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Doubling the global pace of progress for energy efficiency (EE):

Applying a "Moore's Law" of EE to technology innovation for off-grid applications

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Abstract

How might the pace of progress on energy efficiency be improved to help provide increased modern electricity access for the global poor? One 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 road-maps can be forceful drivers of technological improvement and change by setting expectations of progress and defining a set of technical performance and cost milestones over a period of one to several decades. Specifically, the development of technology road-maps has been used to drive technology progress in computer technologies, energy efficiency technologies (especially lighting), solar photo-voltaic modules and batteries. Applying a similar process to a wide range of energy end-use technologies—heating, air conditioning, ventilation, refrigeration, power electronics, insulation, etc.—with a specific focus on off-grid applications can potentially accelerate global progress on energy efficiency improvement. This memorandum specifically argues that accelerated progress in energy efficiency will be critical in providing more affordable and more universal access to modern energy services access. The global market for modern energy access includes the more than 1 billion people who are currently without access to electricity but who wish to acquire such access in the next decade if not sooner. This memorandum shows that the economic conditions of this market will likely require substantially more ambitious efficiency improvement goals from energy efficiency technology road maps than are provided by the economic conditions in more developed countries. Equations that can help quantitatively define these goals are also presented.

Table of Contents

1. Introduction

Empirical descriptions and forecasts of technology improvement trends such as Moore's law[1] and learning curves tend to show only a weak dependence on purely economic drivers. Rates of technological progress can be roughly constant over several decades, but can be very different between technologies. In some sense, the rate of technology improvement is "exogenous" to the evolution of the economy: i.e. while technological improvement strongly influences the evolution of relative prices in the economy (Baumol, 1967), prices in the economy sometimes only weakly influence the long term rate of technological progress. In other words, technology performance improvement rates may be malleable under the influence of changing expectations of technological progress or changing policy influences (Van Buskirk, et.al., 2014; Stewart, 2010). If engineers see a technical path to improving a technology, given several years to a decade of research and development, engineers may be able to make the cost of the improved technology drop exponentially.

The academic literature tends to view Moore's law as being sustained through a combination of industry expectations, government and industry research investments, market demand, and collective industry collaboration. Moore's law thus may be a collectively-organized self-fulfilling prophesy. Much of this industry collaboration was semi-formally articulated through the development of technology road maps that documented consensus market expectations of what performance improvement rates were likely to be possible in computer technology research and development (Shaller, 1997).[2] Then given the expectations of technology trends, a wide range of market actors developed products consistent with these expectations.

To aid in setting long term technology expectations and creating efficiency technology roadmaps for 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. (Appendix A of this memorandum provides a detailed derivation/description of MLEE). This memorandum argues that a key implication of MLEE is that if research and development of energy efficiency technologies targets super-efficient appliances for off-grid applications, then this should lead to a major acceleration of energy efficiency improvement rates. A major acceleration of residential clean energy services for hundreds of millions of developing country households is likely have global implications[3] for clean energy technology progress in general over the next decade. Widespread adoption of new technology leads to competition and, often, lower technology prices. This analysis provides a quantitative estimate of what efficiency improvement milestones need to be met if the Sustainable Energy for All (SE4All)[4] goal of ensuring "universal access to modern

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[1] Moore's Law is the statement made by Gordon Moore in the 1970's 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] From (Shaller, 1997): "'The Semiconductor Industry Association puts out a technology roadmap…Everyone in the industry recognizes that if you don't stay on essentially that curve they will fall behind.'"

[3] See for example the IIASA Global Energy Assessment at: www.globalenergyassessment.org

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

energy services" is to be achieved in the most cost effective manner possible within the next decade. If universal access to electricity for more than one billion people currently disconnected from centralized electricity grids is going to be achieved at maximum cost-effectiveness, it will be necessary to also satisfy or exceed the complementary SE4All goal of "doubling the global rate of improvement in energy efficiency." The theory behind MLEE provides a specific, quantitative method for forecasting the energy efficiency improvement that can help cost-effectively achieve the SE4All target of doubling the energy efficiency improvement rate in global product markets.

For energy efficient lighting, the historical pace of progress of energy efficiency has approximately doubled with the creation of robust technology research and development programs for solid state lighting (i.e. light emitting diodes (LEDs)). These programs are guided by long term technology development roadmaps. One of the consequences of the accelerated rate of technology improvement for lighting efficiency has been the rapid expansion of modern lighting services throughout the developing world.[5] This rapid adoption of new, highly efficient off-grid lighting technologies has undoubtedly helped reinforce accelerated technological improvement in global lighting product markets.

