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PHOTOVOLTAIC MODULE ASSEMBLY AS APPROPRIATE TECHNOLOGY IN PAKISTAN

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ABSTRACT
This paper describes photovoltaic module assembly as appropriate technology in Pakistan. The paper begins by describing a three-week workshop in July 2009, in which a group of twenty unemployed people in Karachi, Pakistan were successfully trained in photovoltaic module assembly. Module components and assembly techniques are summarized. Factors pertinent to sustaining the project as a viable business enterprise, including the beneficial social externalities are discussed and analyzed. System designs for use in both urban and off-grid rural settings are proposed and energy outputs from the systems are simulated. In summary, the paper presents a thorough case study for expanding the utilization of photovoltaic technology in developing nations.

INTRODUCTION
With a population of over 170 million, Pakistan is the sixth most populous nation in the world. A developing country by almost all standards, the poverty rate is currently estimated at 25% and the overall literacy rate is 56% [1]. Pakistan's economy is predominantly agro-based, though efforts are being made to develop and expand the industrial base. One of the greatest challenges facing the country is providing for a rapidly growing population. Despite a population growth rate of over 2% per year, the health and education sectors remain largely neglected, with the largest share of the annual federal budget going towards defense. These budget priorities have led to high infant and maternal mortality rates as well as shortages in housing, water and energy. A related challenge is the problem of rural-urban migration whereby vast numbers of people from the countryside migrate to the major cities in search of employment, contributing to the problem of urban sprawl. In summary, the socioeconomic issues facing Pakistan are very similar to those of most developing countries in the world [2].

Access to affordable and reliable sources of energy is essential for the socioeconomic progress of developing nations such as Pakistan. In 2006, Pakistan's energy use per capita was 480 kWh, which is almost 6 times less than the international average [3]. Only 55 % of the people have access to electricity, with large areas of the vast countryside excluded from the national grid [4]. Pakistan also faces a critical power deficit of over 4,000 MW [5]. As a result, utilities resort to load-shedding on a regular basis, which can continue for several hours a day during the summer season in particular. Moreover, almost 80 % of Pakistan's electricity is generated from fossil fuels, which made up about 25% of the total import bill in 2007, and is a huge burden on the exchequer [6].

Renewable energy resources that are technologically viable and have prospects to be exploited commercially in Pakistan include hydropower, bio-energy, wind energy and solar energy. Solar energy, in particular, is an extremely viable prospect. Much of Pakistan, especially the southern provinces of Sindh and Balochistan, receive an average solar irradiance of about 200 W/m^2 and 3,000 hours of sunshine a year, which rank among the world's highest insolation averages. Hence Pakistan is an ideal candidate for the utilization of both photovoltaic (PV) and solar-thermal technologies [7].

This paper describes a three-week workshop in Pakistan in which twenty unemployed people were instructed in PV module assembly, using methods well-matched with the principles of appropriate technology. The paper first describes the workshop activities and summarizes the module components and assembly techniques. Next, factors relevant to sustaining the project as a viable business enterprise, including the beneficial social externalities are discussed. Energy output from modules when used in both urban and off-grid rural applications is simulated. Finally, current challenges inhibiting the large-scale implementation of the project are discussed.

WORKSHOP ACTIVITIES
During a three-week workshop in July 2009, a group of twenty unemployed people in Karachi, Pakistan were successfully trained in low-tech PV module assembly. The workshop was conducted by Richard Komp Ph.D, director of US-based non-government organization (NGO) Skyheat Associates and author of the book **Practical Photovoltaics Revised 3rd Edition** [8]. Komp has pioneered a PV module assembly method well-

matched with the principles of appropriate technology, using only locally available materials, except for the encapsulant and the solar cells. He has conducted PV assembly workshops in countries such as Nicaragua, Mali and Haiti, making use of off-spec solar cells that are rejected by major manufacturers. Currently groups in these countries are assembling dozens of panels a year, providing unskilled workers with opportunities for long-term gainful employment and economic independence [9].

Galaxy of Youth (GOY), a Pakistani-based NGO focused on welfare projects for expanding opportunities for the youth, was the primary partnering organization and platform for the project in Pakistan. The Institution of Electrical and Electronics Engineers Pakistan (IEEEP) and the Pakistan Alternative Energy Development Board (AEDB) also provided expertise and resources.

Fourteen 60-Watt PV modules were assembled by the participants during the workshop. The participants came from very diverse economic and academic backgrounds, ranging from uneducated refugees from troubled areas in the northern part of the country to local Karachiites with diplomas and college degrees. However, the PV module assembly methods taught were relatively straightforward, such that people of all skill and experience levels were able to learn the techniques equally well.

Off-spec, 15 cm x 8 cm, 0.5 V, 3.6 A, poly-crystalline silicon PV cells manufactured by Evergreen Solar were used in the workshop. The cells were rejected by the manufacturer primarily due to cosmetic defects, and hence were guaranteed to provide the same performance and efficiency as regular on-spec cells.

