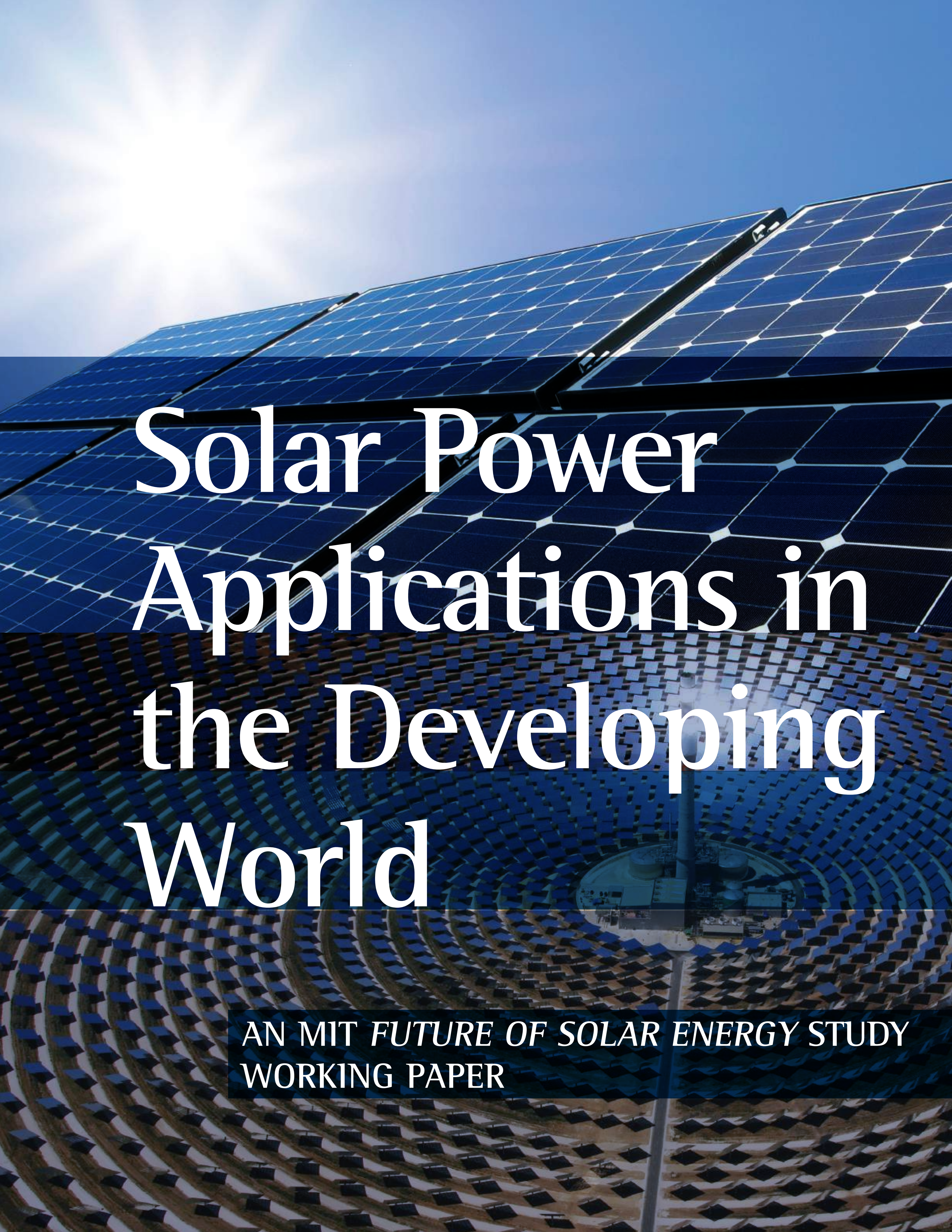

Solar Power Applications in the Developing World

AN MIT *FUTURE OF SOLAR ENERGY* STUDY
WORKING PAPER

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Introduction

This paper investigates the important and distinctive roles that small- and large-scale solar technologies can play in the developing world, where many people are gaining access to modern energy services for the first time, and where energy demand is rapidly increasing. We cite examples relating to sub-Saharan Africa and India, but not China, which, despite having the developing country attribute of rapid demand growth, is unlike other developing countries in that it is already almost fully electrified and has an advanced and well-financed energy sector.

The potential for solar power to displace coal-fired generation and thereby help reduce pollution and greenhouse gas emissions is of considerable interest with respect to China, as it is for most other developing countries, including India.[i] But it is also of interest to developed countries in which broadly similar approaches to encourage and finance solar deployment are being pursued.[ii]

We focus on applications with wide applicability and high potential impact that are unlike those encountered in the developed world. The existence of such applications reflects the distinctive nature, and relative immaturity of developing country electricity systems and markets. Where it takes place, electric system expansion often favors distribution over generation, creating chronic supply shortfalls in many countries and a resulting over dependence on rapidly deployable, but expensive diesel generation. Densely populated urban areas are also often favored over hard-to-reach rural areas, where the cost of providing service is typically much higher and revenues per connection are much lower. These patterns have two important consequences: First, solar power may be cost-competitive in many developing countries where diesel generation is widespread, making utility-scale solar attractive. Second, when deployed at the home or community scale, solar may be one of the few practical options available to large rural developing country populations that lack reliable grid access. We examine both situations in this paper.

[i]Whereas among developed countries the annual rate of demand growth for electricity is relatively low, averaging less than 1% within the Organization for Economic Cooperation and Development (OECD) since 2000, in the developing world it is far higher, ranging from 4% in Africa at large to 6% in India, and 11% in China in the same period. Through mid-century, demand growth in developing countries is likely to moderate, but, in the aggregate, it is forecast to remain well above typical OECD levels. Accordingly, by mid-century under plausible policy, economic growth, and technology adoption scenarios, non-forest related CO_2-equivalent emissions from developing countries, excluding India and China, collectively will exceed those of the United States and other developed countries combined, and will be only slightly less than the sum of emissions in India and China. These claims are based on a breakdown of regional and country emissions as forecast under the SRES A1F1 (Special Report on Emissions Scenario) Minicam scenario using Climate Rapid Overview and Decision Support (C-ROADS), a climate simulation program built from a systems dynamics model. In the simulation, developing countries are all countries excluding the United States; all of Europe, including the United Kingdom, Russia and the former Soviet Republics; Canada; Australia; New Zealand; Japan; and South Korea.[1]

[ii]Many developing countries, including China, India, and South Africa, are pursuing aggressive policies to encourage solar investment using policy instruments such as mandated portfolio standards and renewable energy credits.[2] While these policies are giving rise to impressive auction prices for solar capacity, neither the capital costs nor the economics of solar power in these countries are appreciably different from those seen in developed countries following similar practices. Levelized costs for solar remain uncompetitive with prevailing conventional generation costs.[3]

1. Small-Scale Devices and Standalone Systems

Kerosene lanterns provide a large fraction of lighting in most developing countries, especially in rural areas where grid power is unreliable or unavailable. This has long been recognized as a sizable potential substitution market for solar-powered lanterns. Table 1 shows the number of people, grouped by developing country region, living in rural and urban areas in 2009, who lacked any form of regular access to electricity, along with a projection for 2030.[iii] Strikingly, virtually all of this population — comprising more than 1.1 billion people and approximately 274 million households[5] — is located either in sub-Saharan Africa or developing Asia. It is also striking that, at least within the assumptions of the economic model used to construct Table 1, the rural population in all parts of the developing world is projected to fall substantially by 2030, except in sub-Saharan Africa, where it will *increase* by more than 15% to 538 million people or roughly half the entire population. Globally, therefore, the opportunity to develop solar-based products and services that can provide even modest electric lighting and other basic modern services, such as phone charging, is both substantial and durable.[iv]