For technologies other than lighting, a similar virtuous cycle of innovation leading to adoption which then leads to further innovation can be accelerated. A renewed initiative for accelerated technology innovation and long term technology road-mapping for air conditioning, heating, ventilation, refrigeration, pumping, electronics, and a whole host of other energy-using technologies and equipment can help drive the innovation cycle faster for these product markets. Such an initiative with a focus on more stringent targets demanded by off-grid applications may not only help mitigate climate change, but may help accelerate and expand the benefits of technology innovation for billions of new consumers for a wide range of energy using products beyond lighting.

2. What drives technology improvement rates?

What drives technology improvement trends? 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 it could have been largely a 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

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[5] See for example: http://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/Automotive%20and%20Assembly/Lighting_the_way_Perspectives_on_global_lighting_market_2012.ashx, (Accessed October 14, 2014) for a description of the global LED market.

for 30 years, spending 12 of these years as CEO. The chips that his company made fueled the computer revolution that occurred from the 1970's and 1990's, and he was directly involved in managing their development.

The historical example of Moore's Law indicates that there is the possibility of changing technology improvement rates through a combination of planning, foresight, research, and development. The question is whether such a process might be replicated to accelerate progress in energy efficiency technologies.

This memorandum presents evidence that energy access for the 1.3 billion people who currently do not have access to electricity can be accelerated by accelerating energy efficiency technology improvement rates. This energy efficiency technology acceleration can be obtained by focusing the economics of the technology on off-grid applications which represent a new, potentially fast-growing emerging market. This market of more than a billion new electricity customers includes developing country households and business utilizing off-grid electricity systems and micro-grids. Off-grid and micro-grid electricity tends to be supplied from either diesel generators or solar photovoltaic (PV) equipment (Brown, et.al., 2012). As described below, such electricity costs roughly from \$0.30/kWh to \$1/kWh to produce in part because many applications are in developing countries where the cost of capital for electricity supply is high. Therefore appliances and products that use such electricity should ideally be much more energy efficient than appliances and equipment that use much cheaper grid-connected utility-based electricity supplies.

3. Relative energy/appliance price changes drive optimum efficiency

Electricity prices to households in developed countries—often subsidized—range between \$0.10/kWh to \$0.36/kWh,[6] but what happens when electricity costs are substantially higher such as \$1/kWh for small scale off-grid solar applications?

When customers have a very high unit cost of electricity then the efficiency that is cost-optimum for appliances used by such customers is correspondingly higher and the corresponding energy consumption of the appliance should be much lower than for comparable appliances in markets with low electricity costs. This is because when the electricity price is high, the increased cost of a higher efficiency appliance can be justified by the higher financial savings per unit energy savings as we illustrate below.

Figure 1 illustrates the life-cycle cost (LCC) as a function of energy use for a small refrigerator. The life-cycle cost is the sum of the purchase price of the appliance and the present value of the operating cost. It is the total cost of ownership of the appliance excluding maintenance costs and assuming that the discount rate reflects the cost of capital.[7] This example calculation has the following three inputs: (1) the baseline price at a reference efficiency which is assumed to be \$300 for a refrigerator that consumes 400 kWh/year, (2) the elasticity of equipment price[8] with

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[6] 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.

[7] See Appendix A for details

[8] 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.

respect to energy use, assumed to be -0.6,[9] 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 is qualitatively the same.

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 the two calculations, but the minimum cost energy use is very different for the two cases. At $0.10/kWh, the minimum cost energy use is 370 kWh/year, but if the electricity price is $0.50/kWh, the minimum life-cycle cost refrigerator uses 130 kWh/year, i.e. 65% less than the low electricity price case.

