economic parameter that is called the elasticity of equipment price with respect to efficiency (ε):

$$AEC_{MinLCC}(t) = \left(\frac{P_0(t)}{P_E(t)}\right)^{\frac{1}{1+\varepsilon}} \left(\frac{\varepsilon \cdot AEC_0^{\varepsilon}}{PWF}\right)^{\frac{1}{1+\varepsilon}} \tag{1}$$

This equation provides a description of how the economically-optimum energy use of an appliance depends on trends in the price of the appliance, trends in electricity price, and changes in the present worth factor (*PWF*) for energy savings investments. The equation notes that, as the price of a baseline[11] appliance drops relative to the price of electricity, so does the energy use of the minimum-cost appliance. Similarly, if appliances are more long lasting (such as with efficient LED lights in comparison to less efficient incandescent lights), and if consumers can finance their purchase over a longer period of time, then the economically-optimum energy use is smaller because the *PWF*[12] for consumer investment increases.

Appendix A provides a detailed derivation and description of this equation.

As we describe below, there is a market of more than one billion customers who are going to obtain access to electricity generated by off-grid or micro-grid infrastructure, and the unit electricity prices faced by these customers is likely to be relatively high. Relevant historical examples suggest that the

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[10] See Appendix B.

[11] A baseline appliance is a reference appliance at a particular quality and energy efficiency. When one talks about appliance price trends, one has to pick a reference point. Typically government statistical agencies measure price trends in terms of a price index that references the mix of products available in the market at a particular time. See for example: http://www.bls.gov/opub/hom/pdf/homch17.pdf for additional technical detail on how the price index for different items may be calculated.

[12] For appliances, the present worth factor is a function of both discount (interest) rate, i, and the appliance lifetime, L. If an initial incremental investment in efficiency is equal to the present worth factor times the operating cost savings, $\Delta P = PWF(i,L) * \Delta OC$, then the efficiency investment just pays for itself (i.e. the incremental net present value impact of the efficiency investment is zero). In other words, it is the payback period for a break-even incremental efficiency investment when the annual operating cost savings is constant in time.

potential market growth for functional products in off-grid markets could be very rapid.[13] However, if these off-grid customers are to minimize the LCC of their appliances and take full advantage of their access to modern energy services, they are going to need appliances that are much more energy efficient than is typical in developed-country markets, where the price of electricity is generally much lower.

Off-grid and microgrid electricity is $0.30/kWh to $1/kWh

Most off-grid and micro-grid electricity is supplied from either diesel generators or solar PV. The following two subsections provide cost estimates for each type of electricity, demonstrating that the current cost of off-grid electricity is approximately in the range of $0.30/kWh to $1/kWh.

High oil prices mean ~$0.30-0.50/kWh electricity for diesel generation

Hundreds of millions of electricity customers around the world rely on diesel generators for either their main electricity supply or for back-up power. Figure 2 illustrates the history of oil prices over the past 25 years.[14] Diesel electricity generation costs are determined mostly by the cost of fuel, with a fuel requirement of 0.28 to 0.4 liter/kWh. Diesel fuel costs are volatile, and correlate over time with the cost of oil, as illustrated in Figure 3.[15] As Figure 2 clearly shows, from 1987 to 2004, the price of petroleum was relatively cheap at approximately $20/barrel. Over the last decade, however, the price of oil has seen a five-fold increase. Indications are that, while prices may periodically drop below $50/barrel, the cost of oil is likely to remain substantially higher than was the case in the 1990’s, at least for some time.

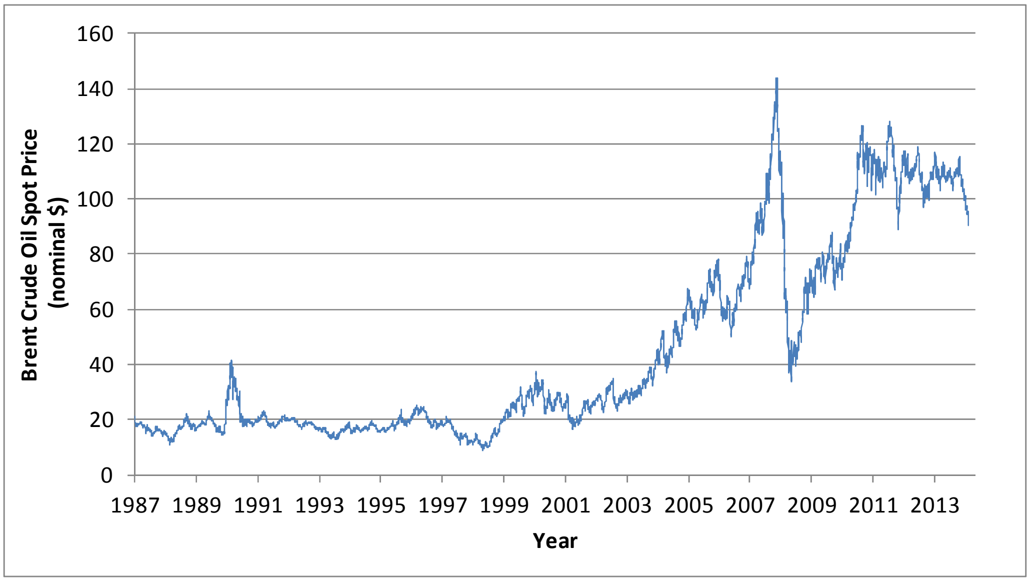

Figure 2: Price of a barrel of oil. Recently there has been a drop in price to ~$50/barrel (not shown). Oil price volatility and prices that are elevated relative to the 1990’s (i.e. 2-5 times the 1990’s average price) may persist for some time.