Table 1. Number of People, in Millions, Who Lacked Access to Electricity in Developing Countries in 2009 and a Projection for 2030[4]

	2009			2030		
	Rural	Urban	Share of population	Rural	Urban	Share of population
Africa	466	121	58%	539	107	42%
Sub-Saharan Africa	*465*	*121*	*69%*	*538*	*107*	*49%*
Developing Asia	595	81	19%	327	49	9%
China	*8*	*0*	*1%*	*0*	*0*	*0%*
India	*268*	*21*	*25%*	*145*	*9*	*10%*
Rest of developing Asia	*319*	*60*	*36%*	*181*	*40*	*16%*
Latin America	26	4	7%	8	2	2%
Middle East	19	2	11%	5	0	2%
Developing countries	1 106	208	25%	879	157	16%
World	**1 109**	**208**	**19%**	**879**	**157**	**12%**

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[iii]The projection for 2030 assumes national policies consistent with actual or anticipated national policy and plans as of 2009 — the New Policies Scenario — a modestly optimistic version of the prevailing economic conditions at that time.[4]

[iv]With approximately 500 million connections and a unique subscriber penetration rate approaching 30%, mobile phone charging has emerged as an important electricity application in sub-Saharan Africa, especially in rural communities.[6]

The value of kerosene used in lanterns annually for lighting by non-electrified households is estimated to total $36 billion, worldwide.[5] Recognizing the potential market opportunity, numerous small companies have begun to intensively market low-cost solar lighting devices in many developing countries in the last five years. These portable, integrated "solar power and light" (SPL) products have begun to displace kerosene lanterns at a noticeable level.[5] The simplest form of SPL is a portable solar light consisting of a small, 2–5 watt (W) solar panel, a primitive charge controller, and a battery integrated into a small plastic housing with one or more white light emitting diodes (LEDs). In early devices, these light fixtures were either florescent or incandescent, and were both costly and inefficient. The recent appearance of low-cost, energy-efficient white light LEDs has given rise to the relatively sudden popularity of SPLs since it has enabled a substantial reduction in panel and battery size, and thereby made simple SPLs widely affordable. Contemporary models, supplying from one to ten times the visible light output of a kerosene lamp, and at the high end of the market, incorporating features such as phone charging, cost from $8 to $60. Indeed, the International Finance Corporation (IFC) estimates that over 90% of households that now use kerosene lighting can, in principle, afford to purchase SPLs with cash on hand, or using short-term credit with monthly payments less than their current out-of-pocket monthly kerosene expenses of $3–$10 (depending on the number of lanterns in use).[v] Figure 1 shows a representative comparison of the costs of a mid-market SPL with phone-charging capability, and the cost of obtaining a similar amount of kerosene lighting plus phone charging from a paid community charging service.[vi]

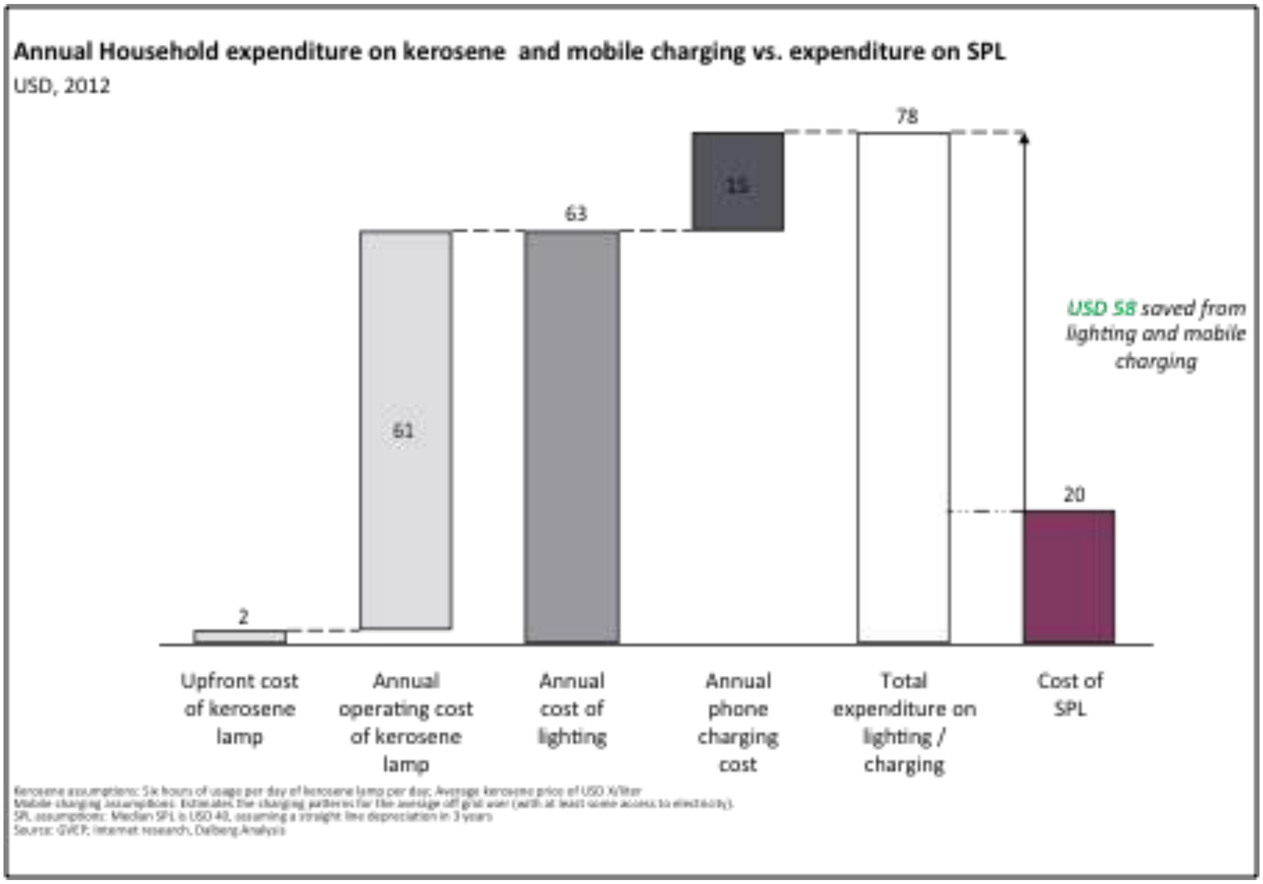
FINDING 1

Multifunction solar voltaic lighting appliances, enabled by low-cost photovoltaic (PV) panels and white-light LEDs, are rapidly gaining a foothold among the approximately 1 billion people in developing countries who lack access to modern energy services, notably for lighting and phone charging.