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

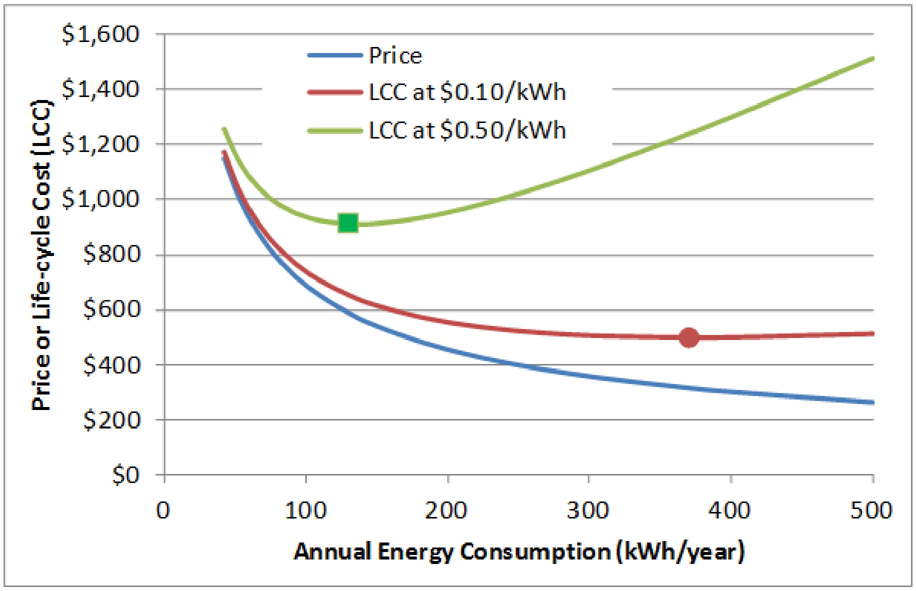

Figure 1: Life-cycle cost curves of a refrigerator for different prices of electricity, assuming an economic payback period of five years. The blue curve is the price of the refrigerator assuming an elasticity of price with respect to energy consumption of -0.6 and a refrigerator price of $300 for an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

4. Moore's Law of Energy Efficiency (MLEE)

If we consider the case where the relative price of electricity and appliances change over time, then the relationship illustrated in Figure 1 can be described in 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

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[9] 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.

depends on a technical economic parameter that is called the elasticity of equipment price with respect to efficiency (ε):

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

This equation provides a description of how the economically optimum energy use of an appliance depends on the 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[10] 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 consumers can finance their purchase over a longer period of time, then the economically optimum energy use is smaller because the present worth factor[11] for consumer investment, *PWF*, increases.

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

As we describe below, there is a market of more than a billion customers who are going to obtain access to electricity at what are likely to be relatively high unit electricity prices. Because of the electricity price difference between these customers and customers in developed-country markets, they are going to need appliances with much higher energy efficiency than what is typical in developed-country markets.

5. 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 estimate 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.

5.1. 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. As can be clearly seen in the figure, from 1987 to 2004, petroleum was relatively cheap at approximately \$20/barrel, but in the last decade oil has seen a five-fold

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[10] 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.

[11] 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.

increase to approximately $100/barrel, and indications are that while prices may periodically drop to below $50/barrel, prices substantially higher than the 1990's are likely to be here to stay.

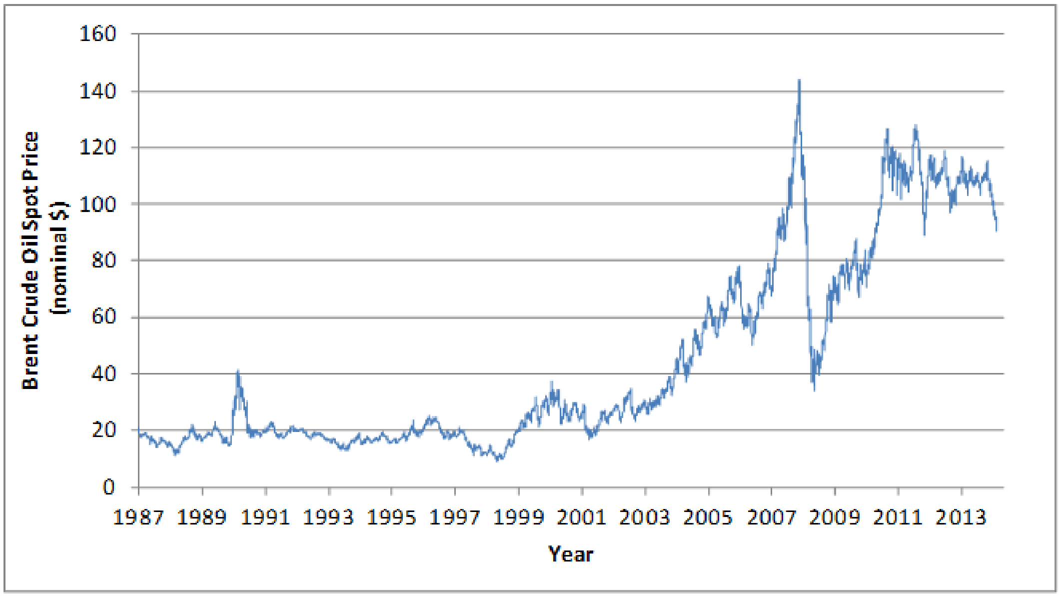

Figure 2: Price of a barrel of oil. Recently there has been a drop in price to ~$50/barrel (not shown). Oil price volatility and prices that are elevated relative to the 1990's (i.e. 2-5 times the 1990's average price) may persist for some time.[12]

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 correlated over time with the cost of oil as illustrated in figure 3. In Sub-Saharan Africa, with a range of oil costs of $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 of distribution, metering, billing, customer service would of course increase the cost of retail diesel-generated electricity relative to the generation cost.