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[13] See Appendix C for information on historical rates of off-grid market growth in Africa.

[14] “Petroleum and Other Liquids, Spot Prices,” Energy Information Administration, http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm, Accessed October, 14, 2014

[15] Source for diesel prices is http://data.worldbank.org/indicator/EP.PMP.DESL.CD, Accessed May 19, 2014

In Sub-Saharan Africa, where oil costs range from $50 to $100 per barrel, the fuel cost of diesel generation is approximately $0.25-$0.41/kWh. Given an average fuel consumption rate of 0.34 liter/kWh for small-scale diesel electricity generation, a price of $0.75-$1.20/liter for the fuel, and a factor of 25% to approximate the cost of maintenance and amortization, the approximate cost of diesel-generated off-grid electricity in Sub-Saharan Africa is $0.30-$0.50/kWh. Additional retail electricity service costs for distribution, metering, billing, and customer service further increase the cost of retail diesel-generated electricity for end-use consumers.

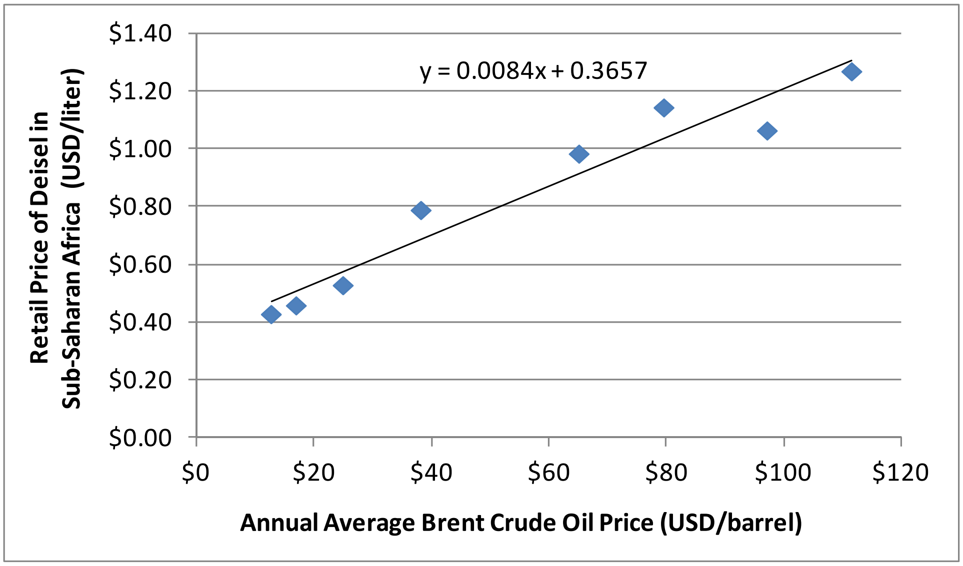

Figure 3: Correlations between the average annual Brent crude oil price per barrel and the average retail diesel price in developing Sub-Saharan Africa.

Small-scale solar electricity costs ~$1/kWh

In general terms, the cost of small-scale solar electricity depends on the price of solar equipment, the efficiency with which the electricity is utilized, the investment period of solar equipment, and how much of the electricity that is generated must be stored in an electrochemical battery. More specifically, estimates of the cost of solar electricity for off-grid applications depend on PV panel sizing, battery sizing, battery chemistry, cost of electronics, design lifetime of the system, cost of case and housing, assumed solar radiation levels, electricity supply reliability, and the relative size of demand during the day vs. the night. Other factors that affect the per-kWh cost of solar electricity are those that affect the sales and financing terms, including distribution mark-up and payment terms (i.e. upfront vs. monthly payments) and discount rate (i.e. the interest rate that reflects the time value of money).

Appendix B provides data on the price of complete solar PV electricity supply systems as a function of daily system electricity output, and then uses this data to provide a current estimate of the per-kWh of solar PV electricity.

Assuming a 5-year payback time on investments in PV infrastructure, then the cost of solar PV electricity supply for a small to medium sized system is approximately $1/kWh. This cost can be higher for very small systems, or when the payback period for the off-grid solar investment is less than 5-years.

How fast must efficiency improve for off-grid customers?

Opportunities for certain energy efficient technologies, especially lighting, to contribute to sustainable development have been identified previously (e.g., Dutt, 1994; Dutt and Mills: 1994). Now that off-grid generation by photovoltaics is more widely available, this opportunity for energy efficient technologies can be expanded to include a broader range of appliances and equipment.

