SOLAR SPECTRUM

NEWSLETTER OF THE RESOURCE ASSESSMENT DIVISION

Volume 11. Issue 2 – November 1998 of the American Solar Energy Society®

SILICON CELL PYRANOMETERS: THE COST OF ACCURACY

by Daryl R. Myers – National Renewable Energy Laboratory – Center for Renewable Energy Resources

Introduction

Since the founding of NREL in 1977, the DOE/NREL Solar Resource Assessment Program, which evolved into the Renewable Resource Assessment Program, including research tasks such as the former Photovoltaic Solar Radiation Research Task and the current Photovoltaic Solar Radiometric Measurements task, has cooperated with the NREL Metrology (calibration and measurements) Laboratory in designing, developing, implementing, and conducting calibrations of thermopile and silicon-detector based radiometers

Because of the low cost and small size of the silicon-cell pyranometers available, such as the Li-Cor (1) SB-200 pyranometer, these radiometers are quite popular. NREL and other government laboratories, such as the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) Solar Radiation Facility (SRF), and more recently Sandia National Laboratories, have performed calibrations on many representatives of these types of radiometers. We are often asked about the accuracy or uncertainty associated with these low cost units vis-à-vis more expensive thermopile (Eppley Laboratory, Kipp & Zonen, Spectrosun) or resistance thermometer (Yankee Environmental Systems) counterparts. This article attempts to summarize recent work addressing the parameters affecting the accuracy of silicon cell based pyranometers, and corrections based on those influences. Most of the credit for the results reported here goes to D.L. King, W.E. Boyson, B.R. Hansen, and W.L. Bower of the Sandia National Laboratories Photovoltaic Systems Division who have done an excellent job of experiment design and reporting of results. All of the figures shown are extracted from the publications quoted in the references.

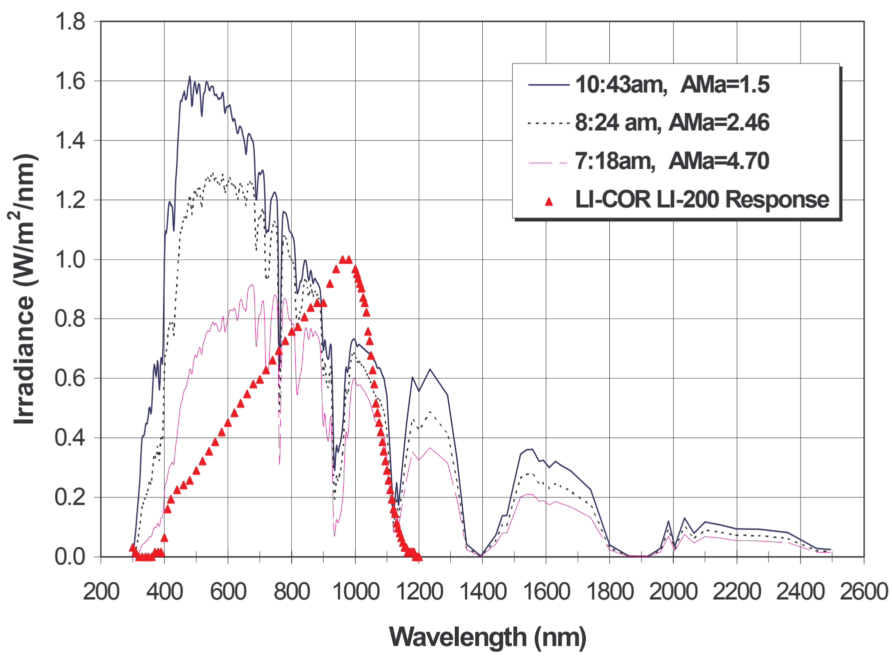

Figure 1. Three solar spectral distributions and spectral response of a silicon cell pyranometer.

Factors Affecting Silicon Cell Pyranometer Accuracy

First and foremost of the factors affecting silicon cell based pyranometers is their **limited range of spectral response**. The

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INSIDE THIS ISSUE

Solar Spectrum is the newsletter from the Resource Assessment Division of the American Solar Energy Society and is published on a semi-annual basis. The purpose of this newsletter is to inform division members of events in the resource assessment field and activities of the division and its members.

Success of the newsletter depends on your contributions.

You are encouraged to send comments, letters, or short articles to the Editor:

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I would like to thank Daryl Myers, Richard Perez, and David Renné for their contributions to this newsletter.

Deadline for contributions to the next newsletter is February 1, 1999.

Several pictures in this newsletter were taken from PixSearch at www.nrel.gov/data/pix/searchpix.html. PixSearch is from DOE/NREL. No affiliation with DOE/NREL is to be implied.