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[12] "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

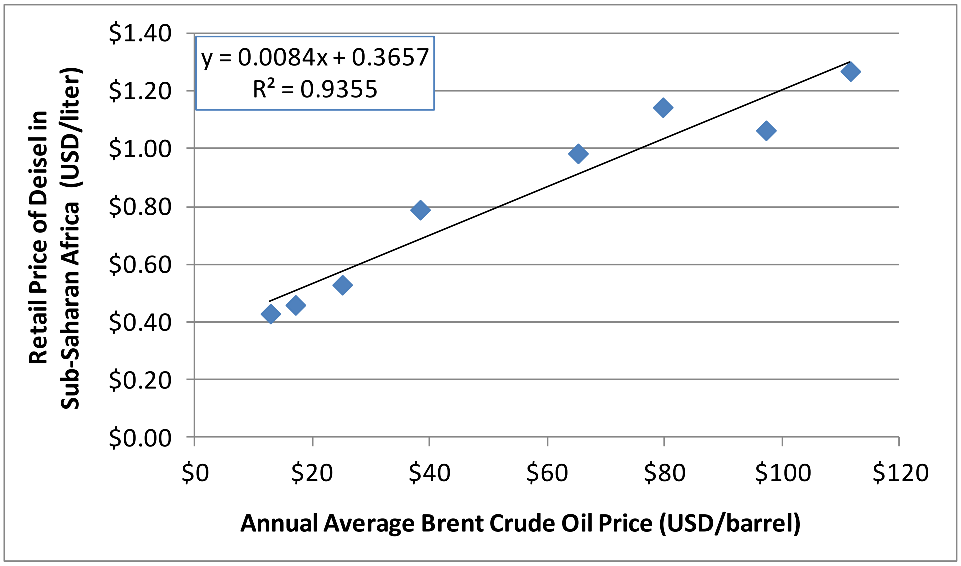

Figure 3: Correlations between the average annual Brent crude oil price per barrel and the average retail diesel price in developing Sub-Saharan Africa.[13]

5.2. 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 period for the investment in solar equipment and how much of the electricity needs to be stored in an electrochemical battery. More specifically, estimates of the cost of solar electricity for off-grid applications depend on 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. during the nighttime. 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 (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 uses this data to provide a current estimate of the per-kWh of solar PV electricity.

Assuming a 5-year payback time, 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.

6. Off-grid market could grow 40%-50% per year 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 adoption of new, related technologies might occur in developing country markets. The two cases reviewed here include:

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

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

These two cases provide an illustration of how rapid adoption of new technology consumer products might be for developing country markets with large numbers of rural customers. These cases are far from unique and some of the earliest mathematical modeling work on interactions between innovation, experience curves, and product adoption was done more than three decades ago on the adoption of electrical appliances in the US from the mid-1940's through the 1970's, e.g. (Bass, 1980).

6.1. 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 needed to provide the service infrastructure for remote rural users using traditional technologies. In addition, both cases take advantage of novel consumer financing strategies including installment payments or pay-as-you-go (PayGo) service models (where consumers pay up front for a small amount of service and then "top-up" payments as they need more service). PayGo business models are becoming particularly popular in emerging markets that have low income consumers (Kalba, 2008), (Pauser, Fuente & Djerma, 2014).

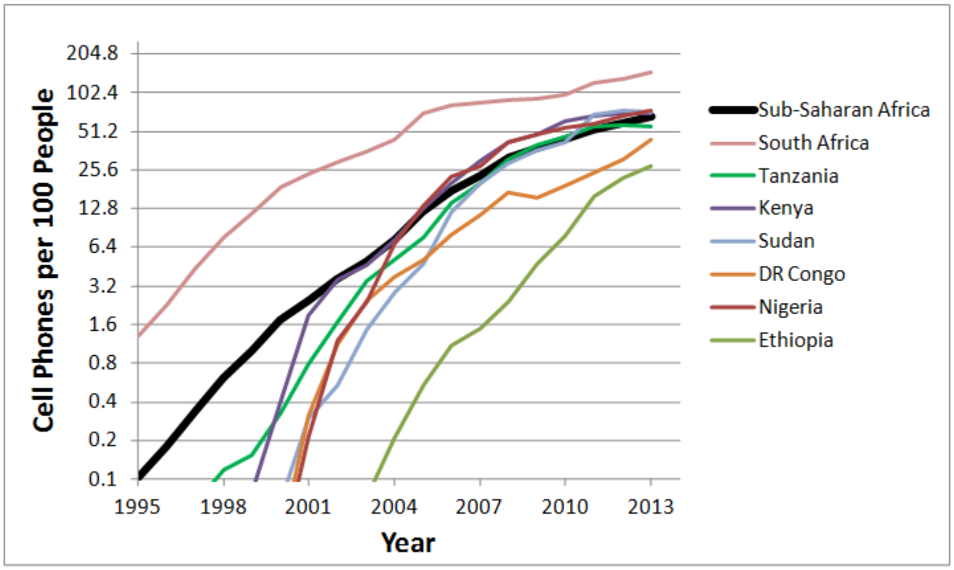

Figure 4: Penetration of cell phones in Sub-Saharan Africa (SSA). The top-most curve is the adoption in South Africa, while the thick black curve is the adoption in developing SSA. Curves are also shown for the six most populous countries in developing SSA.