However, if the world sets an ambitious target for facilitating energy access—such as enabling a substantial percentage of the rural developing world to, by 2025, obtain access to electricity with efficient appliances that are minimum-cost for their needs—then historical rates of energy efficiency improvement for many appliances and energy-using equipment need to be accelerated. If a billion or more customers in the developing world are going to have access to cost-optimized appliances utilizing off-grid solar electricity, they will need appliances that are much more efficient than are typically available today. Without an acceleration in energy efficiency improvement, products that can provide economically-optimum energy efficiency for off-grid customers will not be available in time.
Taking the case of the refrigerator cost curves presented in Figure 1, at electricity prices of $0.50/kWh, an economically-optimum refrigerator must be more than 2.8 times as efficient as a base-case refrigerator that is optimum at $0.10/kWh. If we represent a 2.8 efficiency improvement as an annually compounded efficiency improvement rate over ten years, the annual rate of efficiency improvement would be 10.8%/year, or approximately triple the roughly 3%/year refrigerator efficiency improvement rate seen in Europe from 2004 to 2011.[16]

Best practice EE technology roadmap: U.S. DOE LED roadmap

The U.S. Department of Energy's (DOE) solid-state lighting research and technology roadmap activities are perhaps one of the most successful energy efficiency technology road-mapping and research processes of the past decade.[17,18] Figure 4 illustrates the rapid increase in luminous efficacy that is expected from the development of LED technologies over the coming decade. Whereas for other lighting technologies, it took perhaps 40 years to double the efficiency of the technology – an annual improvement rate of 2%/year – it is expected that LEDs may achieve efficacies of approximately 200 lumens/watt by 2020. Comparing this to the maximum efficacies of approximately 120 lumens/watt seen in 2010, this represents a compound improvement rate of more than 5%/year.

This rapid acceleration in the efficiency improvement of lighting technologies has not occurred in a vacuum, but rather has been strongly driven by a systematic process of collaborative planning by government and industry that has resulted in the creation of a detailed technology development vision.[19] This vision specifies both price and performance expectations for technological improvement over a period of more than ten years into the future. The vision also lays out the market, different categories of product types, and expectations for improvement in the efficiency of different product components.

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[16] http://mappingandbenchmarking.iea-4e.org/shared_files/595/download

[17] http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html

[18] DOE has also created technology roadmaps for photovoltaic systems, HVAC, appliances, windows, low GWP refrigerants, water heating (source: http://www.nrel.gov/docs/fy13osti/59155.pdf, http://energy.gov/eere/buildings/listings/technology-roadmaps).

[19] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf

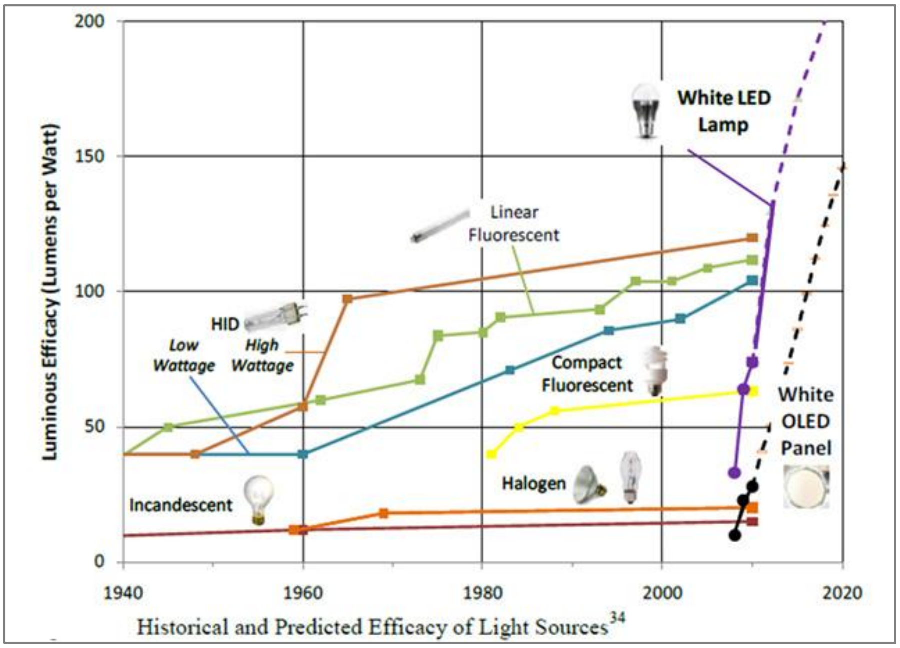

Figure 4: Acceleration of luminous efficacy represented by development of light emitting diode (LED) technologies.

Creating efficiency technology roadmaps to address off-grid applications

Even though energy efficiency technology roadmaps for off-grid appliances may not garner the scale of resources and technical detail of DOE's LED road-mapping process,[20] it may be fairly straight-forward to start a series of technology roadmap discussions. Given that off-grid solar PV systems[21] represent a substantial market niche, a discussion can begin amongst policymakers, technologists, financial institutions, manufacturers, and suppliers of off-grid solar systems, focused on which appliance designs and technologies are likely to be most effective for off-grid solar applications.