[v] Unsubsidized prices for kerosene in 2013.[5,7]

[vi] While the majority of SPLs include their own solar panels and are individually owned, there are also examples of community charging services, such as those offered by Engineering Global Growth (EGG) Energy in Tanzania, that offer community battery, phone, or SPL charging services in which power is provided from the grid, a small diesel generator, or small (i.e., <1kW) solar arrays. In some business models the SPLs may be owned by a local entrepreneur who rents charged lanterns to many customers who are usually required to pay some form of deposit. SPL charging services are also sometimes provided through schools to students as an inducement to their parents to send them each day to classes.

Figure 1 Comparison of the Annual Cost of Kerosene Lighting with the Cost of a Simple Solar Lantern with Integrated Phone Charging Functionality[vii]



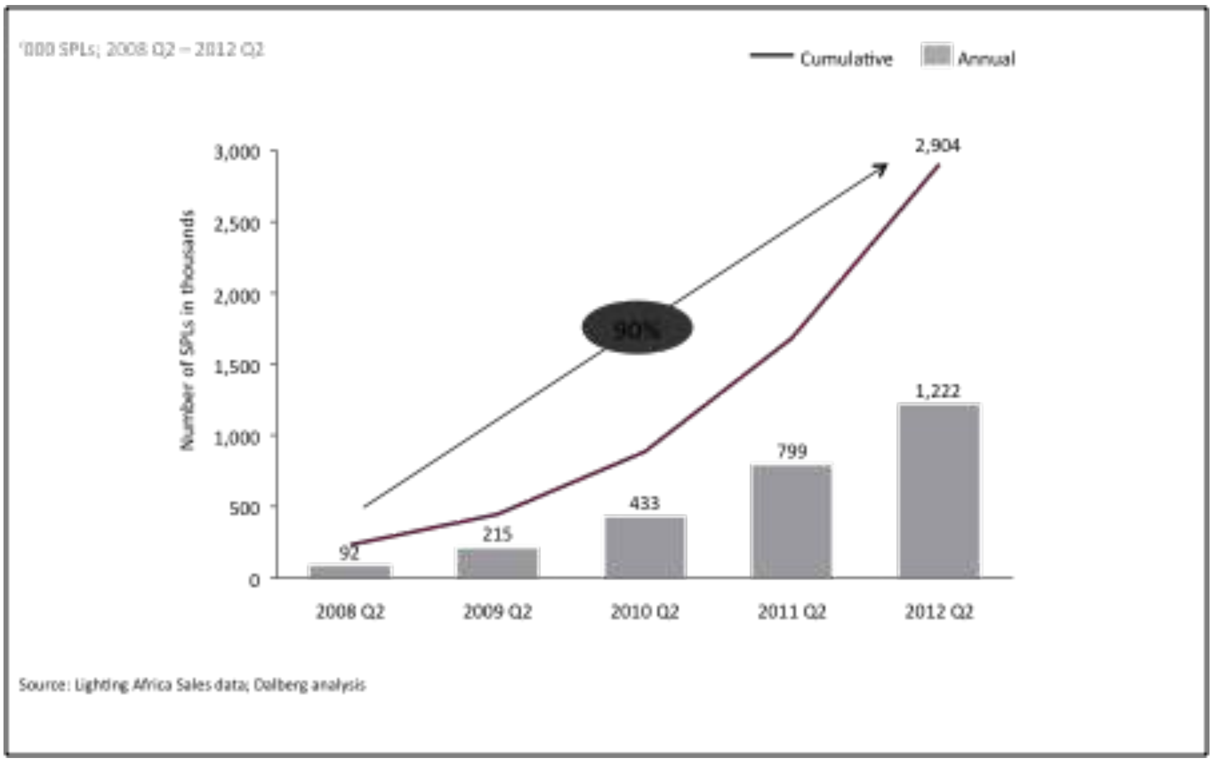
(Note: Expenditures are shown in 2012 U.S. dollars)

More complex "plug-and-play" systems, or "kits," have recently emerged that provide some degree of expandability in the form of optional modular lighting fixtures, multiple charging ports, and plug power capable of operating small appliances such as direct current (dc) televisions, radios, and fans. These systems, which may cost hundreds of dollars, typically have larger panels (10–25 W) and batteries, and more sophisticated controllers than simpler lantern-like devices.

[vii]Included with the permission of Lighting Africa, a joint IFC and World Bank program that catalyzes and accelerates development of commercial off-grid lighting markets in sub-Saharan Africa as part of the World Bank Group's wider efforts to improve access to energy.[7]

As Figure 2 shows, the global SPL market has grown very rapidly, with annual sales roughly doubling each year since 2009. We estimate total sales to date exceed 5 million units, which is still far short of the IFC's total estimated addressable market of close to 200 million households for such devices. Recent evidence[5,7] indicates a widespread preference for traditional kerosene lighting, which is considered to be more reliable and more visually pleasing than the relatively harsh lighting provided by simple LED fixtures.[ix] Therefore, greater and sustained use and sales of SPLs will likely depend not only on cost, but also on future improvements in manufacturing quality and standardization, as well as aesthetic factors such as lighting quality. Nevertheless, the rapid expansion of the SPL market to date, as well as the size and vigor of this essentially new and largely untapped market (Figure 3), should encourage solar entrepreneurs and innovators.

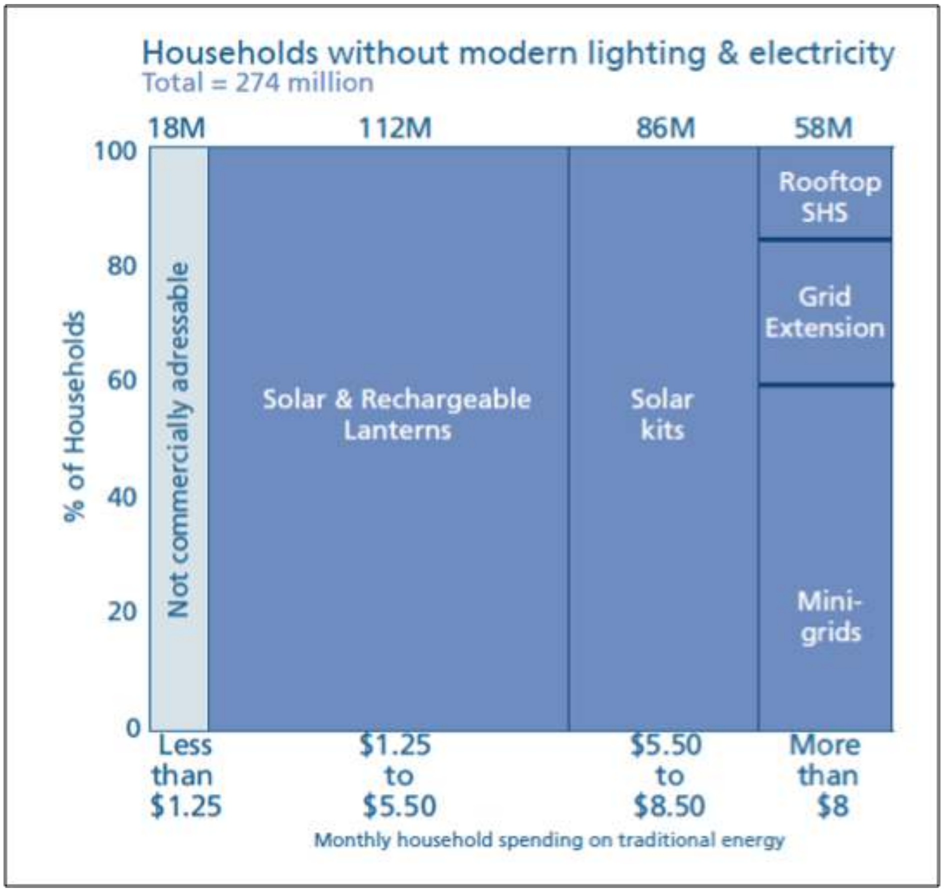
Figure 2 Annual and Cumulative Growth of SPL Sales Globally Since 2008[viii]



[viii]Included with the permission of Lighting Africa.