The pace of adoption of cell phones in Africa since 1995 is illustrated in figure 4. When adoption is less than one cell phone per 100 people it appears that cell phone adoption has grown at an annual rate of 100% or more. Above a saturation of one phone per 100, the adoption appears to grow at an annual rate of approximately 50% until adoption reaches 10% to 20%. At that point adoption growth slows, decreasing towards zero at saturations near one cell phone for every person.

6.2. 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,[14] which started 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 a monthly installment package has enabled the systems to be affordable for cash-constrained customers throughout rural Bangladesh.

The annual installation rate of solar home systems by Grameen Shakti is illustrated in figure 5. 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 this period, where early in the period growth is rapid and then growth levels 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 is 46%. Given exponential growth in annual installations, cumulative adoption of solar home systems during this period also grows exponentially at approximately the same growth rate.

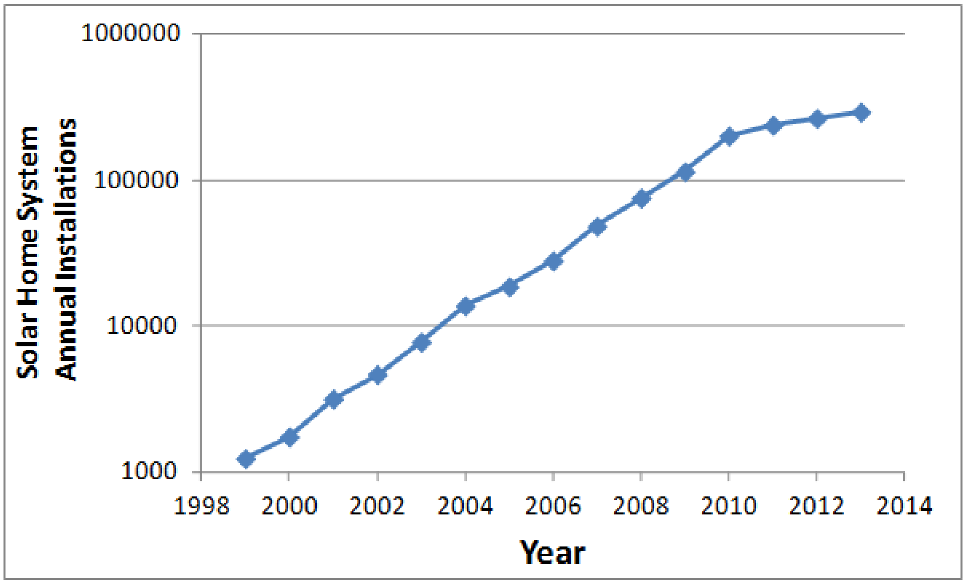

Figure 5: Annual installation of solar home systems by Grameen Shakti.

7. How fast must efficiency improve for off-grid customers?

If the billion or more off-grid customers in the developing world who need electricity access over the next decade are going to have access to cost-optimized appliances with off-grid solar electricity, they need appliances that are much more efficient that what are typically available today. The opportunity for energy efficient technologies (especially lighting) to contribute to sustainable development have been identified previously (e.g., Dutt, 1994; Dutt and Mills: 1994). Now with more widely available off-grid generation by photovoltaics, the opportunity for energy efficient products has expanded to a broad range of appliances and equipment.

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

If we set an ambitious target of allowing a substantial percentage of the rural developing world to obtain access to electricity over the next decade with efficient appliances that are minimum-cost for their needs (i.e. by 2025), then historical rates of energy efficiency improvement for many appliances and energy using equipment need to be accelerated to provide economically optimum energy efficiency for such off-grid customers.

Taking the case of the refrigerator cost curves presented in figure 1, at $0.50/kWh an economically optimum refrigerator will be more than 2.8 times as efficiency 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 is 10.8%/year, or approximately triple the roughly 3%/year refrigerator efficiency improvement rate seen in Europe from 2004 to 2011.[15]

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

DOE's 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.[16] Figure 5 illustrate the rapid increase and 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 result in efficacies of approximately 200 lumens/watt by 2020. Comparing this to the maximum efficacies of approximately 120 lumens/watt seen in 2010, this represents compound improvement rate of more than 5%/year.