Technology roadmaps for efficient off-grid applications could begin with a market assessment of the demand for appliances and equipment in the off-grid market, proceed to an assessment of the future cost of electricity for such applications over the next decade, and conclude with an assessment of the degree to which efficiency and equipment prices need to improve in order to most economically address the expected demand for off-grid energy services. Once the various end-uses are appropriately identified (e.g. refrigeration, information and communications technologies, pumping and water treatment), a process for identifying ambitious, yet reasonable technology, cost, and performance trends can help guide the development of those technologies that can best address the needs of the off-grid market.

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[20] In the near- to medium-term, the total global market for off-grid appliances is likely to be substantially smaller than the global lighting market, which has been the target of the DOE solid-state lighting program.

[21] The IEA has published a technology roadmap for solar PV that provides long-term cost and performance targets for solar technologies (source: http://www.iea.org/publications/freepublications/publication/pv_roadmap.pdf). The IEA also has a fairly comprehensive technology roadmap for energy storage (source: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf).

Summary and Conclusion

This memorandum presents an argument—based on the previous experience of computer technology and solid-state lighting—that rates of technology innovation may be somewhat independent of economic drivers, as well as somewhat malleable. The memorandum also argues that current appliance and equipment energy efficiency is not currently cost-optimized for the needs of approximately 1.3 billion potential customers who are currently disconnected from electricity grids.

For customers disconnected from electricity grids, the relevant electricity cost estimates are those from diesel generators and solar PV systems with battery. We note that these costs are likely to be in the range of $0.50/kWh to $1/kWh, compared to a range of $0.10/kWh to $0.35/kWh for grid-connected customers in developed countries. This cost differential implies that the efficiency-level required for the off-grid customer base needs to be substantially higher than what is common in product markets optimized for grid-connected customers.

Solid-state lighting is currently undergoing rapid rates of technological improvement. This is in part due to a robust research investment and technology road-mapping program administered by the U.S. Department of Energy, which has been active for more than a decade. One key to the success of this program was the establishment of a long-term vision of technology development that could articulate how solid-state lighting would become the lighting of the future, even though for many years solid-state lighting did not substantially out-perform competing technologies in the market. This process for achieving rapid, yet long-term technological improvement does not have to be limited to lighting.

For technologies other than lighting, a virtuous cycle of innovation leading to adoption, which then leads to further innovation, is possible. A renewed, joint initiative by policymakers, solar off-grid equipment and service suppliers, appliance and equipment manufacturers and financial institutions concerned with poverty reduction can accelerate technology innovation through a long-term technology road-mapping process. In this memorandum we show that there is a large base of potential customers in global markets that need much higher levels of product efficiency than is currently provided by on-grid appliances. Furthermore, the vast majority of energy end-uses—including air conditioning, heating, ventilation, refrigeration, pumping, electronics, etc.—could benefit from a faster innovation cycle for energy efficient technology, and large increases in efficiency are theoretically possible given that current technologies are operating far from their ideal thermodynamic limit (Farese, Gelman & Hendron, 2012). Such a road-mapping initiative has the potential to double the rate of energy efficiency improvement, and in so doing may help accelerate and expand the benefits of technology innovation for billions of new consumers and a wide range of energy-using products beyond lighting. Such an initiative could also transform the market for highly-efficient appliances and equipment overall, to the benefit of communities in both off-grid and grid-connected settings.

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Appendix A: Calculation of Minimum LCC Annual Energy Consumption

The cost of an appliance includes not only its purchase price, but also its operating cost. If efficiently-operating markets are minimizing the total ownership cost of an appliance, then we need to understand the structure of these costs.

The analysis below is adapted from the recent paper "A retrospective investigation of energy efficiency standards: policies may have accelerated long-term declines in appliance costs," specifically equations (S20) to (S26) in the supplemental information (Van Buskirk, et.al., 2014).

The total consumer impact is often calculated using the energy-related life-cycle cost (LCC), which is the sum of the purchase price P_A and a discounted sum of energy-related operating costs $OC(t)$. Assuming a yearly compound interest rate i, the present value of an expense n years in the future (in the year y_n) is discounted to $OC(y_n)/(1+i)^n$.[22] The sum of price and operating costs throughout the appliance lifetime is then:

$$LCC = P_A + \sum_{n=1}^{L} \frac{OC(y_n)}{(1+i)^n} \tag{A1}$$

where L is the lifetime of the appliance, i is the interest or discount rate, and y_n are a discrete number of L years over which the appliance is in operation.

