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Solar power in developing countries: will PV-supported micro-grids provide the next wave of demand?

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ABSTRACT

Traditional markets for PV will be scaling back on the level of demand for PV, but there are already signs that the developing countries will be stepping in to pick up the slack. This will be a combination of both standard grid-connected and micro-grid types of installation. Micro-grids present the opportunity for countries to develop a cell-phone type of model for power distribution whereby regions without electrification can have a regional power source that allows for local access. This market is projected to become significant in the next several years, as the access to lower cost PV makes this option more easily implemented. This paper evaluates the market size of what has been an overlooked 'niche' for PV and describes the key considerations for a micro-grid installation, the developing conditions favouring installation, and some of the specifics of a micro-grid case study. The point is made that the grid-connected market will be increasingly assisted by the micro-grid segment as the latter becomes a significant source of PV demand and energy provision. Contrary to common notions, the micro-grid and hybrid off-grid segments will play an increasing role, even in areas with a grid in place.

Introduction

The beginnings of new market dynamics are becoming apparent in the PV industry. The trend to reduce incentives is already gaining momentum and the elimination of feed-in tariffs is likely in the next few years. This will certainly have an impact on the demand from the traditional demand sources. In the past decade it has been mostly Europe that has driven the demand for PV, but this is rapidly changing as country by country the surges begin to decrease. Spain came and went, Italy was big last year but is backing off, the Czech Republic is no longer mentioned, and now there is even the unthinkable – Germany may be approaching 'saturation'. In the meantime, Greece and Portugal – while they are awash in sun – have a very cloudy economic future to support any significant PV implementation. The US is engulfed in a race to cut spending, and Japan is still recovering and rebuilding its economy.

So where are the drivers for the next wave of PV adoption? The global PV market cannot depend on the bellwether countries to increase their PV demand and expand the market. Developing countries are in a unique position to step in and pick up the slack, and it may well be in the context of the micro-grid that this will happen. Bottom-up electrification initiatives are happening in the developing world, and are proving to be efficient and cost-effective entry-level strategies. Micro-grid applications for rural electrification represent a major opportunity. While many systems have historically featured diesel-distributed energy generation, the largest growth sector opportunity is for PV, in some hybrid power generation type of mode, as PV steadily replaces carbon-based power generation [1–5].

Developing countries with growth opportunities

Because energy is a requirement for economic growth, there is an increased focus by the various developing countries on addressing this need. Recently, many countries have established rural electrification programmes and national electrification agencies. The UN Millennium Development Goals (MDGs), adopted in 2000, contain no targets specifically related to energy; however, Richenda Van Leeuwen [6] of the UN Foundation points out that 2012 has been declared by the UN as the International Year

	Population without electricity (millions)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
Africa	587	41.9	68.9	25.0
North Africa	2	99.0	99.6	98.4
Sub-Saharan Africa	585	30.5	59.9	14.3
Developing Asia	799	78.1	93.9	68.8
China and east Asia	186	90.8	96.4	86.5
South Asia	612	62.2	89.1	51.2
Latin America	31	93.4	98.8	74.0
Middle East	22	89.5	98.6	72.2
Developing countries	1438	73.0	90.7	60.2
Transition economies & OECD	3	99.8	100.0	99.5
World	1441	78.9	93.6	65.1