[xi]Serviceability, quality, reliability, and lighting performance are known to be serious challenges as many unscrupulous or incompetent suppliers have entered the SPL market. The World Bank has played an important role in addressing these challenges through its Lighting Africa program.[8]

Figure 3 Breakdown of the Addressable Market among Non-electrified Households for Off-Grid Electric Products and Services, Plus Grid Extension Based on the Assumed Ability to Make Monthly Payments[5]



2. Small Grids and Solar Home Systems

Figure 3 also identifies a group of some 58 million households that could be candidates for more costly electricity services including: 1) grid extension which, assuming service is available, often involves a connection fee that is beyond the means of normal households; 2) rooftop solar home systems (SHS), which have been sold to relatively prosperous consumers in remote areas of the developed and developing world at scales ranging from tens of watts to tens of kilowatts for many years; and 3) so called mini-grids.

Traditional mini-grids that use diesel generators to serve hundreds or even thousands of consumers within a compact service area are common in developing countries. They provide relatively expensive (often more than $0.50 per kilowatt-hour [kWh]) 110- or 220-volt ac power on a metered or flat-fee basis to mixed residential and commercial consumers, health clinics, and government offices that lack access to national grids, but that are willing and able to pay a premium for service to a local operator. To reduce their dependence on diesel, some mini-grid operators use biomass gasifiers to run converted diesel generators, and others use wind or small hydro-electric systems when feasible. While the role for mini-grid solar power may be large in the future, the upfront cost of building a solar PV mini-grid with sizable battery storage and a power inverter capable of providing equivalent standalone ac service is presently too high — thus, solar is seldom selected.[x]

Solar home systems use the same basic components as SPLs (i.e., PV panel, charge controller, battery, and one or more light fixtures), but serve the market for basic electricity service both within the usual SPL range, and well above it. Typically, these systems, which have solar panel sizes in the range of 15–100 W, cost between $500 and $2,000. SHS owners also value the grid-like experience of permanent fixtures, switchable lights, and one or more multi-purpose sockets. Unlike SPLs, which are manufactured, SHSs are built into the home and must also be maintained there. This issue, in addition to their larger size, adds to their upfront and operating costs. They may also include inverters to deliver ac power at still higher cost.

Nevertheless, when long-term financing is available, the flexibility and expandability of these systems, along with their ability to power loads like televisions and fans, make them popular in many developing countries. This is seen notably in India and Bangladesh, where social lending and micro-finance programs, such as those offered by Grameen Shakti and SEWA Bank among many others, along with government subsidies, make SHSs affordable in many rural communities. Further, high population densities in South and Southeast Asian countries are favorable for SHS dealers because servicing and installation operations can be much more efficient, and therefore less costly. By contrast, the SHS market has developed at a much slower pace in sub-Saharan Africa, where population densities are far lower, government incentives are less prevalent, and micro-lending is largely absent.

[x]A notable exception, with promise for solar mini-grid applications for rural hospitals and clinics, is the Organic Rankine Cycle (ORC) combined heat and power system under development by STG International.[9] The economics of the system, which requires direct normal incidence insolation, make it useful only in locations with frequent clear sky conditions, but the system can be preferable to both PV and diesel power for micro-grids. This is in part because the large fraction of solar energy that is not converted into electricity has value for thermal applications such as sterilization and bathing.

Although we introduced SHS as an off-grid technology, it is important to appreciate that many of these systems are used to provide backup power for rural households already connected to a grid. This is a very common situation in India where, despite a concerted and reasonably successful effort over the past decade to provide universal grid access, total generating capacity is far below the level that would be required to achieve universal electrification and seems likely to remain far below demand for many decades.[xi] The result is that, although our discussion so far has focused on the 1.1 billion rural poor in the developing world who lack grid access altogether, there is a very large and possibly equally durable market for small solar systems among an additional number of people who do not have *reliable* access to electricity.

3. Solar Micro-Grids

Recently, a number of examples of solar micro-grids (SMG) have emerged in India that provide many of the features of SHSs, but at SPL-like costs. Since they effectively eliminate the possibility of individual system theft and greatly reduce the system maintenance burden for subscribers, SMGs offer the possibility of providing improved electricity service within a much larger share of the developing world rural market.

There is no widely accepted definition of what constitutes a micro-grid, but we use the term here to refer to a dc distribution system, with captive generation, that is operated as a business and typically serves fewer than 100 separate households. For an SMG, the associated generation system might typically comprise less than a few kilowatts (kW) of peak module capacity along with a charge controller and the equivalent of several days of battery storage.

The economics and potential impact of SMGs on the small energy services market are analyzed in a recent publication,[11] which models a system consisting of a bank of batteries and PV panels connected through a charge controller to a low-voltage dc distribution network.[xii] The modeled system provides lighting and phone charging services through a network to subscribers who pay a one-time connection fee and a flat monthly service fee thereafter, regardless of their individual electricity consumption (which is not metered). This monthly fee, referred to as the levelized cost of service (LCOS), includes the levelized cost of electricity (LCOE) as well as shared and subscriber resident hardware, operations and maintenance, overhead and other administrative costs, plus a small profit.

The fact that battery and solar panel costs decline rapidly with increasing size across the range typical of SPLs, SHSs, and SMGs, gives SMGs a substantial relative cost advantage through economies of scale for an equivalent amount of delivered energy. This advantage obtains as long as the additional cost of providing the distribution network, after compensating for any distribution losses, is smaller than the cost savings that result from the use of larger batteries and panels.

[xi]The Indian Planning Commission has projected that achieving its target of universal electrification by 2030 would require an expansion of grid-connected generation to 960 gigawatts (GW) from its present level of approximately 200 GW.[10] There are many reasons for the shortfall and slow rate of generation expansion in India.[11]

[xii]The analysis is based on a model of the fee-for-service SMG operated by Mera Gau Power Corporation in Reusa, in the Indian state of Uttar Pradesh. Mera Gao is a rapidly expanding, privately owned company that currently operates similar SMGs in 380 villages.[12]

FINDING 2

Solar micro-grids take advantage of the cost reductions that can be achieved by aggregating the large number of small solar modules and batteries that would typically be deployed in individual solar home systems into centralized power sources with a small number of larger panels and batteries.