Now we decompose the operating cost into cost components. The operating cost of an appliance can be written in terms of the price of energy, $P_E(y)$, which can vary from year to year, and annual unit energy consumption (AEC), which we assume for simplicity is the same from year to year for a given appliance. This means that the equation for LCC can be rewritten as:

$$LCC = P_A + AEC \sum_{n=1}^{L} \frac{P_E(y_n)}{(1+i)^n} \tag{A2}$$

This equation can be further simplified if we define the lifetime-weighted average electricity price for the appliance as:

$$\overline{P_E} = \frac{\sum_{n=1}^{L} P_E(y_n)/(1+i)^n}{\sum_{n=1}^{L} 1/(1+i)^n} \tag{A3}$$

and if we define the present worth factor (PWF) as the ratio of the present value of operating costs to annual operating cost discounted at interest rate i over a lifetime of L years. The PWF is the function of interest or discount rate that converts annual costs over a lifetime L into a present value:

$$PWF = \sum_{n=1}^{L} \frac{1}{(1+i)^n} = \frac{1-(1+i)^{-L}}{i} \tag{A4}$$

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[22] If operating cost is measured in inflation-adjusted dollars, the inflation-adjusted interest rate is used. We assume operating costs and interest are charged at the end of the year in which they occur.

Using these newly defined quantities of average energy price and present worth factor allows us to rewrite the formula for LCC in a relatively simple form:

$$LCC = P_A + PWF \cdot \overline{P_E} \cdot AEC = P_A + PVOC \tag{A5}$$

This formula says that the total cost of an energy-using appliance is the sum of purchase price and the present value of operating costs (*PVOC*), where *PVOC* is equal to the annual energy use times the price of energy times the economic payback period.

At any particular point in time, the price of an appliance may be a function of annual energy consumption, *AEC*. Typically price observed in the market for products with similar features but greater efficiency may be higher at any particular point in time, i.e. price increases with decreasing *AEC*. We can approximate this price vs. *AEC* relationship with a power law equation with a negative exponent:

$$P_A = P_0 \cdot \left(\frac{AEC}{AEC_0} \right)^{-\varepsilon} \tag{A6}$$

where P_0 is a reference price at which the annual energy use of the appliance is equal to a reference energy use AEC_0. In general, both P_0 and ε may change over time.

Note that when we approximate the relationship between price and annual energy consumption by a power law, then the change in price with respect to annual energy use is given by the following simple equation:

$$\frac{dP_A}{dAEC} = -\varepsilon \cdot P_0 \frac{AEC^{-(1+\varepsilon)}}{AEC_0^{-\varepsilon}} = \frac{-\varepsilon \cdot P_A}{AEC} \tag{A7}$$

where $-\varepsilon$ is often referred to as the elasticity of price with respect to annual energy use.

Specifically, we can use this equation to calculate the incremental cost of conserved energy (*CCE*)[23] as a function of elasticity, price, annual energy consumption, and payback period:

$$\begin{aligned} CCE &= -\frac{1}{PWF} \cdot \frac{dP_A}{dAEC} = \frac{\varepsilon \cdot P_A}{PWF \cdot AEC} \\ &= \frac{\varepsilon \cdot P_o \cdot AEC_0^{\varepsilon}}{PWF \cdot AEC^{1+\varepsilon}} \end{aligned} \tag{A8}$$

Note that the minimum life-cycle cost condition is met when *CCE* is equal to the price of electricity. This occurs when the following relationship is satisfied:

$$\frac{dPVOC}{dAEC} = PWF \cdot \overline{P_E} = -\frac{dP_A}{dAEC} = \frac{\varepsilon \cdot P_A}{AEC} \tag{A9}$$

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[23] Meier, Alan Kevin. "Supply curves of conserved energy." (1982).

Using this relationship, we can calculate the mathematical equation that the annual energy consumption needs to satisfy when it is minimizing the LCC for the consumer:

$$AEC_{MinLCC} = \frac{P_A}{P_E} \cdot \frac{\varepsilon}{PWF} \tag{A10}$$

In order to estimate the specific time dependence of product energy consumption under cost-minimizing conditions, we can calculate the value of AEC_{MinLCC} even more explicitly in terms of P_0 and AEC_0:

$$AEC_{MinLCC}(t) = \left(\frac{P_0(t)}{P_E(t)}\right)^{\frac{1}{1+\varepsilon}} \left(\frac{\varepsilon \cdot AEC_0^{\varepsilon}}{PWF}\right)^{\frac{1}{1+\varepsilon}} \tag{A11}$$

where in this version, we have noted which inputs into the equation may vary over time. This last equation is useful when we know how the price of an appliance (P_0) at fixed energy use or efficiency is changing over time. This equation embodies our “Moore’s Law of Energy Efficiency” (MLEE).

Note that this equation for MLEE provides an estimate of how the economically optimum energy use will vary as a function of the time-varying parameters that characterize the appliance price and energy price. If at fixed energy use or efficiency, the price of an appliance relative to the price of electricity is decreasing at *X*% per year, and if the elasticity □ is approximately constant over time, then the minimum LCC energy use should decrease at a rate of *Y*% per year where $Y = X/(1+\varepsilon)$.