Sylgard 184, a two-part silicone elastomer manufactured by Dow Corning was used to encapsulate the cells. The encapsulation method employed was developed by Marco Antonio Perez, a Nicaraguan peasant working with the Grupo Fenix (a renewable energy group in Nicaragua) under the direction of Dr. Komp [10]. Other than the cells and the encapsulant, all other materials and components required for module assembly including the aluminum frame, common window glass, connecting wires, terminal strips, soldering irons and solder, were available locally in Karachi. In addition, two large rolls of 75 g/m^2 standard printer paper and thin polyvinylchloride (PVC) plastic material were also obtained locally.

Each 60-Watt PV module was assembled using 36 individual cells connected in series to provide a rated voltage of 18 V. The first step in the module assembly was soldering the PV cells together in series using 15-cm long, narrow tin-plated copper ribbons, as shown in Figure 1.

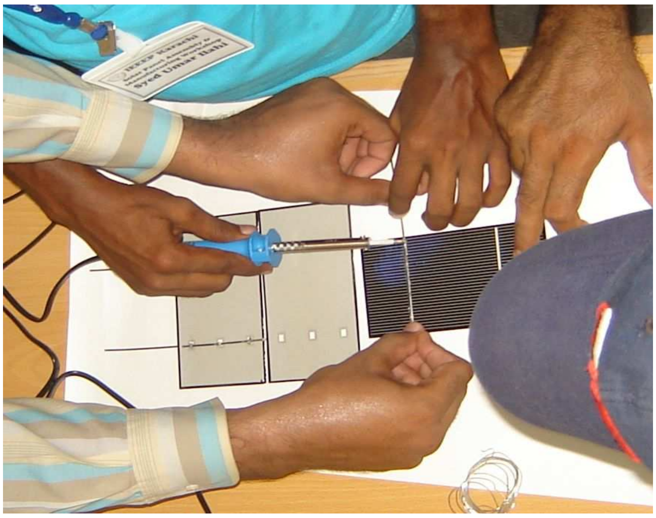

Figure 1. Soldering ribbon on to the PV cells

Participants were instructed to solder three strings of 12 cells each, in order to fit all 36 cells on a 51 cm x 107 cm sheet of glass. The voltage and current of each string of 12 cells was tested in sunlight, as shown in Figure 2, before proceeding to the next step of encapsulating the cells.

Figure 2. Testing the voltage and current output of the cell-strings in sunlight

To prepare for the encapsulation process, six layers of newspaper were sandwiched between two layers of polyethylene plastic material on a hard, flat surface. This served to soften the surface as well as protect the workspace. Next, a sheet of PVC plastic material was placed on the surface, followed by a sheet of plain white printer paper. Both sheets were cut to dimensions slightly larger than the glass and the paper was marked with the 51 cm x 107 cm glass dimensions, to facilitate the placement of the cell strings.

The three 12-cell strings were then laid on the paper face-up with minimal space between them. The strings were placed such that the positive end of one string was adjacent to the negative end of the next string. Also, the ribbon-ends at the ends of the strings were passed through slots cut in the paper in order to facilitate the series connection between the cell-strings after encapsulation. Figure 3 shows the cells being laid on the paper before encapsulation.

Figure 3. PVcells laid on plain white printer paper in preparation for encapsulation

Next, 400 ml of the Sylgard silicone was thoroughly mixed with 20 ml of the accompanying catalyst. The silicone was then carefully and evenly poured over the cells and the gaps between the strings, as shown in Figure 4. After the pouring process was complete, the silicone was carefully spread across all the cells to ensure an even coating.

Figure 4. Pouring the silicone to encapsulate the strings of cells

In the encapsulation process, the encapsulant impregnates the porous layer of paper underneath the cells via capillary action and ensures complete moisture sealing. The porosity of the paper is a critical factor in the process. Moreover, the ease and effectiveness of this particular encapsulation method is what makes low-tech PV module assembly a viable prospect and allows for assembly of modules comparable to commercially manufactured modules in quality and durability [10]. Commercially manufactured modules typically use ethyl vinyl acetate (EVA) to encapsulate the cells using expensive laminating machines.

After a few minutes, the glass was laid on top of the cells, using the marks made on the paper to assist in positioning. The glass "floats" on the layer of silicone spread on the surface of the cells. Next, heavy weights were laid on top of the glass to provide pressure and squeeze out air towards the glass edges. Air gaps would increase the module's reflectivity and hence reduce its electrical output.

The module-in-making was then left to cure overnight at room temperature, which is about 30 C during summer in Karachi, allowing for relatively quick curing. After curing, the module was turned over and the soldering connections behind the paper were completed. After retesting the electrical output, the module was framed with locally purchased aluminum to provide mechanical strength. A terminal strip was also included for ease of use. Figure 5 shows participants with two completed 60-Watt modules, ready for installation.