COMPARISON OF THE SOLAR MICRO-GRID AND SOLAR HOME ENTERPRISES

Economies of scale also extend to the cost of maintaining a single SMG serving a given number of subscribers as compared to the same number of individual SHS or SPL systems providing similar service. The maintenance obligation in the subscriber-model SMG inherently rests with the system operator and is included in the LCOS. On the other hand, practices vary widely among SHS and SPL sellers, and maintenance is frequently left to the buyer, who typically does not perform it, resulting in premature system failure. Some SHS sellers offer service contracts at additional cost to the buyer, or assume the costs of maintenance for one of more years at the insistence of the bank financing the system purchase. In that case, the costs are built into the sales price. When included as a business cost for hypothetical SMG and SHS regional utilities offering similar levels of energy service as well as maintenance, Campanella finds that the combined economies of scale for the SMG give over 60% lower monthly customer costs.[11]

SMGs have become economic only recently as solar module prices have fallen to their present levels, and should be expected to proliferate should module prices fall further. A corresponding drop in the cost of storage batteries would provide at least as strong a stimulus in light of their large share of the total system cost. When professionally installed and maintained by the equivalent of a regional utility that owns many similar systems within a compact service area, SMG services have the potential to be both more reliable and longer lived than individually owned systems. They also greatly reduce investment risk on the part of individuals for whom the prospect of purchasing a SPL or SHS using savings or borrowed cash (assuming the individual has access to financing) can be a significant barrier. Moreover, SMGs can be expanded, within limits, to meet demand growth — both in terms of service area and subscriber load. Thus they can provide backup or primary power for a limited range of applications to households in areas that are poorly served, and that are likely to remain so for many decades, by underpowered state and national power utilities.

FINDING 3

As module prices decline, solar PV with battery storage is becoming a viable alternative, or supplement, to diesel generation on isolated grids. It therefore represents a new option for rural communities that lack electricity service.

RECOMMENDATION 1

Solar micro-grids should be accommodated within national regulatory regimes in a way that protects public safety, keeps up with growth in demand, and provides reasonable assurances to investors. However, regulation should not equate to enforcing parity with large grids in terms of tariffs or technical specifications, since this will tend to drive costs up significantly and discourage further innovation and deployment in this important emerging application space.

4. Grid-Connected Solar – The Example of Kenya

In light of its high cost and intermittency, it might seem unlikely that solar power would play a significant role in the expansion plans of developing-country utilities, which are typically starved for low-cost, base-load capacity. However, for countries with small overall demand, building base-load capacity with traditional low-cost technologies, such as coal and natural gas, is often infeasible for a variety of reasons. For example, to be economic, coal-fired plants must have capacities large enough to exceed existing demand, which makes them risky and unattractive investments. Gas generators can be deployed economically at more modest scale, but like coal, access to gas typically depends on secondary investments in ports, pipelines, liquefied natural gas (LNG) terminals, railways, transmission lines, or other infrastructure that cannot be financially justified to serve a single power plant.

Consequently, fixed and leased fuel-oil plants (i.e., diesel, bunkers, and kerosene) are used extensively in developing countries, notably in sub-Saharan Africa, to provide incremental capacity as well as flexibility to national grids that are frequently too dependent on seasonally variable hydropower. This is in marked contrast to the situation in developed countries, which generate less than 2% of their electricity from fuel oil. For developing countries in aggregate, the corresponding figure is 20%, and for the least developed countries, it can be as high as 45%.[xiii] The cost of generating power using fuel oil is very high, and at \$0.26–\$0.42/kWh or more, it is close to double the cost of solar PV on an LCOE basis.[13,14]

These facts point to the possibility of using grid-connected solar PV, which can be built quickly and in small increments, to displace a significant amount of fuel oil (mainly diesel), and thereby reduce system-wide generating costs. Rose has investigated this opportunity in a case study on Kenya.[15] Kenya's grid is representative of the grid in many other African countries in that it has little marginal generating capacity and is heavily reliant on hydropower, with highly variable year-to-year output. As a result, power shortages are common and a substantial amount of fixed and leased diesel generation is deployed to meet demand. In 2011, 32.7% of the power on the Kenyan grid was supplied from fuel-oil generators. This is somewhat above the average value of 21.7% for countries in sub-Saharan Africa, but it is comparable to the 27.8% fuel-oil share for countries in Latin America and the Caribbean and 35.4% in Pakistan in the same year.[xiv]

While diesel generators can be ramped up or down relatively quickly to accommodate demand, solar PV output varies in an uncontrollable manner throughout the day and falls to zero at night. The main difficulty, therefore, in relying extensively on solar PV to displace diesel is providing a means of buffering the highly intermittent output of PV generators on the time scale of a day or longer without requiring additional investment in large-scale energy storage. A potentially very low-cost approach is to interoperate the added solar capacity with existing reservoir hydropower plants, which in Kenya account for almost 50% of installed grid generating capacity. The strategy is to partially curtail hydro output at times when solar output is high, and then release it during evening hours. In this scenario, water is retained in the reservoirs for

[xiii]This is based on limited International Energy Agency (IEA) data for only 100 out of 156 developing countries, and 15 out of 49 "least developed countries" (LDCs).

[xiv]These are unweighted averages that represent the generation mix of a typical country in the region based on available data for 100 out of 156 developing countries and only 15 out of 49 LDCs.[16]

short periods with only modest net daily accumulations or drawdowns, depending on daily and seasonal demand and hydrological conditions.[xv] In this way, the hydro reservoirs provide short-term storage for solar energy generated during daylight hours at no cost.

Rose uses a realistic representation of the generation assets available in Kenya in 2012, and three possible generation mixes in 2017 that would provide as much as a doubling of capacity,[15] as specified in the national energy plan.[19] Geothermal capacity plays an important role in the 2017 plan. Kenya, somewhat uniquely, has considerable potential geothermal capacity.

Four scenarios are considered:

1. A **2012** system scenario reflecting existing demand and supply.

2. An optimistic **2017 National Plan** scenario based on Kenya's 2011 National Plan, which assumes substantial investment in coal and gas supply infrastructure and high demand growth.

3. A somewhat pessimistic **2017 Geo High** scenario that assumes continued annual demand growth at the current rate of 6%.[xvi] Investments in renewable energy (geothermal and hydro) cited in the National Plan are made, while fossil energy investments in the National Plan are not made.

4. A more pessimistic **2017 Geo Low** scenario based on **2017 Geo High**, but with only half of the investment in renewables, and a substantial increase in diesel generation to keep up with growth in demand. This scenario broadly reflects the historical pattern of investment.

EFFECT OF SOLAR PV ON THE 2012 POWER SYSTEM SCENARIO

The calculations used to generate results for this scenario are based on a lowest-cost unit dispatch model, and include all generators and reservoirs. The entire load is aggregated into a single node, and all PV generation is assumed to be located in close proximity to the load at utility scale (i.e., it is implicitly assumed that there is no impact to the distribution system, and that the only incremental transmission and distribution costs are those associated with wheeling power onto the grid at the substation level in a manner consistent with other power plants).

Figures 4 and 5 show the generation profiles for a sample week in 2012 with 0 MW and 500 MW of PV added to the grid, respectively. In the figures, "Hydro RoR" and "Hydro Res" refer, respectively, to run-of-river (RoR) hydro (i.e., with no appreciable storage) and conventional reservoir hydro backed by a large storage dam. A comparison of the figures indicates that adding solar capacity has the effect of reducing diesel output, with hydro output shifted into the evening hours as solar output declines.

[xv]The Kenyan system operator currently employs a variety of disparate planning software tools, including VALORAGUA[17] and Wien Automatic System Planning (WASP),[18] in conjunction with comparison metrics such as LCOE for capacity planning.[19] Correctly assessing value to intermittent renewables such as solar and wind, however, requires methods such as those described here in which an integrated system model and temporal representation of supply and demand are employed.