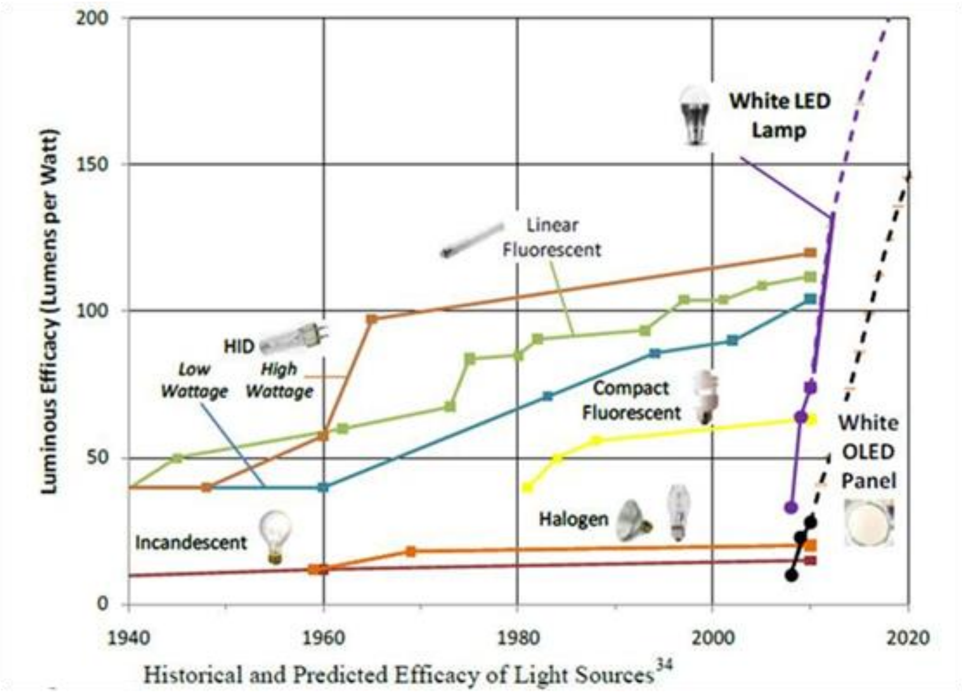

Figure 6: Acceleration of luminous efficacy represented by development of light emitting diode (LED) technologies.

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

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

This rapid acceleration in the efficiency improvement of lighting technologies has not occurred in a vacuum, but has been driven strongly by a systematic process of collaborative government/industry planning that has resulted in the creation of a detailed technology development vision.[17] 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.

9. Creating efficiency technology roadmaps to address off-grid applications

The U.S. DOE has created technology roadmaps for photovoltaic systems, HVAC, appliances, windows, low GWP refrigerants, water heating. [18] [19] Even though energy efficiency technology roadmaps for off-grid appliances may not be able to 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 focused on off-grid applications. Given that off-grid solar PV systems represent a substantial market niche, a discussion can begin amongst policy makers, technologists, financial institutions and manufacturers and suppliers of off-grid solar systems regarding which appliance designs and technologies are likely to be most effective for off-grid solar applications as these systems become more prevalent throughout the developing world.

The IEA has published a technology roadmap for solar PV that provides long term cost and performance targets for solar technologies.[21] The IEA also has a fairly comprehensive technology roadmap for energy storage.[22]

Technology road-maps for efficient off-grid applications could begin with a market assessment of the appliance and equipment demand from the off-grid market, proceed to an assessment of the future cost of electricity for such applications over the next decade, and provide an assessment of the degree to which efficiency (and equipment price) need to improve in order to most economically address the expected off-grid energy services demand.

Once the various end-uses are appropriately identified (e.g. refrigeration, information and communications technologies, pumping and water treatment), a process of identifying ambitious, yet reasonable technology, cost and performance trends can help guide a process of developing those technologies that can address the needs of the off-grid market more cost-effectively over the next 5-10 years.

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

[18] http://www.nrel.gov/docs/fy13osti/59155.pdf

[19] http://energy.gov/eere/buildings/listings/technology-roadmaps

[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] http://www.iea.org/publications/freepublications/publication/pv_roadmap.pdf

[22] http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf

10. Conclusion

This memorandum presents an argument—based on experience with computers and solid-state lighting and other technologies—that technology innovation rates may be somewhat independent of economic drivers, and somewhat malleable. The memorandum also argues that current appliance and equipment energy efficiency is not currently cost-optimized for the needs of the 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 $0.30/kWh to $1/kWh compared to a range of $0.10/kWh to $0.36/kWh for grid-connected customers in developed countries. This implies that the efficiency required for the off-grid customer base needs to be substantially higher than what is currently 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 pushed by the U.S. Department of Energy that 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 was going to be the lighting of the future even though for many years it did not substantially out-perform competing technologies in the market.