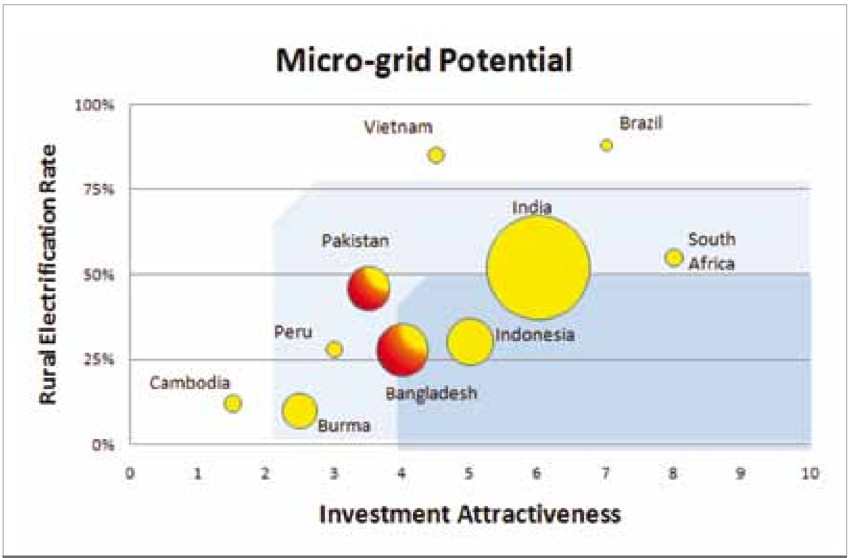
Source: International Energy Agency (IEA) 2010 [7]

Table 1. Summary of the extent of the need for rural electrification among different developing regions: regional aggregates of electricity access as of 2010.

of Sustainable Energy for All, and the goal of universal energy access by 2030 is one of the three goals of the Initiative and the Year. Citing the World Energy Outlook 2010 on energy poverty [7], the focus of which is to expand energy access at the household level, Van Leeuwen emphasizes that over 1.4 billion people, 85% of whom live in rural areas, have no access to electricity. Sub-Saharan Africa remains the biggest challenge, where nearly 70% of the people are without energy access. Van Leeuwen corroborates that there is a sizeable market for micro-grid and off-grid electrification projects, consistent with the International Energy Association's illustration that, in order for those 1.4 billion people to achieve access to energy by 2030, 70% would have to be supplied by micro-grid (75%) or off-grid installations (25%) [7].

The SolarVision analysis sees the growth opportunity for developing regions as significant, especially starting in the next few years as a few key elements fall into place: the lowering of the price for solar PV, the continued rise in diesel fuel costs, the increasing need to address developing countries' desire for local energy, the growing focus by governments, and the increase in urgency for pollution reduction from carbon-based sources. Grid extension will of course play a role, but the decentralized options will have a major contribution as the extension will be too expensive in some cases.

The SolarVision forecast for micro-grid growth indicates that the levels of micro-grid/partial-grid PV demand could grow to nearly 10GW in the next decade, and then approach a significant fraction of the levels of grid-connected PV demand in subsequent decades. Fig. 1 shows some of the details behind this visionary forecast – namely the drivers and relative investment potential. This chart presents the mix of developing countries and the PV micro-grid opportunity. The level of micro-grid viability increases (blue tones) to the right, as does the investment attractiveness in general terms. The vertical axis is the rate of rural electrification. Note that for some of the developing countries, the urban electrification is nominally high, but there is still a driver for micro-grid adoption in a partial- or auxiliary-grid mode, as will be further discussed below. The solar potential is the degree of 'yellow,' and the size represents the number of people in that country without direct access to electricity. For clarity and illustrative purposes, only a select subset of countries is presented.



Source: SolarVision

Figure 1. The PV micro-grid opportunity based on IEA 2010 assessments.