[xvi]Annual average for the period 2009–2011.[20]

Figure 4 Hourly Generation Profile for a Sample Week in 2012 with No Solar Added to the System

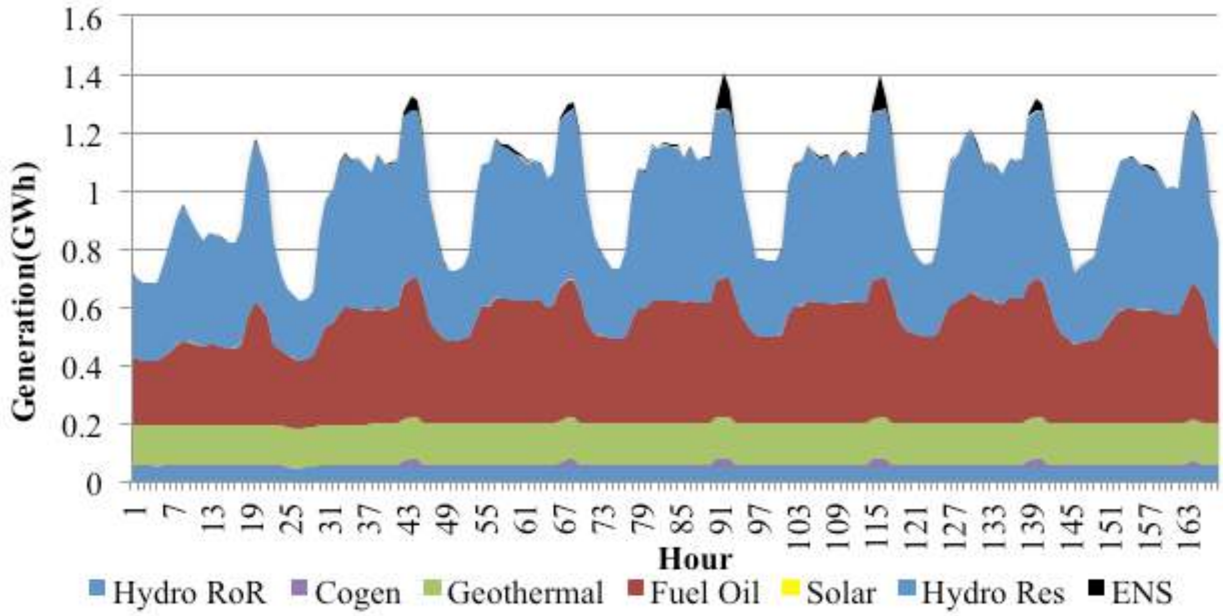


Figure 5 Hourly Generation Profile of a Sample Week in 2012 with 500 MW of Solar PV Added to the System

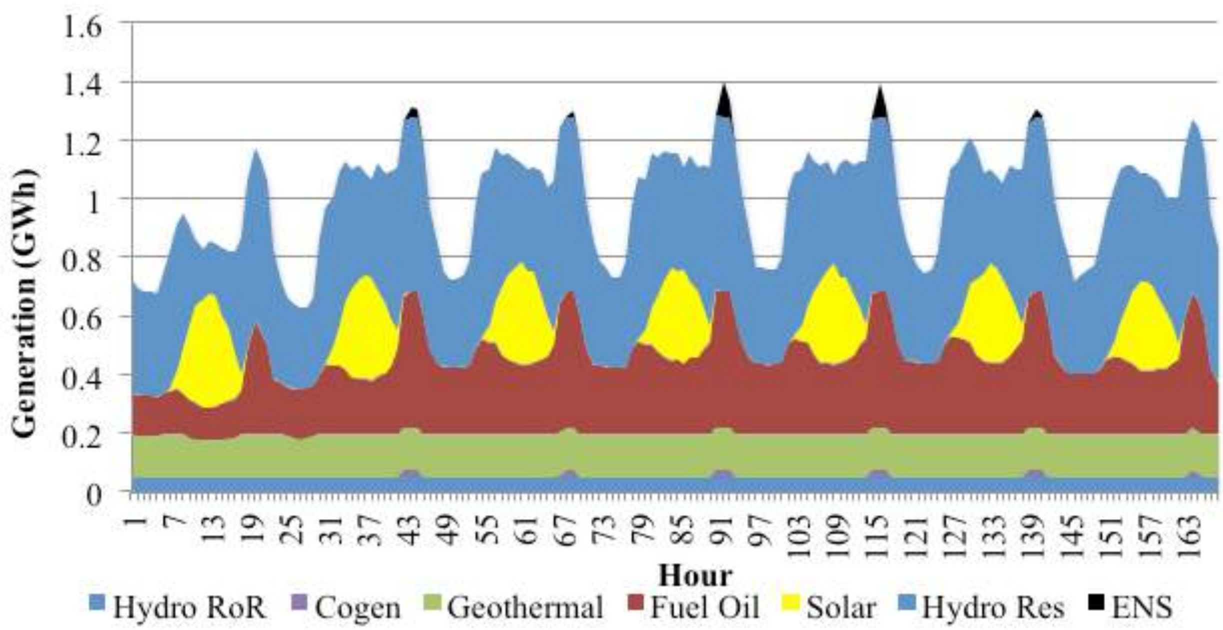
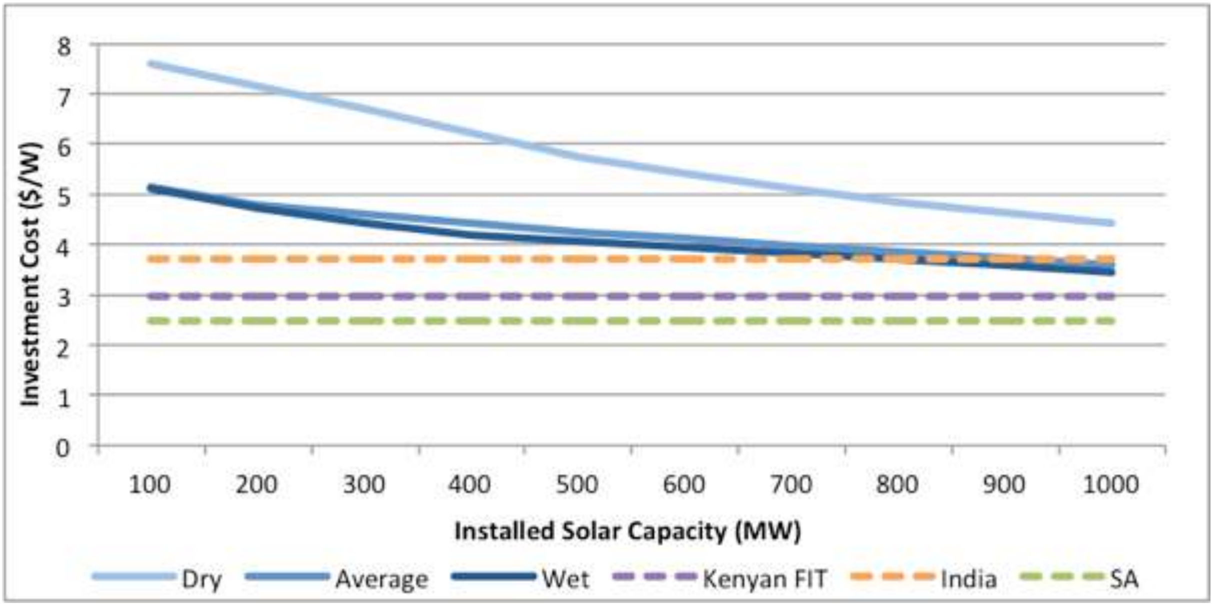


Figure 6 Value of Solar PV Investment at a Range of Penetration Levels



Note: Values shown are for the 2012 simulation year. The dashed lines provide a comparison to investment costs based on revenues from remuneration schemes in Kenya and actual prices in India and South Africa.