Figure 5. Two completed 60-Watt modules

About four man-hours of labor were required to assemble a module from start to finish. Along with 60-Watt modules, participants were also instructed in cutting broken or cracked PV cells to make standard sized smaller cells for the design and assembly of 30-Watt modules, small 6-Watt modules for cell-phone charging applications, and small solar battery chargers. Moreover, participants were also taught how to install and wire solar modules and fabricate aluminum mounting frames. The workshop participants installed the fourteen modules made during the workshop in three different locations in the city.

POTENTIAL SOCIOECONOMIC IMPACT

Photovoltaic module assembly as appropriate technology can serve to provide gainful employment for Pakistani workers, as well as play an important role in the management of Pakistan's energy crisis. The material costs of the 60-Watt module manufactured at the workshop were less than $1.5 per peak-

Watt, with the imported cells and encapsulant material making up about 80% of the total cost. According to preliminary business plans drawn up by local investors interested in the business model, solar modules can be manufactured in Karachi for a production cost of less than $2 per peak-Watt, inclusive of overhead and labor costs. Given that pre-assembled, imported solar modules from China and Germany are available in local markets for about $4 per peak-Watt , the business prospects for modules assembled locally, using the labor intensive techniques described above, are very bright. The government of Pakistan has also deemed the import of unassembled components for renewable energy products such as solar modules, duty-free, which is an added economic bonus and incentive [7]. Moreover, both local and imported varieties of balance of system components such as charge controllers and inverters are available in Pakistani markets.

The model will reap the greatest benefits for Pakistan if implemented in rural areas not connected to the national power grid. AEDB has already begun implementation of its Solar Home Systems program (initiated in 2005) through which individual households in remote villages, at least 20 km away from the national grid, are being provided with small PV systems, primarily for lighting [11]. However, relatively expensive imported modules have been used in such systems. Developing a program and infrastructure to employ villagers to assemble and install solar modules in their own villages would contribute to the sustainable energy industry at the grassroots level. Being a labor intensive process, PV assembly can provide much needed jobs directly in impoverished rural areas, helping slow the rural-to-urban migration that is the bane of Pakistan and many other developing countries. Also, the use of locally available materials will drive costs down, prevent money from leaving the local economy, and encourage the growth of subsidiary support industries. Current existing NGOs and government organizations which provide micro-credit services can assist in making the PV systems more accessible and affordable. Indigenous module assembly using local labor would also lead to a greater sense of ownership and responsibility amongst end-users, which is critical to the success of any development project. Providing access to energy is also an extremely important tool in poverty alleviation: The provision of light during nighttime can enhance productivity and prevent indoor pollution caused by kerosene lamps. Finally, the ability to operate televisions and radios would provide greater access to education and information to rural households.

SOLARSIM METHOD FOR PREDICTING PHOTOVOLTAIC POWER OUTPUT

Power output of the PV panels is predicted using the SolarSim software [12]. The method used by SolarSim is to first predict total solar radiation on the collector surface, and then predict PV power output using performance data of the PV panels and power conditioning equipment. The method is described below.

The procedure for calculating total solar radiation on a surface at any orientation is called the Hay, Davies, Klucher, Reindl (HDKR) method [13]. The method uses location, time and hourly total solar radiation on a horizontal surface data to predict hourly total solar radiation on a surface at any orientation.

Hourly total solar radiation on a horizontal surface, I_h, can be measured by relatively inexpensive solar pyranometers and is included in most data sets of typical meteorological data. For example, Typical Meteorological Year TMY [14], Energy Plus Weather EPW [15] and International Weather for Energy Calculations IWEC [16] files all contain 8,760 hourly records of I_h data and are available for hundreds of U.S. and international sites. The method for calculating solar radiation on the collector surface is demonstrated using TMY2 files, but is easily adapted for other data sources.

Calculate Local Solar Time

Hourly data in TMY2 files are recorded in standard time. To calculate local solar time, adjustments must be made to account for the longitude within the time zone and perturbations of the earth's rate of rotation. To do so, calculate the day of the year in degrees, B, from the day of the year, n, (1-365):

$$B = (n-1)\ 360 / 365 \quad (1)$$

Calculate the equation of time, E:

$$E = 229.2\ [0.000075 + 0.001868 \cos(B) – 0.032077 \sin(B) – 0.014615 \cos(B) – 0.04089 \sin(2B)] \quad (2)$$