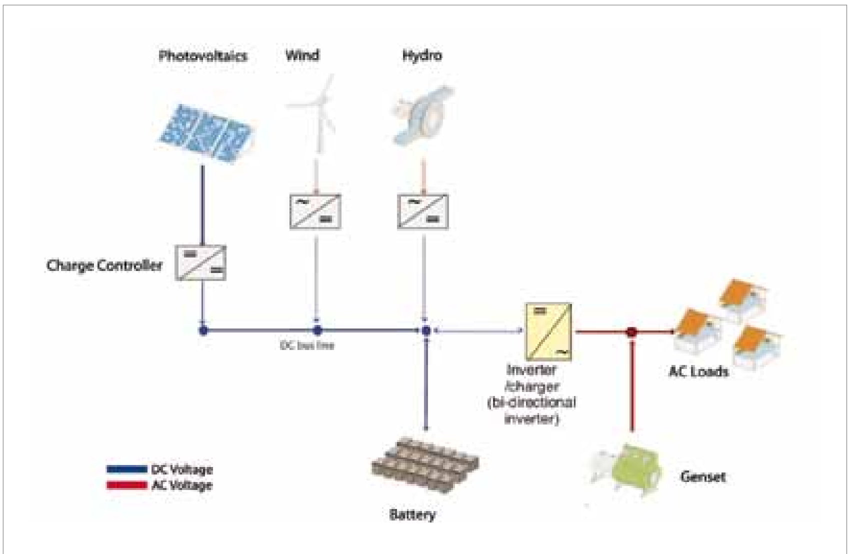
As an example of some of the development financing, one source is coming from the Asia Development Bank (ADB). This organization has pledged US$9 billion, including projected private sector funds, for support of on-grid and partial-grid developments to the level of 3GW in the next two years – a very aggressive strategy. While the majority is grid connected, there will still be micro-grid deployment for rural electrification.

At present, less than 0.25% of Asia's overall electricity production comes from solar power, but the aim is to increase that contribution to 3% to 5% in the near future with financial support using seed money. Seethapathy Chandler, chairman of the ADB Energy Committee, has indicated that there is significant potential for solar energy; he has also highlighted that "solar is already cheaper in [various] places where they have to use diesel generators" [8].

What is a micro-grid and how is PV a part?

Solar PV plays a vital role in meeting the basic energy needs for such services as lighting and clean water in the developing world; however, those needs are growing quickly while resources remain few. These conditions are perfectly suited to a PV micro-grid solution, which provides reliable, comparatively low-cost power in a more amenable timeframe than a traditional grid. An example of rural electrification solutions with mixed sources is shown in Fig. 2.

A micro-grid (or mini-grid) is a village- or district-level concentrated web of distributed energy sources, energy storage and loads of up to 500kW that normally operate connected to an electricity grid. The various energy sources are tied together on their own feeder, which is then linked to the grid at a single point of common coupling. A micro-grid may be viewed as peer-to-peer transmission of energy, which is more networked and symmetrical, without a master controller or central storage unit that is critical for operation. Its reliability hinges on its diverse generation sources and ability to function and be controlled independently as needed (i.e. during a brownout or blackout). Micro-grid energy sources may consist of an evolving mix of standard and renewable options. In a manner similar to



Source: Alliance for Rural Electrification (ARE)

Figure 2. Examples of mixed-source rural electrification solutions.

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Source: ARE

Figure 3. Micro-grid in Tibet.

the early hybrid cars, the beginning stage may have more fossil fuel utilization, but this would decrease with time. Standard power-supplying sources in a micro-grid may also utilize novel equipment such as a microturbine to maximize efficiency while being augmented by PV. Over the course of time, the energy mix would become dominated by PV and possibly other renewables such as small wind, micro-hydro and biogas. Figs. 3 and 4 show examples of a micro-grid in Tibet, and rural off-grid PV in a small village in Cuba and in South Africa.

Micro-grids can be similar to the cell-phone model

The cell-phone model for micro-grids is a low-cost, limited-resources approach to energy delivery on a limited scale and which targets small localities. Original implementation of cell-phone technology and subsequent expansion of coverage occurred very rapidly, at comparatively low cost, with limited infrastructure and without overburdening the existing telecom infrastructure. In fact, in developing countries more people own cell phones than refrigerators. Just as cell phones are helping to lift the poor out of poverty, micro-grids could help shoulder developing countries' growing thirst for electricity without overburdening aging transmission lines or investing massive amounts of capital and time in constructing traditional power plants to meet this demand.