In our particular case of developing technology improvements that can benefit off-grid customers, we envision an application of equation (A11) where the price of electricity trends from the current on-grid cost (i.e. \$0.10 to \$0.15/kWh) to the off-grid cost of electricity (i.e. \$0.50/kWh to \$1/kWh). In this case, as the price of electricity trends to favor off-grid customers, equation (A11) tells us how the annual energy consumption of the appliance needs to trend to be able to produce appliances that are cost-minimum for those off-grid customers.

Appendix B: Off-grid Solar Electricity Cost Estimate

In this section we review some publicly-accessible data for the cost of solar electric equipment and efficient appliances, and provide estimates of the marginal cost curve for off-grid solar electricity.

Estimates of the cost of solar electricity for off-grid applications will depend on several important factors. Some factors regard elements of the engineering design of the system: panel sizing, battery sizing, battery chemistry, cost of electronics, design lifetime of the system, cost of case and housing, assumed solar radiation levels, electricity supply reliability, and the relative size of demand during the day vs. the night. Other factors that affect the per-kWh cost of solar electricity are those that affect the sales and financing terms, including distribution mark-up and payment terms (i.e. upfront vs. monthly payments) and discount rate (i.e. the interest rate that reflects the time value of money).

Each of the cost factors can vary rather dramatically between off-grid solar electricity systems, depending on the particular application and socio-economic context under consideration.

For this particular analysis, we consider the case of small-scale residential applications for low-income households in developing countries. A particularly good, recent review of the market is provided by the Consultative Group to Assist the Poor (CGAP, http://www.cgap.org/).[24] The financing terms provided by this market ranges from 18 months to five years, and solar systems range from devices with less than 1 Watt peak (Wp) to solar home systems with 200 Wp. Because smaller systems tend to have relatively larger fixed costs, the per-kWh cost of electricity from off-grid solar systems tends to decrease with system size. To illustrate the variation of costs with system size we review the price data from a solar system provider that publishes list prices and performance characteristics for a fairly wide range of off-grid solar system sizes (www.yakesolar.com). This provider has systems ranging from 15 Wp to 1520 Wp, which range in price from $165 to $11,000. The price vs. daily output for these systems is illustrated in Figure B-1 below.

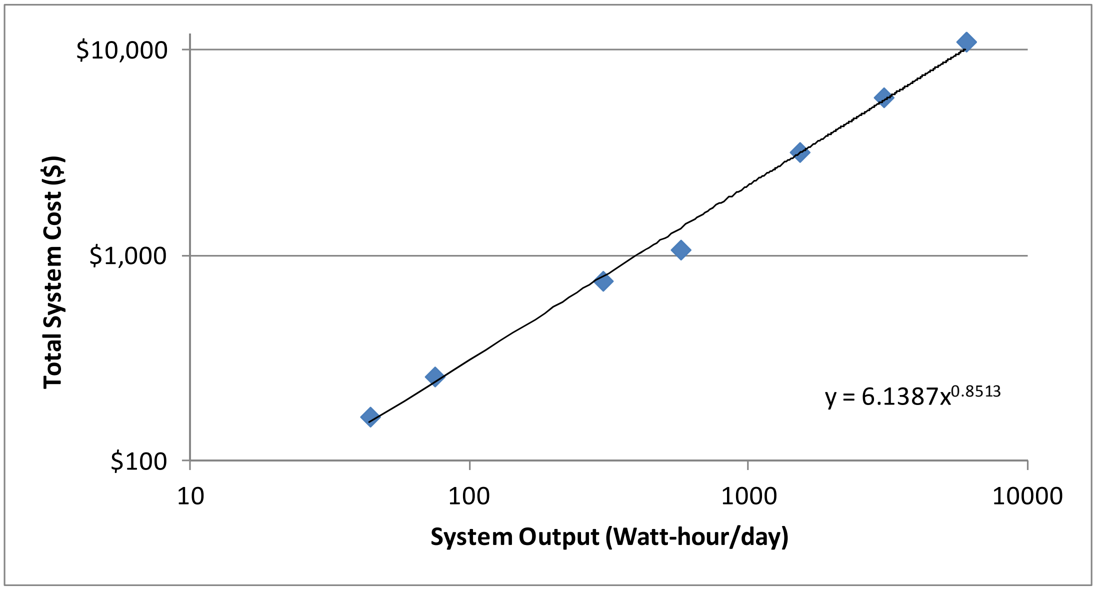

Figure B-1: Retail cost vs. system daily output (in watt-hours/day).

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[24] https://www.cgap.org/sites/default/files/DigitallyFinancedEnergy%20_FINAL.pdf

Figure B-1 illustrates the relationship between cost and system daily output where both axes have a logarithmic scale. The equation on the plot is the power-law relationship between the cost and the output. The fact that the exponent of this power law is less than one indicates that the marginal cost of the system output decreases with system size.