Calculate the standard longitude, lngstd, from the time zone number, tz, (which is listed in the TMY2 header):

$$lngstd = -15\ tz \quad (3)$$

Calculate the local solar hour, hrsol, from the standard hour, hrstd, (which is the time used in TMY2 files) and the local longitude, lngloc, (which is listed in the TMY2 header):

$$hrsol = hrstd + [4(lngstd – lngloc) + E] / 60 \quad (4)$$

Convert from solar hour (1 to 24), hrsol, to solar hour angle (degrees), ωsol, such that ωsol corresponds to the midpoint of the hour over which the solar radiation is measured:

$$\omega sol = [(hrsol – 12) \times 15] – 7.5 \quad (5)$$

Calculate the Angle Between Normal to Collector and Sun

Declination, δ, is the angle between the earth's axis and the perpendicular to the sun-earth axis:

$$\delta = 23.45 \sin[360\ (284 + n) / 365] \quad (6)$$

The angle between the perpendicular of the collector and south, γ, is defined such that γ = –90 for east facing collector, γ = 0 for south facing collector, γ = 90 for west facing collector and γ = 180 for north facing collector. The angle between the collector and the horizontal, β, is defined such β = 0 for a horizontal collector and β = 90 for a vertical collector.

The local latitude, φ, is listed in the TMY2 header. From solar geometry, the cosine of the angle between the normal to the collector and the sun, $\cos(\theta)$, is:

$$\cos(\theta) = \sin(\delta)\sin(\varphi)\cos(\beta) - \sin(\delta)\cos(\varphi)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\varphi)\cos(\beta)\cos(\omega sol) + \cos(\delta)\sin(\varphi)\sin(\beta)\cos(\gamma)\cos(\omega sol) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega sol) \quad (7)$$

The cosine of the angle between the normal to the horizontal and the sun, $\cos(\theta z)$, is:

$$\cos(\theta z) = \cos(\varphi)\cos(\delta)\cos(\omega sol) + \sin(theta)\sin(\delta) \quad (8)$$

Calculate Beam and Diffuse Radiation on Horizontal Surface

The mean radiation normal to the earth-sun radius at the edge of the atmosphere is called the solar constant, g_{sc}. The value for the solar constant, g_{sc}, used by the Illuminating Engineering Society of North America is 1,350 W/m2 [17]. The mean radiation parallel to the earth's surface at the edge of the atmosphere, I_o, is:

$$I_o = g_{sc}\,[1 + 0.033\cos(360\,n / 365)]\cos(\theta z) \quad (9)$$

The hourly clearness index, kt, is defined as the ratio of the radiation on a horizontal surface, I_h, from the TMY2 file, and Io:

$$kt = I_h / I_o \quad (10)$$

The total solar radiation on any surface is the sum of the diffuse and beam components. Using empirical data, Erb developed a relationship between diffuse, I_d, and total, I_h, radiation on a horizontal surface:

$$I_d / I_h = 1 - 0.09\,kt \quad (\text{when } kt \le 0.22) \quad (11)$$

$$I_d / I_h = 0.9511 - 0.1604\,kt + 4.388\,kt^2 - 16.638\,kt^3 + 12.336\,kt^4 \quad (\text{when } 0.22 < kt \le 0.80) \quad (12)$$

$$I_d / I_h = 0.165 \quad (\text{when } kt > 0.80) \quad (13)$$

Thus, the diffuse, I_d, and beam, I_b, components of total solar radiation on a horizontal surface are:

$$I_d = (I_d / I_h)\,I_h \quad (14)$$

$$I_b = I_h - I_d \quad (15)$$

Calculate Beam Radiation on Collector

The ratio of the cosine of the angle between the normal to the collector and the sun, $\cos(\theta)$, and cosine of the angle between the normal to the horizontal and the sun, $\cos(\theta z)$, is:

$$R_b = \cos(\theta) / \cos(\theta z) \quad (16)$$

R_b represents the fraction of direct radiation incident on the collector. From solar geometry, the beam radiation on a collector at any orientation is:

$$Itb = Ib\,Rb \quad (17)$$

Calculate Diffuse Radiation on Collector

As solar radiation passes through the atmosphere, both its directional and spectral properties change due to absorption and scattering. The diffuse component of solar radiation has four sources: circumsolar, isotropic, horizontal and reflected.

The diffuse component of solar radiation from the area surrounding the solar disk depends on sky clarity, as characterized by the ansiotropic index, A_i:

$$A_i = I_b / I_o \quad (18)$$

The diffuse component of solar radiation from the area surrounding the solar disk, It,cs, is then:

$$It,cs = I_d\,R_b\,A_i \quad (19)$$

From solar geometry, the diffuse component of solar radiation spread evenly over the sky, It,iso, is:

$$It,iso = I_d\,[(1 + \cos(\beta)) / 2]\,(1 - A_i) \quad (20)$$

From solar geometry, the diffuse component of solar radiation from the horizon, It,hz, is:

$$It,hz = I_d\,[(1 + \cos(\beta)) / 2]\,(1 - A_i)\,(I_b/I_h)^{1/2}\sin^3(\beta/2) \quad (21)$$