The technological development that distinguished the early cell phones was the use of multiple cell sites and the ability to transfer calls from one site to the next without the need for costly landline infrastructure and maintenance. Similarly, a single micro-grid or aggregate of localized micro-grids may operate independently of a centralized grid by switching between diverse power sources. This is especially important in developing countries such as Lebanon and India where the population endures episodes of prolonged power outages. Not only is the grid unreliable, but grid transmission can cost upwards of US$1 million per mile, making grid extension to rural villages or other areas with low population densities too expensive. As an alternative to grid extension, the cell-phone model allows for staged implementation of energy provision.

Key issues: affordability and reliability

The affordability of PV is improving as module costs drop and the incentive increases with volatile oil prices. Further module price decreases will come, and as new modes of energy storage become viable, the PV-integrated micro-grid becomes increasingly realizable by the developing countries with resources that must be prioritized.

Van Leeuwen [6] views increasing global recognition, supportive and predictable government policies, and workable payment structures as being critical to facilitating a reimbursement environment that would be attractive to private interest in rural micro-grid projects in developing countries. SolarVision has been providing guidance to a range of rural electrification customers in developing countries, including India and Latin American countries (such as Panama, Cuba and Chile), as well as Azerbaijan, Indonesia and some clients in Africa. Customers are trying to understand not only the various renewable energy technologies of micro-grids, but also the complexities of short- and long-term financing. Many different sources of financing and creative pricing strategies can and must be used to meet diverse electrification needs throughout the developing world. Some of these include microfinance loans, public/private cooperatives, international funds, standard bank loans and targeted subsidies.

Simon Rolland, secretary general of the Alliance for Rural Electrification (ARE), asserts that easier access to finance and the capacity of business and/or government to institute an easily applicable and replicable business model are integral to the success of rural micro-grid electrification projects. Rolland [9] also points out that developing a business model for a project involving rural electrification with renewables can be difficult due to the complexity of the technology involved; varying resource and load requirements; and questions of who owns, operates and maintains the system.

The key advantage of a micro-grid is its use of dispersed generation sources and its inherent reliability – the ability during an electricity grid outage to isolate itself from the grid seamlessly, with little or no disruption to the loads within the micro-grid. In India, where electricity is subsidized, the intermittency of the grid is so common that wealthier consumers who can afford it over-invest in backup off-grid systems. These households often have two switches – one flipped on when the grid is up and the other when the grid is down. In a more extensive configuration this arrangement acts as a partial auxiliary-grid.

At the other end of the spectrum, small villages exist in India where, although the grid may pass overhead, the expense of tying in the village is viewed as too great when compared to the limited income generated by villages with low consumer density. The micro-grid concept is a well-

Source: A. Skumanich

Source: ARE

Figure 4. Micro-grids deployed in Cuba (left) and South Africa (right).

Location	Application	Average energy output	Maximum daily peak load	Microgrid electricity generating resources					Battery storage	Funding sources
				PV	Small wind	Small hydro	Genset(s)	Gas turbine cogen		
Naperville, IL, USA	Substation operation	4,500kWh/yr	1.31kW	(5kW)						Local government, private
UCSD, CA, USA	University (small city)	221,000MWh/y	42MW	(1.2MW)			(Diesel)	(30MW)		State government, private
Bellavista, Jambeli Archipelago, El Oro province, Ecuador	Households, school, naval station	97,090kWh/yr	26kW	(35kW)	(20kW)		(Diesel)		✓	N/A - model only
Padre Cocha, Peru	Households, commercial, industrial, institutional	109,500kWh/yr	22kW	(28kW)			(Diesel)		✓	International, local government, private
Lao PDR	Households	57,488kWh/yr	8kW	(2kW)		(12kW)	(Diesel/ Jatropha)			Private–public partnership

Table 2. Comparison of various micro-grid configurations.

suited strategy for electrification of these rural villages. Combining a variety of distributed resources enables a community to generate sufficient electricity in the event of a prolonged power outage in order to operate emergency services, such as a police station or hospital, and ensures that citizens have sufficient power to meet their essential needs. Likewise, when the electricity grid disruption ceases, the micro-grid reconnects flawlessly to the grid, without adversely affecting the quality of power. Micro-grids are completely compatible with a centralized grid and serve as purposeful, more affordable components of grid expansion [4]. Again, this constitutes a partial-grid mode.