Figure B-2 illustrates the marginal cost of electricity output as a function of system size. This cost is calculated by examining the incremental cost of the system divided by the incremental capacity of the system between successive system sizes, and this using this ratio as the marginal cost for the mid-point capacity between the two system sizes. What we find, is that the incremental cost per unit capacity tends to decrease as we examine larger systems. It also shows that the marginal cost of solar electric supply capacity for these systems ranges from approximately $3.75/Wh/day trending to between $1.50 and $2.00 per Wh/day of marginal capacity for large system. There is an unusually low estimate of the marginal cost for one system size.[25]

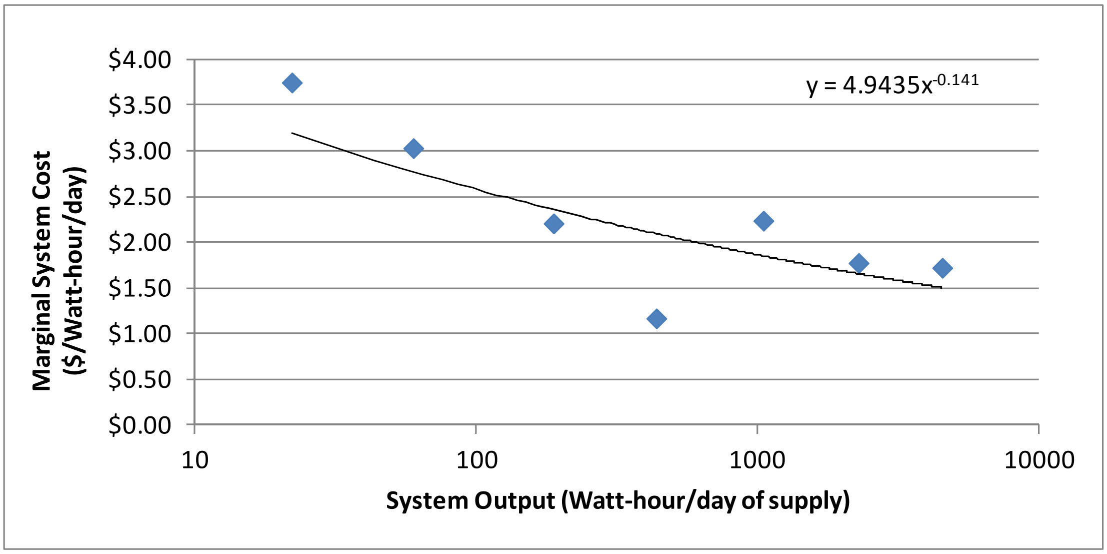

Figure B-2: Marginal retail cost vs. system daily output (in watt-hours/day).

When we combine the low range of capacity costs (~$1.75) with a fairly long[26] payback period for the investment (5 years), we get the relatively high cost of electricity of approximately $1/kWh:

($1.75/Wh/Day) *(1000 Wh/kWh) / [(365 days/year) * (5 years)] = $0.96/kWh

Note that because of the higher cost of incremental capacity for the smallest solar home systems, the per-kWh cost for the smaller systems will be nearly twice the cost for the larger systems.

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[25] The daily capacity provided by the manufacturer is estimated using non-standard methods: inconsistency in the methods for estimating the output of each system will carry through the marginal cost calculation to produce variability and errors in the marginal cost estimate.

[26] Discount rates and investment risks in developing countries tend to be very high. For a more detailed discussion on adjusting policy analysis to the context of a country in Africa see (Van Buskirk, et.al., 2007)

Appendix C: Historical Rates of Off-Grid Market Growth in Africa

Very rapid technological innovation is often associated with very rapid technology adoption. This section examines two historical examples of technology adoption in order to help assess how fast innovation and the adoption of new, related technologies might occur in developing country markets. The two cases reviewed here include:

1. Cell phone adoption in Africa from 1999 to 2012, and
2. Solar home lighting system adoption in Bangladesh from 1999 to 2013.

These two cases provide an illustration of how rapid the adoption might be for new-technology consumer products in developing country markets with large numbers of rural customers.[27]

Cell Phone Adoption in Africa

At least superficially, the historical case of cell phone adoption has similarities to the evolving adoption of distributed solar electric products in Africa. In both cases, the new technology avoids much of the need for expensive capital investment in distribution wires, which are necessary to provide the service infrastructure for remote rural users using traditional technologies. In addition, both cases take advantage of novel consumer financing strategies, such as installment payments or pay-as-you-go (PayGo) service models, where consumers pay up-front for a small amount of service and then make "top-up" payments if and as they need more service. PayGo business models are becoming particularly popular in emerging markets that feature low-income consumers (Kalba, 2008), (Pauser, Fuente & Djerma, 2014).