The reflectivity of the ground in front of the collector, ρg, ranges from about 0.1 for dark surfaces to 0.8 for snow. From solar geometry, the component of solar radiation reflected from the ground, It,ref, is:

$$It,ref = I_h\,\rho g\,[(1 + \cos(\beta)) / 2] \quad (22)$$

The total diffuse solar radiation incident on a collector at any orientation is:

$$It_d = It,cs + It,iso + It,hz + It,ref \quad (23)$$

Total Solar Radiation on Collector

The total solar radiation incident on a collector at any orientation, It, is the sum of the beam and diffuse components:

$$It = It_b + It_d \quad (24)$$

Calculate Efficiency of PV Collector

PV collector efficiency, ηc, declines as the temperature, T, of the collector increases. The efficiency-temperature coefficient μ characterizes this decline from a reference efficiency η,ref at a reference temperature Tc,ref, and is defined as:

$$\mu = d\eta / dT = (\eta c - \eta ref) / (Tc - Tc,ref) \quad (25)$$

where the reference efficiency ηref is the collector efficiency at reference conditions of It = 1,000 W/m2 and Tc,ref = 25 C. Thus, the efficiency of the collector is:

$$\eta c = \eta ref + \mu\ (Tc - Tc,ref) \quad (26)$$

The temperature of the collector, Tc, can be calculated from a steady-state energy balance on the collector:

$$\tau\alpha\ It - It\ \eta c + Ul\ (Tc - Ta) = 0 \quad (27)$$

where τ is the transmittance of the glazing, α is the absorbance of the solar cell and Ul is the overall heat loss coefficient of the panel. Panels are tested to measure normal operating cell temperature (NOCT) at It = 800 W/m^2, air velocity 1 m/s, air temperature Ta = 20 C and disconnected so that ηc = 0. Thus, the energy balance can be solved to give τα/Ul in terms of the published performance specification NOCT:

$$\tau\alpha/Ul = (NOCT - 20)\ (C)\ /\ 800\ (W/m^2) \quad (28)$$

Once τα/Ul is known, the Tc can be calculated from the energy balance for actual operating conditions. Substitution gives the collector efficiency ηc in terms of air temperature and reported performance specifications ηref, μ, Tc,ref and NOCT:

$$B = (n-1)\ 360\ /\ 365 \quad (29)$$

$$\eta c = \eta ref + \mu\ [Ta - Tc,ref + It\ (\tau\alpha/Ul)\ (1 - \eta ref)\ ]$$

Calculate Power Output of PV Collector

The total power output of a collector, W_e, is then expressed in terms of collector area Ac, solar input It, and the efficiencies of the collector, ηc, and power conditioning equipment ηe.

$$W_e = Ac\ It\ \eta c\ \eta e \quad (30)$$

URBAN CASE STUDY: KARACHI, PAKISTAN

Karachi is Pakistan's largest city and the financial and industrial hub of the country. Located along the coast of the Indian Ocean, the city has a mild, arid climate with temperatures ranging from 30 to 44 degrees Celsius during the summer (April to August) [18]. The proximity to the coast also keeps humidity levels high throughout the year.

The Karachi Electric Supply Company (KESC) generates and supplies electric power to the city. However, due to the mismatch between demand and supply capacity, the utility resorts to load-shedding, which can continue for several hours a day, especially during the summer. Moreover, electricity is also very expensive in Pakistan. In order to meet certain stipulations in loan agreements with the International Monetary Fund (IMF), the government has enforced an increase in the power tariff by over 30% since October 2009. Further increases are expected in the coming months due to rising world oil and gas prices, alongside other domestic factors [19]. Currently, households in Karachi consuming between 300 kWh/month and 1,000 kWh/month pay about $0.15 /kWh for electricity [20]. Apart from the distress caused to citizens, the present situation also has crippling effects on the city's industrial sector and investment climate.

During periods of load-shedding, the most common coping mechanism for middle and upper-class households is to use portable electric generators or uninterruptible power supply (UPS) systems. While an appropriately sized generator can meet most of a household's load requirements, including air conditioning and refrigeration, they cause pollution and have high operational and maintenance costs. Alternately, UPS's, consisting of an inverter, battery storage and a control system, are typically rated at about 1.5 kVA and are primarily used to power basic appliances such as lights and fans, and possibly televisions and computers, given sufficient installed battery capacity.

Purchasing PV modules could be an attractive option for UPS users as the essential balance-of-system components such as the batteries and inverter are already installed, hence reducing system costs to a large extent. A PV system could supplement the electricity supplied by the grid to either charge the UPS batteries or meet household loads directly. Moreover, during long periods of load-shedding, a PV system would continue to charge the UPS batteries during the day.

Salient features of the simulation of the energy output of a PV system are presented for a UPS-using household in Karachi. EPW data sets containing typical meteorological data over a year-long period for Karachi were obtained from the U.S Department of Energy website [15]. The cost and performance specifications of the modeled PV cells were assumed to be identical to the Evergreen Solar cells used in the workshop.