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The selection of a particular micro-grid technology can have far-reaching consequences for the sustainability of the services. Technical failures of even the most perfectly matched micro-grid system may result from an absence of indigenous capability. Community involvement (of both men and women) is necessary for successful operation, whether the system is locally or regionally maintained. Locally trained staff members often migrate to urban areas to exploit their new skills. In view of this, a consistent, reliable source of power from any micro-grid system depends on selection of trainees, particularly women, who are likely to remain in the area. Rolland [9] suggests that the best scenario is where a micro-grid project is community initiated but privately managed. This relationship strikes an ideal balance between community, government and private business.

Implementation: working systems in different contexts

Hybrid power systems typically rely on renewable energy to generate 75–99% of total supply [10]. The dominance by renewables empowers these systems with independence and lower energy prices over the long term. In many cases, a diesel generator is used as a backup to assist during periods of high loads or low renewable power availability. The battery backup size can be lower and suffers less stress than in a 100%-renewable power system, prolonging battery lifetime significantly and reducing replacement costs. Thorough site and community surveys are a basic foundation for any mini-grid project, regardless of the technology selected. Oversizing certain components, such as wiring and inverters, can accommodate future demand growth and facilitate micro-grid expansion.

Implementing sustainable hybrid micro-grids involves complex technical, financial and organizational issues which must address the end-users and their needs, capacity building and training, financing, and institutional strength [11]. Table 2 summarizes the technical aspects of several case studies of hybrid micro-grid installations in the US and developing countries.

Case study: City of Naperville, Illinois, USA

Very few examples of micro-grids exist in the US; however, interest continues to grow. The city of Naperville, Illinois, has made significant efforts over the last two decades to update its power grid and incorporate smart grid technology to improve reliability, cost competitiveness and efficiency. The city is partnering with the Galvin Electricity Initiative, a non-profit initiative to build smart micro-grid projects based on its 'Perfect Power' system architecture. While much of the city's focus is on utilizing smart grid technology to improve efficiency and reliability, it has also expanded its use of renewable energy by adding a 25-module, 5kW solar array to one of its substations. The array generates solar energy to offset the substation building's common energy requirements. The solar array's estimated yearly energy production is 4500kWh.

Case study: University of California at San Diego (UCSD), California, USA

UCSD's campus-wide micro-grid is recognized as one of the most technologically advanced in the world. It serves a 1200-acre, 450-building campus with a daily population of 45,000, running two 13.5MW gas turbines, one 3MW steam turbine and a 1.2MW solar-module installation that together supply 221GWh/yr, which is 86% of the campus's annual power [12]. UCSD recently began demonstrating the integration of smart grid technology with onsite renewable energy production to provide the power system optimization and energy market optimization capabilities necessary to ensure the reliability, energy efficiency and cost efficiency of the school's micro-grid. The smart grid improvements will also manage the response of the micro-grid to market energy prices on an hourly basis. This case is an example of a partial-grid connection in that, although the UCSD system is nominally a micro-grid, it operates in parallel with the grid – the latter supplying the remaining 14% of the needed energy.

Case study: Bellavista, Jambeli Archipelago, El Oro province, Ecuador

Hybrid micro-grids are, under most scenarios, the cheapest long-term option for rural electrification. Site-specific simulation of a PV and small-wind hybrid micro-grid system operating in a village on the island of Bellavista, located in the Jambeli Archipelago, El Oro province, Ecuador, was conducted by ARE using HOMER, a software tool developed by the US National Renewable Energy Laboratory and widely used in rural electrification planning. Modelling results demonstrate that a hybrid power system combining PV, small wind and a diesel generator set (genset) is the least expensive solution if small hydro is not an option. This combination has a low consumption of diesel fuel, and final costs determined by the model are 23% lower than hybrid PV, hybrid small-wind and 100% diesel generator systems. Of particular note from the modelling results is that, under the site-specific conditions presented in this case, diesel generator systems become prohibitively expensive when the fuel price per litre increases from $0.70 to $1.50 [10].