A small amount of unmet demand or "energy non-served" (ENS) occurs in both scenarios during peak hours. While in principle, ENS might be reduced by adding solar capacity and using the hydro energy conserved during daylight hours, the present hydro system presently lacks sufficient turbine power to convert this energy into electricity fast enough to meet the peak evening load.

The annual value of displaced diesel generation to the system operator can be readily converted to a value per watt of solar capacity. The result for a range of annual hydrological conditions for the 2012 system is shown in Figure 6.[xvii] The value per watt is equivalent to the amount the operator would be justified in paying a solar system owner for each watt he maintains on the system. Unsurprisingly, the value of solar PV is highest in dry hydrological conditions in which more production from fuel-oil plants is required.

Figure 6 provides a comparison of these values, with results estimated from recent renewable energy auctions in India and nearby South Africa.[21,22] For all hydro scenarios and penetration levels, maximum investment values are higher than those based on revenues from the current feed-in-tariff (FIT) for grid-connected solar PV in Kenya.[23] The auction comparisons show that up to 800 MW of solar PV panels could be economically feasible at bid prices seen in India. The investment value at any penetration level tested is justified as compared with the most recent bid prices experienced in South Africa.

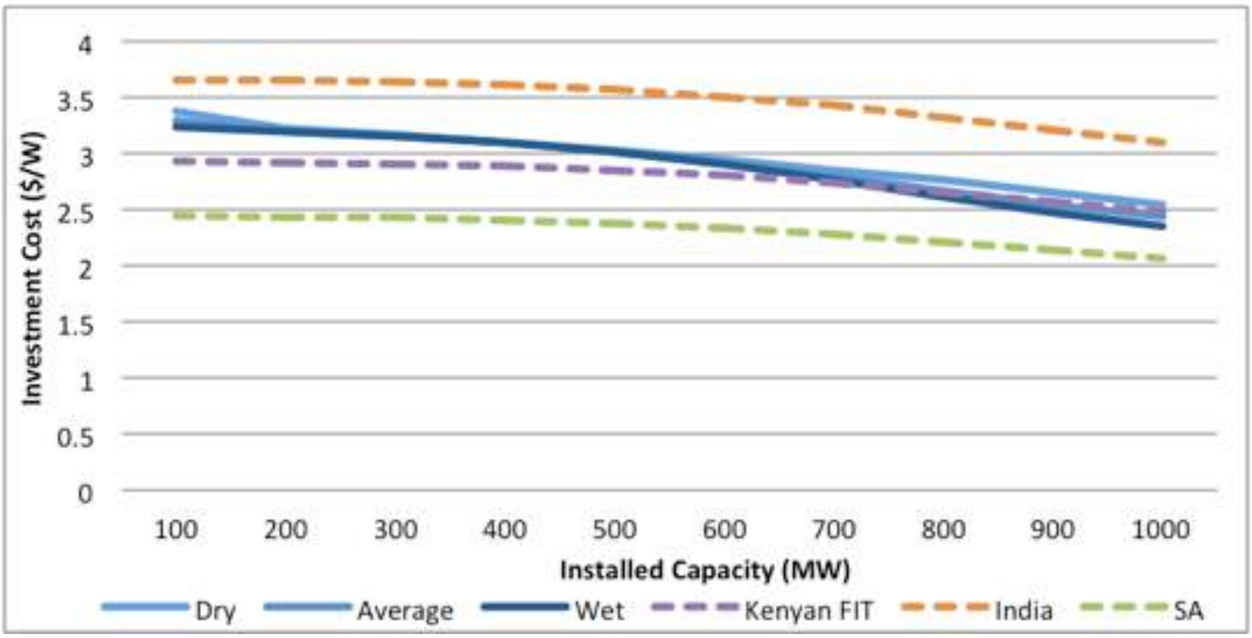
[xvii]The calculations depend strongly on discount rate and module lifetime, assumed to be 5% and 20 years.

[xviii]These comparisons are made to provide points of reference as the savings in system production costs in these countries will be different from those calculated for Kenya. A further check is the average cost of private solar PV projects in the least developed countries, which has been estimated at $3/W.[24] Calculated values remain above this level for all hydro scenarios and penetration levels, further indicating that high levels of solar penetration may be economically justified in Kenya.

TOTAL COSTS OF THE 2017 SYSTEM

In both the **Geo High** and **National Plan** scenarios for 2017, the addition of low-marginal-cost geothermal capacity and the elimination of high-cost kerosene generation from the system makes solar investment far less attractive. Indeed, it is uneconomic at any level in the **Geo High** scenario, and for the **National Plan** scenario is justified only at the South Africa auction rate for at most 400 MW. On the other hand, in the less optimistic **Geo Low** case (Figure 7), which serves as a proxy for lower investor interest in geothermal exploration and development, solar regains its investment appeal.

Figure 7 Value of Solar PV Investment in the 2017 Geo Low Simulated Year



Summary

The case study described in this paper illustrates the feasibility of using solar PV at grid scale to displace fuel-oil generation in a developing country context. It is remarkable that fuel oil (which provides 38% of Kenya's generation) could be substantially driven out of Kenya's system through *policy measures* to support interoperation of hydro and solar PV, without subsidies and assuming contemporary solar pricing.[xix]

The case of Kenya is far from unique. As we noted, fuel oil is used for power production in far greater quantities in many developing countries than in developed countries, and many developing countries have significant existing hydro reservoir capacity that could be used to mitigate the diurnal variability of solar PV. Conducting a broad survey of developing countries to assess the overall potential for diesel displacement would seem justified.

While the construction of more reservoir hydro capacity could help to accommodate high levels of PV and other intermittent technologies in many countries, we urge the use of system-scale modeling rather than comparative LCOE calculations to properly predict its value in the context of a system expansion plan. We have presented results that clearly show that, while the LCOE for solar power is a constant independent of the load curve as well as the amount of solar on the system and the detailed generation mix, the *value* of solar power to the system operator is a strong function of all three.

Without sufficient free storage in the form of curtailable reservoir hydro capacity, the economics of diesel displacement by solar are less obvious, but not necessarily unattractive. For example, it may be economic for island nations in the Caribbean and South Pacific that rely heavily on fuel oil but typically lack hydro capacity to transition substantially to solar PV if system operators can use existing diesel generators to compensate for solar variability directly. This depends on the ability of diesel generators to ramp up and down quickly (which may impact their maintenance costs and life spans unfavorably), as well as the amount of additional fuel consumed by ramping, and the impact on system costs of fixed capacity charges owed to merchant generators. As in the case study on Kenya, an appropriately granular system analysis is required to understand overall cost implications.[xx] We also note that the mode in which PV is deployed is likely to interact with land use constraints since it is clear that island nations, or densely populated countries like India and Bangladesh — unlike those of sub-Saharan Africa — may be forced to favor rooftop over ground-based systems, irrespective of their higher cost.