The system should be sized to provide power for key equipment for a few hours every day, be small enough to fit on typical rooftops, and inexpensive enough to fit within typical upper-middle class household budgets. To meet these criteria, we propose a PV system rated at 600 Watts for a UPS-using household with an average electricity consumption of at least 300 kWh/month. A system rated at 600 Watts is selected because:

1) As illustrated below, a PV system rated at 600 Watts can operate independently of the grid, and still provide power for the limited operation of lights and fans for a few hours every day.
2) The area spanned by the PV modules (inclusive of frames) would be about 5 m^2. A larger array might not be reasonably accommodated on the roof of a house.
3) Assuming an installed price of $3 /peak-Watt, the capital cost of the system would be about $1,800, which is within reasonable investment spending limits for upper-middle class households in Pakistan.

Karachi is situated at a latitude of 24 degrees north, just above the Tropic of Cancer. We assume the modeled PV array is oriented due-south and is mounted at a fixed slope of 20 degrees from the horizontal, for the entire year. While a 24-degree slope optimizes the yearly PV energy output, a more gentle 15-degree to 20-degree slope allows for marginally better performance in the hotter summer months, when the electricity shortage is more severe.

Figure 6 shows the average daily solar radiation incident on the cells of the 600-Watt PV array when tilted at 20 degrees from the horizontal, as well as the average monthly temperature in Karachi.

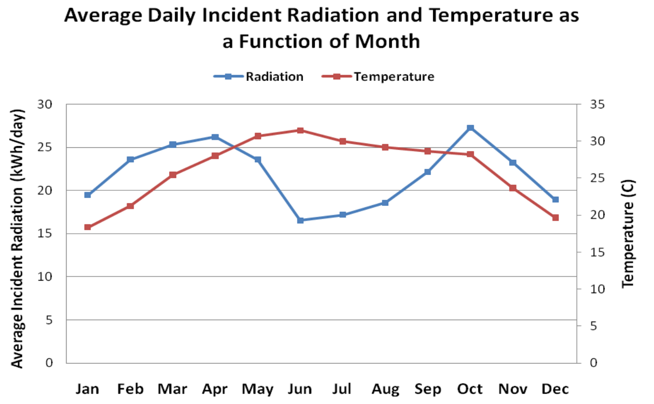

Figure 6. Average temperature and solar radiation incident on the array.

As is evident in Figure 6, April and October have the highest average incident radiation, while June has the least. The fall in incident-radiation levels in the April-June period is caused by local cloud cover during the monsoon season.

One disadvantage of a stand-alone UPS is that in the event of a long power breakdown spanning several hours, the batteries inevitably run down before being recharged by the grid. A UPS coupled with a PV system could prove most useful during such a situation, as the PV system would charge the batteries during the day.

Ideally, during a long power-breakdown, the PV array should provide sufficient charge to the batteries during the day, in order to provide enough back-up power to operate lights and fans for a small household, during the night. Issues such as battery autonomy are not considered in this model as it is assumed that the battery capacity is originally determined by the larger UPS capacity, with the PV system providing supplementary power.

In the SolarSim simulation of EPW data, the minimum solar radiation incident on the array is 9.67 kWh/day on January 14th and the maximum solar radiation incident on the array is 28.3 kWh/day on April 2nd. However, instead of examining the PV output on these days, it would be more instructive to analyze the PV output at the 10th and 90th percentiles of incident radiation during the year, shown in Figure 7, as they provide a better representation of typical low and high radiation-days.

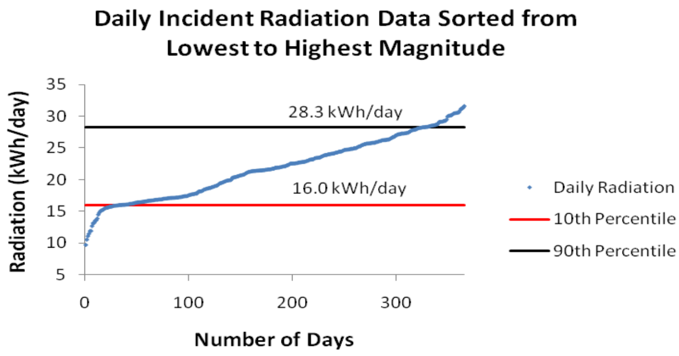

Figure 7. 10th and 90th percentiles of daily incident radiation on the 600-W array during the year

The incident radiation values and corresponding days of the 10th and 90th percentiles are 16.0 kWh/day and 28.3 kWh/day on August 15th and May 4th respectively. The hourly PV energy output model for these two days is shown in Figure 8 below.