Case study: Padre Cocha, Peru

Padre Cocha is a small village of nearly 2500 people situated in the Peruvian Amazon, where almost 95% of the population has no electricity supply due to the expense of grid extension and diesel fuel. In July 2003, a remote area power supply (RAPS) hybrid micro-grid system serving 240 consumers began operation. The RAPS system consists of two solar arrays with capacities of 14kWp and 150kWh/day (totalling 300kWh/day), and a diesel generator of 128kW. Each solar PV array includes 180 solar PV modules of 80Wp each, 240 storage batteries of 375Ah, rectifier systems, a charger and a 40kW inverter. The system delivers electricity to the distribution grid at 240V (AC). The total daily average energy consumption is nearly 220kWh, 30% of which is produced by PV and the rest by the diesel generator [11].

The total cost of the system is estimated at US$577,000, but in 2004 the organization that implemented the system reported an expenditure of $2 million on administration, promotion, studies and equipment acquisition, mainly financed by a private donor, the International Lead and Zinc Research Organization, the Common Fund for Commodities, the Sandia National Laboratory and the Loreto Regional Government. The operation and maintenance costs, including purchase of fuel and provision for battery replacement, are US$37,704 per year. Since the RAPS was commissioned, a local community organization has been responsible for the system's administration, operation and maintenance [10].

The local community fully participated in this project; however, the community's technical and management capacity is limited and the system was incapable of generating its own revenues to cover the O&M costs. Based on regional socioeconomic studies, various tariff schemes have been considered in an effort to cover management, operation, and maintenance and replacement costs, but the current financial performance of the RAPS system is not sustainable and a higher tariff needs to be established [10].

Case study: Lao People's Democratic Republic (PDR)

Sunlabob, a private renewable energy provider based in Lao PDR, collaborated with a local non-governmental organization to involve the local community in bringing electricity into their homes. This particular hybrid micro-grid system combines a 12kW small hydro generator with a 2kWp PV system and a 15kVA diesel generator, which is also capable of operating on jatropha biodiesel. The three-phase grid mainly operates on the hydro generator. With a daily peak load of 8kW, the system meets nearly all of the village load demand, and since the energy from hydro and PV is large enough to cover these needs, the diesel genset is almost never used. Batteries are not an integral component of this system, since hydropower is available for night loads. Solar PV was added for the dry season, as well as the genset for emergency backup.

Sunlabob participates in a community-tailored private–public partnership, where public partners funded the fixed assets (public infrastructure and village grid), after which ownership was then legally transferred to the village. Sunlabob, as the private local energy provider, financed the moveable assets. Consequently, Sunlabob owns and is responsible for the power generation system and charges a fee to each household based on its consumption. The company employs two villagers to operate the system and collect the fees. Although the village officially owns the micro-grid, the maintenance is carried out by Sunlabob. The community also participated in the investment with in-kind work for the construction and therefore remains vested in the ongoing successful operation of the system.

Sunlabob plans to expand its local distribution network and connect it with a nearby grid in order to attract interest from the utility by highlighting the fact that small hybrid grids can supplement the main grid with added generation infrastructure and capacity, as well as social support. This provides a unique and seemingly effective organizational set-up, benefiting end-users, the utility and Sunlabob.

This project demonstrates the different challenges facing a private company looking to pursue a rural electrification project; high investment costs, low subsidies, obligation to collaborate with the utility, long-term collaboration and relations with local players were all issues that Sunlabob encountered. The project is running without any kind of public support, and this case study shows that long-term private sector involvement is possible if the right support schemes are set up, particularly in terms of regulatory flexibility [10].