[xix]Any investments in transmission and distribution that may be required in a system expansion plan are admittedly not considered in the models we have discussed — therefore, we stop short of claiming that only policy changes are required here. However, to the extent solar could be added into the distribution network in a distributed manner with substantial choice as to location, it is reasonable to think that additional grid costs would not be exorbitant. To deal with this correctly would require a full multi-nodal analysis.

[xx]Concentrated solar power (CSP) with salt storage can provide dispatchable solar power during evening hours, and it is an obvious candidate for diesel displacement that, unlike PV, does not necessarily depend on reservoir hydro. However, we have not included an analysis of CSP in the Kenya case study for two reasons: a) it is presently more expensive than PV and cannot be built as quickly nor in small increments, which creates a barrier to investment that may be prohibitive in the developing country context; and b) CSP is harder to site because it requires clear skies and flat land. Consequently, in its present state of development, CSP is seldom preferred for developing country applications.

Finally, while we have focused on the use of hydropower to compensate for variable solar output, we note that when low-cost natural gas is available, adding fast-ramping gas turbo generators may be an attractive means of performing the same function. The advent of low-cost gas in developing regions, such as East Africa, as a result of offshore finds in Tanzania and Mozambique, makes this — as well as direct displacement of fuel oil with gas — a credible near-term option. We recommend that in these situations, in addition to using system-scale analysis to develop lowest-cost capacity expansion plans, governments examine the possible benefit of deploying solar as a means to offset domestic gas consumption and thereby increase export revenues that might then be returned to ratepayers or deployed to greater overall economic effect.

FINDING 4

Large amounts of solar generation can be incorporated into developing country grids in a manner that is financially attractive and technically feasible, provided that more expensive grid-connected generation (notably diesel) is available to be displaced and that a variable supply exists to offset diurnal solar variability. Extensive reservoir hydro in many sub-Saharan African countries can meet this offsetting requirement.

RECOMMENDATION 2

System planners in developing countries should employ system-level models to make investment decisions based on the value of solar rather than its cost, especially when their systems make use of expensive diesel generation that solar could displace.

5. Concluding Remarks

This paper has offered a number of examples of the distinct roles solar technologies are playing, and could play in developing countries at many scales — from the smallest scale, in which billions live without reliable access to electric lighting, charging services, or the ability to power small machines and appliances, to the grid scale where we conclude solar power can be introduced economically at a high penetration rate to displace more expensive alternatives, such as diesel generation. We have also pointed out that unique opportunities are beginning to emerge as a result of low solar prices for small grid systems powered exclusively with solar PV that can provide primary and backup power in rural areas where the realization of reliable grid power is decades in the future.

Technologists and entrepreneurs are appropriately beginning to pay attention to these opportunities, and are using design, manufacturing, and business know-how to address them. Programs that support serious efforts to develop and commercialize novel solar applications at all scales are needed, and should be supported by developed country governments and the international community at large.

Notes

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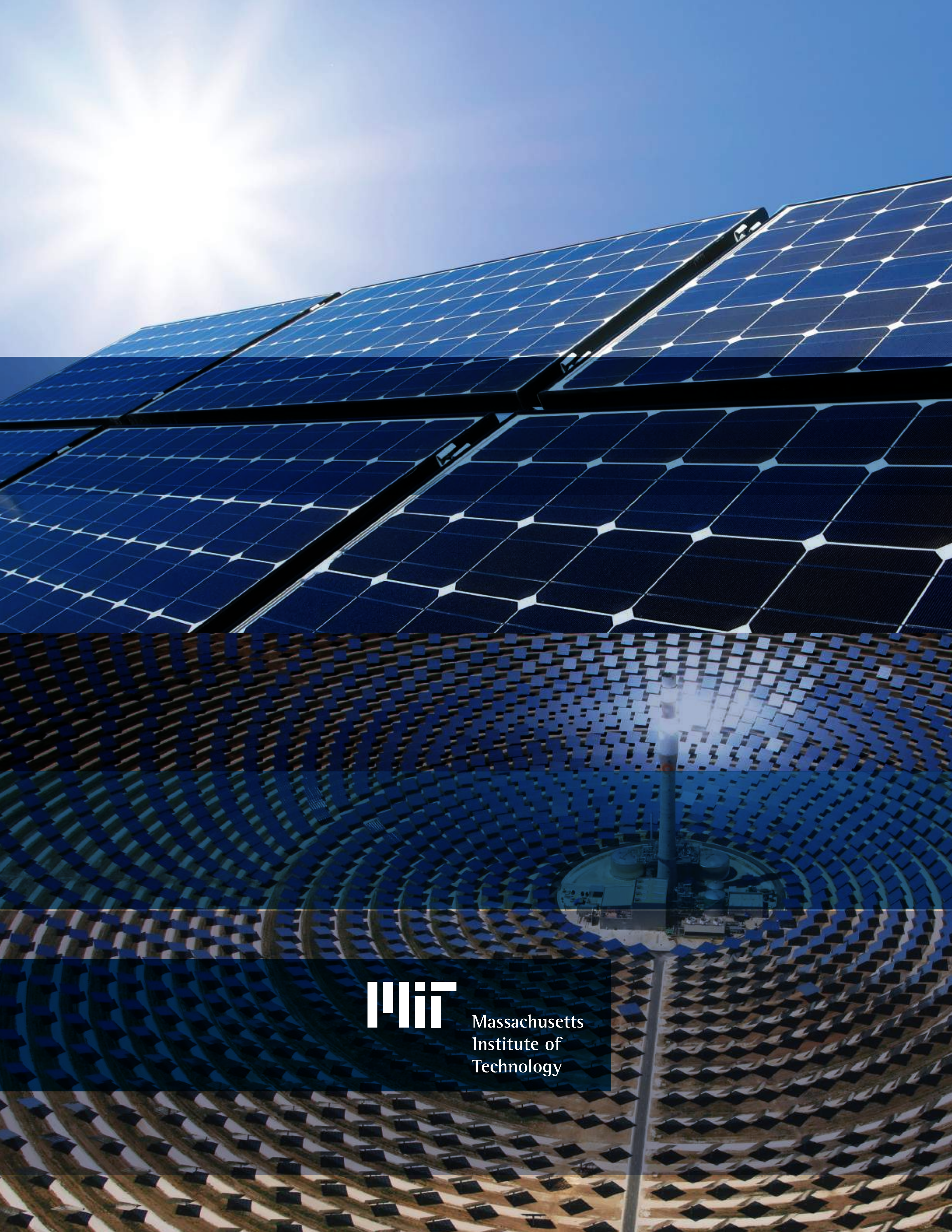
Acronyms

C-ROADS	Climate Rapid Overview and Decision Support
CSP	Concentrated Solar Power
EGG	Engineering Global Growth (Tanzania)
ENS	Energy Non-Served
FIT	Feed-In Tariff
IEA	International Energy Agency
IFC	International Finance Corporation (World Bank)
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Service
LDC	Least Developed Countries
LED	Light Emitting Diode
LNG	Liquefied Natural Gas
OECD	Organization of Economic Cooperation and Development
ORC	Organic Rankin Cycle
PV	Photovoltaic
RoR	Run-of-River
SHS	Solar Home System
SMG	Solar Micro-grid
SPL	Solar Power and Light
SRES	Special Report on Emissions Scenario
WASP	Wien Automatic System Planning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