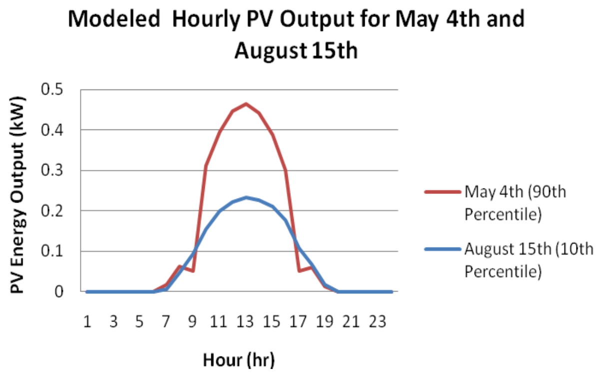

Figure 8. Modeled hourly PV energy output for May 4th and August 15th

The total daily energy outputs from the PV system at the 10th and 90th percentile incident radiation values are the areas under the two curves in Figure 8, and are 1.8 kWh and 3.0 kWh respectively.

The energy output model implicitly assumes a 90% efficiency for the inverter. However, losses through the distribution system, charge regulator and batteries still need to be accounted for. The efficiency of the battery charging process for lead-acid batteries (often used for UPS's in Pakistan) is a function of the state-of-charge and the battery charging rate, and is typically estimated as 80% [21]. However, when the batteries are fully charged, the power from the PV system goes directly through the inverter, without experiencing any losses due to battery efficiency.

For modeling purposes, we conservatively assume an overall constant efficiency of 80% to account for losses through the batteries and distribution system. Hence, the available energy from the PV modules at the 10th and 90th percentile incident radiation values would be 1.4 kWh and 2.4 kWh respectively

The average power consumption of a ceiling fan and a small compact fluorescent bulb are about 75 Watts and 13 Watts respectively. Tables 1 and 2 provide one combination each for how the daily energy output from the PV system at the 10th and 90th percentile incident radiation values can be utilized for fans and lights.

Table 1. Energy utilization at 10th percentile of incident daily radiation energy in one year

	Required Power (W)	Quantity	Total Required Power (W)	Hours used per day (hr/day)	Energy Consumed (kWh/day)
Light(s)	13	4	52	4	0.2
Fan(s)	75	2	150	8	1.2
Total					**1.4**

Table 2. Energy utilization at 90th percentile of incident daily radiation energy in one year

	Required Power (W)	Quantity	Total Required Power (W)	Hours used per day (hr/day)	Energy Consumed (kWh/day)
Light(s)	13	2	26	4	0.1
Fan(s)	75	3	225	10	2.3
Total					**2.4**

In other words, for 90% of the year, a 600-Watt PV system in Karachi provides at least enough energy to power four lights for four hours per day and two fans for eight hours per day. Similarly, for 10% of the year, enough energy is provided to power two lights for four hours per day and three fans for ten hours per day.

According to the energy model, the annual output of the 600-Watt PV system would be 870 kWh/year, after adjusting for losses. At current electricity prices, this results in a savings of $130/year. Hence, assuming a capital cost of $1,800, the simple payback period for the PV system would be about 14 years.

However, the simple payback period by itself is not an adequate indicator for investing in a PV system, given the high escalation rate of energy prices. If the annual increase in energy prices is forecast as 5% /year, and the PV system has a life of 30 years, the return-on-investment (ROI) for the 600-Watt PV system for a UPS-using household is 11%.

OFF-GRID RURAL APPLICATION CASE-STUDY: THAR DESERT, PAKISTAN

The Thar Desert, located along the Indian border in south-eastern Pakistan, mostly consists of barren tracts of sand dunes covered with thorny bushes. While there are a few thriving towns connected to the national electricity grid and accessible via road, Thar is also home to around 7,000 thousand villages, many of them in remote locations miles away from the nearest paved road [2]. The Thar area has a tropical desert climate; during the months of April, May and June daytime-temperatures can reach up to 50 degrees Celsius [18].

Lighting and access to information via television or radio are important functions for a household in this remote area. Table 3 shows an estimation of the resulting loads.

Table 3. Estimated electricity loads for village household

Lights	4, 13-Watt compact flourescent bulbs	On at night for 3 hours
Television	1, 50-Watt nine-inch-television	On at night for 1 hour

Hence, the total energy required would be:

4 lights x 0.013 kW/light x 3 hr/day + 1 television x 0.05 kW/television x 1 hr/day = 0.21 kWh/day

Weather data sets containing typical meteorological data for Thar are not available. However, EPW data is available for Barmer, India, a desert town located near the Pakistani border. Consequently, the Barmer EPW data is used for this simulation.

Using the same methodology as described in the Karachi case-study, but assuming the village in question is located at the same latitude as Barmer (26 degrees north), daily incident-radiation values and PV energy output were simulated. The array is oriented due-south at a fixed 26 degree slope to optimize the annual energy output.