Much has been learned, and is now being implemented

Several examples reflect some of the learning points. From a recent SolarVision engagement in Cuba [2,3], a key point highlighted was that high-level government support and commitment of the populace are necessary for a successful energy reinvention on any appreciable scale. Cuba created its own path towards a new energy paradigm by applying concepts such as distributed generation, efficiency, education and the gradual expansion of solar energy across the country.

India's long-view commitment for expanding its solar capacity is another key point. Such a strategy shows the intent of government support and specifically targets opportunities for entrepreneurial investment. India also intends to request both monetary and technological backing from developed nations in order to meet its Solar Mission objectives. Without such an ambitious plan, this type of support could not be won.

Financing of solar PV projects, whether micro-grid scale or large utility scale, remains a limiting factor. Limited financial resources from international non-profit-making organizations, private ventures and governments have created a pent-up demand for PV in the micro-grid context. However, the prices are dropping and the urgency for energy is increasing to the point where these developing countries are at a crossover point and seriously looking at how to implement some mode of micro-grid.

> "Financing of solar PV projects, whether micro-grid scale or large utility scale, remains a limiting factor."

The broader view is that these countries are interested in hybrids of solar with cogeneration. The hybrid mode combines a mix of PV, diesel and/or other elements such as micro-hydro. While the upfront costs of buying diesel generators may be dramatically lower, operational costs are increasing. Strictly diesel systems simply do not make sense when considering volatile oil prices; however, use of a diesel hybrid system can reduce the cost of batteries, which can be expensive and unreliable if not properly maintained [9]. Indeed, in some regions (e.g. Nepal) the cost of petrol is even higher because of transportation, and micro-grids are already financially viable and are being implemented.

A key area in which research is needed, according to Van Leeuwen [6], is smart grid technology applications with a focus on efficiency that may leapfrog into these newly electrified rural areas – again similar to the cell-phone model. Additionally, she would like to see more research and development of energy-efficient appliances for use in developing countries.

Conclusion

PV is well suited to being a key component in micro-grids. The global grid-connected PV capacity is rapidly approaching 30GW, with most of this growth taking place in the last 10 years. Micro-grid and off-grid segments are showing strong potential to become major components in the PV market. The estimated opportunity for micro-grid/partial-grid installations starting in the next several years could reach levels approaching 10GW in the next decade. Indeed, as the leading developed nations scale back on incentives, and even on the actual installations, it is likely that the micro-grid market will ramp up into a position that will provide a major demand market for solar. A noteworthy point is that even in countries with a grid, the intermittency of the grid itself is driving the consideration of micro-grids as support.

The worldwide movement away from fossil fuel energy sources to renewables is a trend based on the desire for energy independence, the reduction of greenhouse gas (GHG) emissions and limited fossil fuel resources. Karen Ward [13], HSBC's senior global economist, recently reported in a research note that there could be less than 49 years of oil supplies left, even if demand were to remain flat. Fossil fuel reserves are finite. Derived from this movement away from fossil fuels is recognition among industrialized and developing countries of the need for non-standard energy provision options. This is especially true in developing regions which lack the basic infrastructure.

The 'hot bowl of soup' metric needs to be added to the more standard ones of dollars per watt and levelized cost of energy. What is this metric? The amount of pollution coming from heating a bowl of soup. There is more air pollution coming from the heating of a bowl of soup in the developing countries than in the grid-connected countries, even with the carbon-based power plants in the latter. Micro-grid implementation is urgently needed to move rural populations away from burning wood and fossil fuels, which has a disproportionate impact on the global carbon levels and is ruinous for the physical and human landscapes exposed to such measures.

The electricity generated by PV and PV-integrated micro-grids is clean, renewable and reliable. The implementation of micro-grids is starting to show promise and is becoming a significant source of market opportunity as well as of energy for global consumption.

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