But the process of rapid—yet long term—technological improvement does not have to be limited to just lighting, and in fact we show that there is a large base of potential customers in global markets that need much higher levels of product efficiency than what is currently provided by on-grid appliances.

For technologies other than lighting, a virtuous cycle of innovation leading to adoption which then leads to accelerated innovation is possible. A renewed, joint initiative by policy-makers, 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 focused on off-grid applications. The vast majority of energy end-uses including air conditioning, heating, ventilation, refrigeration, pumping, electronics, etc., could benefit from a faster technology innovation cycle for energy efficient technology. Large increases in efficiency are theoretically possible because current technologies are operating far from their ideal thermodynamic limit (Farese, Gelman & Hendron, 2012). Such an initiative may not only help mitigate climate change, but can help accelerate and expand the benefits of technology innovation for billions of new consumers—both on- and off-grid—and for a wide range of energy using products beyond lighting.

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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 is also influenced by its operating cost. If efficiently operating markets are minimizing the total ownership cost of an appliance including the purchase price and the operating costs, 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" (Van Buskirk, et.al., 2014), specifically equations (S20) to (S26) in the supplemental information.

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 $OC(y_n)/(1+i)^n$.[23] The sum of price and operating costs throughout the appliance lifetime is then:

$$LCC = P_A + \sum_{n=1}^{L} \frac{OC(y_n)}{(1+i)^n} \tag{B1}$$

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:

$$LCC = P_A + AEC \sum_{n=1}^{L} \frac{P_E(y_n)}{(1+i)^n} \, , \tag{B2}$$

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

$$\overline{P_E} = \frac{\sum_{n=1}^{L} P_E(y_n)/(1+i)^n}{\sum_{n=1}^{L} 1/(1+i)^n} \, , \tag{B3}$$

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:

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[23] 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.

$$PWF = \sum_{n=1}^{L} \frac{1}{(1+i)^n} = \frac{1-(1+i)^{-L}}{i} \quad . \tag{B4}$$

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:

$$LCC = P_A + PWF \cdot \overline{P_E} \cdot AEC = P_A + PVOC \tag{B5}$$

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:

$$P_A = P_0 \cdot \left(\frac{AEC}{AEC_0} \right)^{-\varepsilon} \tag{B6}$$

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:

$$\frac{dP_A}{dAEC} = -\varepsilon \cdot P_0 \frac{AEC^{-(1+\varepsilon)}}{AEC_0^{-\varepsilon}} = \frac{-\varepsilon \cdot P_A}{AEC} \tag{B7}$$

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*)[24] as a function of elasticity, price, annual energy consumption and payback period:

$$\begin{aligned} CCE &= -\frac{1}{PWF} \cdot \frac{dP_A}{dAEC} = \frac{\varepsilon \cdot P_A}{PWF \cdot AEC} \\ &= \frac{\varepsilon \cdot P_o \cdot AEC_0^{\varepsilon}}{PWF \cdot AEC^{1+\varepsilon}} \end{aligned} \tag{B8}$$

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:

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

$$\frac{dPVOC}{dAEC} = PWF \cdot \overline{P_E} = -\frac{dP_A}{dAEC} = \frac{\varepsilon \cdot P_A}{AEC} \tag{B9}$$

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:

$$AEC_{MinLCC} = \frac{P_A}{\overline{P_E}} \cdot \frac{\varepsilon}{PWF} \tag{B10}$$

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:

$$AEC_{MinLCC}(t) = \left(\frac{P_0(t)}{\overline{P_E}(t)} \right)^{\frac{1}{1+\varepsilon}} \left(\frac{\varepsilon \cdot AEC_0^{\varepsilon}}{PWF} \right)^{\frac{1}{1+\varepsilon}} \tag{B11}$$

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 ε 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 (11) where the price of electricity trends from the current on-grid cost (say \$0.10 to \$0.15/kWh) to the off-grid cost of electricity (\$0.50/kWh to \$1/kWh). In this case as the price of electricity trends to favor off-grid customers, equation (11) 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. during the nighttime. 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 (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 different 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/).[25] The financing terms provided by this market range 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).[26] 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.