The PV system should be sized to meet the daily load for the majority of the year, while relying on battery storage when PV output falls short of daily requirements. It was found that a 60-Watt PV system can meet the required daily loads 75% of the year.

The 25% percentile of incident solar radiation is 2.03 kWh/day and occurs on January 16th in the EPW file. The PV energy output is the area under the curve in Figure 9, and is 0.29 kWh/day. Assuming a battery efficiency of 80%, the available energy would be 0.23 kWh. Hence a 60-Watt PV system provides sufficient energy to meet the loads 75% of the time.

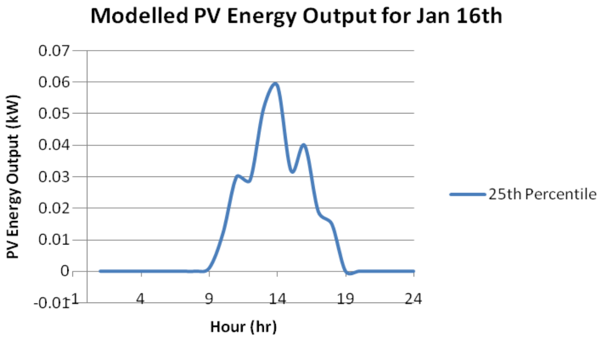

Figure 9. Modeled hourly PV energy output for Jan 16th in the Thar Desert

A battery autonomy of three days is more than adequate for the sunny desert environment, and is also appropriate given that the PV-system has been designed to meet the load 75% of the year.

Assuming a maximum depth-of-discharge of 50% and a voltage of 12V, the required battery capacity is:

210 Wh/day x 3 days / (12 Watts/Volt x 0.5) = 105 Ah

For remote rural home applications, a blocking diode can serve as a rudimentary replacement for a sophisticated charge regulator. The diode will prevent the battery from discharging back through the modules during the night.

Typically, the capital costs of a PV system are beyond what a remote village household can afford. However, if micro-credit facilities are available, and the loan payback installments are equivalent to the cost of kerosene which would have been otherwise purchased by villagers to provide lighting, a PV system could prove to be a viable option.

CURRENT CHALLENGES AND FUTURE PLANS

The difficulties associated with importing the PV cells and silicone, along with their high cost, are two of the main obstacles to the large-scale implementation of the concept demonstrated at the PV assembly workshop. Other than Evergreen Solar and Dow Corning, no other suitable sources of unassembled PV cells and silicone have been found. While the quantity of imported materials for the three-week workshop could be carried by passengers travelling by air from the U.S to Pakistan, such an arrangement would not be feasible for the fabrication of PV modules on a larger scale. The cells and the silicone would need to be shipped in a large quantity and importers would have to fulfill all necessary customs procedures and formalities; hence increasing the capital requirements and complexity for setting up a small PV assembly unit. Given the dearth of financial resources and lending facilities for small-scale projects in Pakistan, such projects are typically managed by the corporate sector, which may divert profit and resources from local workers [23].

Another barrier in obtaining sources of finance is the lack of familiarity and information about renewable energy technologies, their high-risk perception, and uncertainty concerning the energy yield and resource assessment. These factors also inhibit the marketing of the final product. Also, given the relative novelty of PV systems in Pakistan, the required subsidiary industries are still in the developing stages. For example, 12 V DC light bulbs for off-grid PV systems, and deep-discharge batteries are not readily available in Pakistani markets.

PV systems also have high up-front costs and long payback periods, putting them out of reach of many households, unless system capital costs are heavily subsidized. This is because the market prices for energy produced from conventional sources do not take into account the environmental costs and damage, and hence mask the advantages of renewable energy options.

Finally, all too often, small-scale renewable energy projects remain confined at the demonstration stage, which restricts the much needed decentralized implementation of the demonstrated concepts in remote areas. Follow-up visits and continued attention is required by project initiators to ensure the sustainability of such ventures.

CONCLUSIONS

This paper described the introduction of photovoltaic module assembly, using off-spec PV cells and a novel encapsulation technique, for the first time in Pakistan. The outcome of a three-week PV workshop in Karachi, Pakistan demonstrated that unskilled workers with little experience could successfully assemble and install PV modules at a competitive cost of under $2 /peak-Watt, and hence achieve gainful employment for themselves if provided with the necessary resources. The case of installing a PV system for a UPS-using household in Karachi was considered and the output of the PV modules was simulated. It was found that a 600-Watt system could generate 870 kWh per year, and at current electricity prices in Pakistan, the simple payback and ROI for the household was calculated to be 14 years and 11% respectively. Similarly, a PV system for a household in a remote village was simulated. A 60-Watt PV system with 105 Ah of battery capacity was found adequate to power four lights for three hours per night and a small television for one hour per night. The practical experience of the workshop as well as the theoretical PV energy output simulations indicate that PV assembly as appropriate technology has great potential to be implemented successfully on a large scale in Pakistan.

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