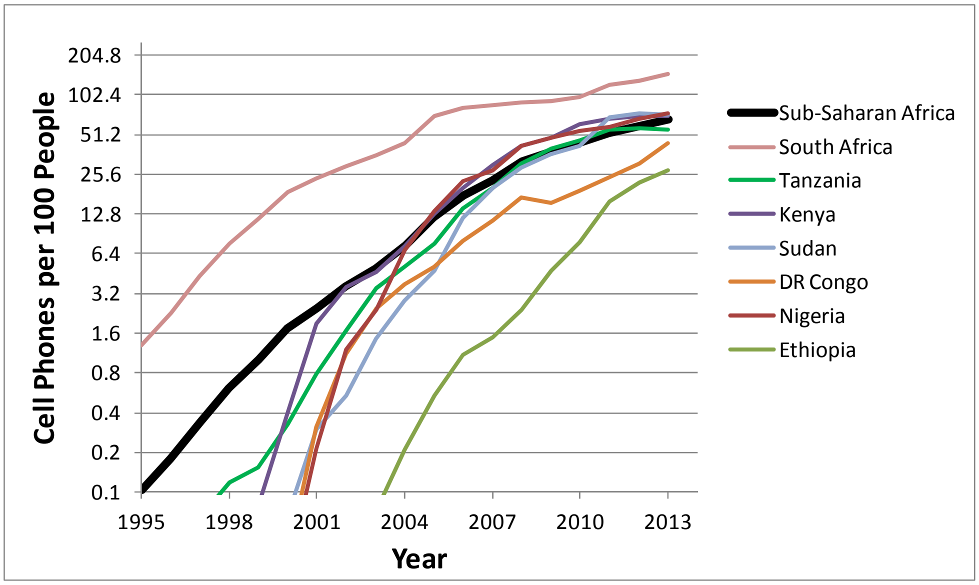

Figure C-1: Penetration of cell phones in Sub-Saharan Africa (SSA). The top-most curve is the adoption in South Africa, while the thick black curve is the adoption in developing SSA. Curves are also shown for the six most populous countries in developing SSA.

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[27] These cases are far from unique. Indeed, some of the earliest mathematical modeling work on interactions between innovation, experience curves, and product adoption was conducted more than three decades ago, looking at the adoption of electrical appliances in the U.S. from the mid-1940's to the 1970's, e.g. (Bass, 1980).

The pace of adoption of cell phones in Africa since 1995 is illustrated in Figure C-1. When cell phone saturation was less than one cell phone per 100 people, it appears that cell phone adoption grew at an annual rate of 100% or more. Above a saturation of one phone per 100 people, adoption appears to have grown at an annual rate of approximately 50% until adoption reached 10% to 20% of the population. At that point adoption growth slowed, approaching zero as saturation neared one cell phone per person.

Adoption of Solar Home Systems in Bangladesh

By 2013, more than two million residential solar home electricity systems had been installed in Bangladesh. Of these, more than a million were installed by Grameen Shakti,[28] which began operating in 1996 using some of Grameen Bank's experience with grass-roots rural retail financing to provide solar home systems with an installment payment plan. The provision of monthly payment plans has made these systems affordable for cash-constrained customers throughout rural Bangladesh.

The annual installation rate of solar home systems by Grameen Shakti between 1999 and 2013 is illustrated in Figure C-2. The adoption and sales growth of solar home systems for Grameen Shakti in Bangladesh shows a pattern that is similar to cell phone adoption in Africa during the same period: growth was rapid early in the period, and then leveled off as solar home systems become more common in the market. The average annual sales growth rate of solar home system installations from 1999 to 2010 was 46%. Given exponential growth in annual installations, cumulative adoption of solar home systems during this period grew exponentially at approximately the same growth rate.

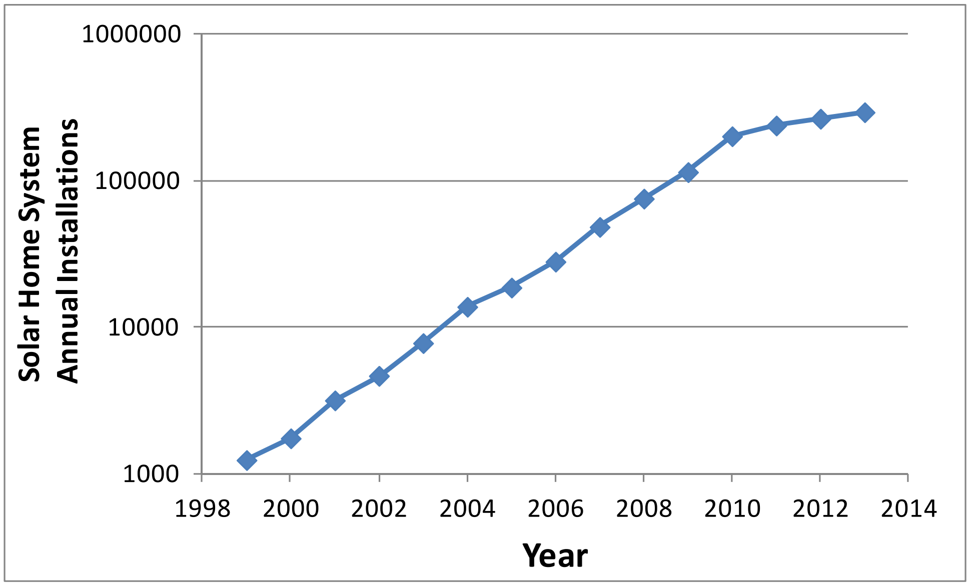

Figure C-2: Annual installation of solar home systems by Grameen Shakti.

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[28] See: http://www.gshakti.org/images/stories/s-2013.gif