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

[26] Accessed July 25, 2014

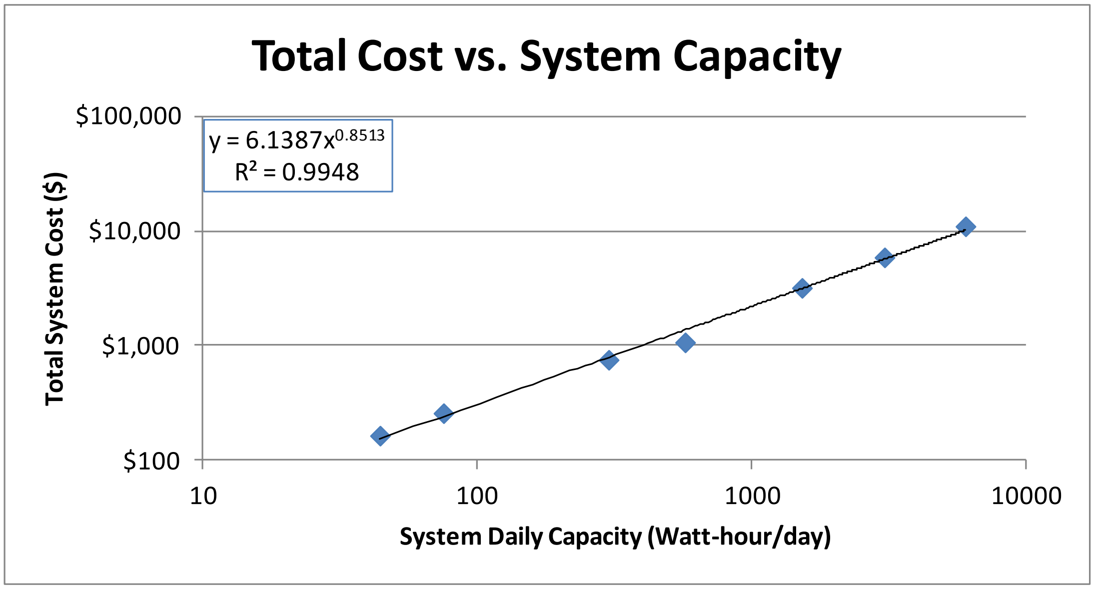

Figure B-1: Retail cost vs. system daily output (in watt-hours/day).

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 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. For one system size, there is an unusually low estimate of the marginal cost.[27]

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[27] 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.

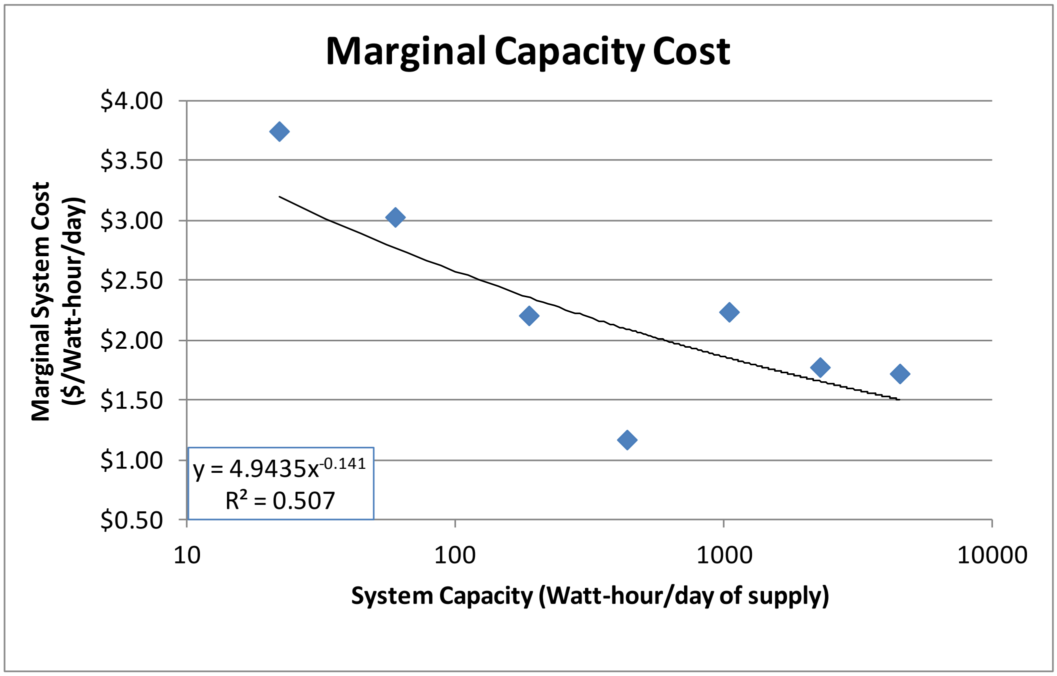

Figure B-2: Marginal retail cost vs. system daily output (in watt-hours/day).

When we combine the low range of capacity costs (~$1.75) with a fairly long[28] 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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[28] 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)