Frank Vignola

UPCOMING EVENTS

February 3-4, 1999
Satellite Workshop II

Golden, Colorado
Information: NREL
David Renné
Tel: 303 275-4648
Email: Dave_Renne@nrel.gov
Richard Perez
Tel: 518-437-8751
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June 12-16, 1999
Growing the Market
SOLAR '99

Portland, Maine
Information: ASES
2400 Central, G-1
Boulder, CO 80301
Tel 303-443-3130
Fax 303-443-3212
http://www.sni.net/solar/

RAD DIVISION

Ballots for the upcoming election will be mailed to RAD division members along with this newsletter.

The following RAD division members and past chairs were selected for the nominating committee: Jim Augustyn, Timothy Townsend, and Eugene Maxwell.

As stated in the bylaws, this year's Vice Chair, **Cecile Warner** will automatically become chair next year.

Gary Vliet of the University of Texas at Austin was nominated for Vice-Chair, and **Roberta DiPasquale** of Analytical Services & Materials, Inc. was nominated for secretary.

Nominees for the four vacant board positions are:

Ray Bahm of Ray Bahm & Associates, **Dan Greenberg** of Ascention Technology Inc., **Rob Nelson** of Augustyn & Company, and **Bill Marion** of NREL.

EMAIL ADDRESSES FOR RESOURCE ASSESSMENT DIVISION MEMBERS

In order to open communications between RAD division members, the following members circulated their Email address at the RAD division annual meeting. If you are not on this list and would like to add your name to the list, contact Solar Spectrum's editor and your Email address will be added to the list and published in the next newsletter.

Augustyn & Company	.aci@ccnet.com
Ray Bahm	.r.bahm@ieee.org
Bruce Bailey	.awssci@delphi.com
Bill Berg	.n/a at this time
John Dunlop	.jrdunlop@mcimail.com
Eppley Laboratory Inc	.eplab@mail.bbsnet.com
Tracy Gardner	.tgardner@nrel.nrel.gov
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Mike Sloan	sloan@vera.com
Frank Vignola	fev@oregon.uoregon.edu

Satellite Workshop II: Satellites for Solar Resource

The second workshop on satellite for solar resource information will be held February 3 and 4, 1998, in Golden, Co at the National Renewable Energy Laboratory.

The objective of this workshop is to bring together solar resource data users and the satellite/ resource assessment specialists. Another important objective of this workshop is to discuss how international collaboration could boost individual national R&D efforts to develop versatile satellite-based solar resource tools and data.

The workshop will feature a series of formal presentations by experts, followed by a discussion session.

Formal presentations will include four sessions:

1. Research and development, including a review of satellites and sensors, an overview of satellite-to-irradiance component modeling, and an overview of worldwide satellite data availability.
2. Existing satellite-derived products
3. The irradiance data user's viewpoint
4. Future products

The discussion session will focus on the following issues:

- Defining R&D, data access, and product development priorities
- Discussing how international collaboration may be most productively used to address these priorities
- Defining an effective collaboration framework

Information about the meeting should be forthcoming on NREL's web site. If you have questions, you may contact Dave Renné at NREL [Tel: (303) 275-4648, or Email: Dave_Renne@nrel.gov] or Richard Perez at SUNY Albany [Tel: (518) 437-8751, or Email: perez@asrc. cestm. albany. edu).

From Pixsearch from NASA/Smithsonian Institution/Lockheed Corp.

EPA's Solar Initiative

Notes from the Web www.epa.gov/solar

The objective of the EPA Solar Initiative is to accelerate deployment of solar energy applications.

As has been noted by EPA Administrator Carol Browner, EPA has a clear environmental interest in seeing the solar energy industry thrive. Some States have used Clean Air funds to support replacement of diesel generators with photovoltaics. Solar energy is also a climate change solution, both in the U.S. and in the developing world. For the roughly two billion people in the developing world currently without electricity, solar is one of the most logical energy choices, both environmentally and economically. The EPA Solar Initiative was developed in response to the interagency Million Solar Roofs Initiative (MSRI), which was announced by President Clinton during his climate change speech at the United Nations in June 1997. The goals of the MSRI are as follows: 1) reduce greenhouse gas and other emissions -- with one million solar energy roofs in place, the MSRI would reduce carbon emissions roughly equal to the annual emissions from 850,000 cars; 2) create high-tech jobs in the solar energy industry - by 2010, approximately 70,000 new jobs could be created as a result of the increased demand for photovoltaic, solar water heating and related solar energy systems; 3) keep the U.S. solar energy industry competitive -- by increasing the domestic market for solar energy, increasing domestic production and reducing the unit cost for solar energy systems, the MSRI will enable U.S. solar companies to retain their competitive edge in the worldwide market, expected to exceed $1.5 billion annually by 2005.

The Solar Initiative is currently an effort to align mostly *existing* resources, applying the latest information technology available to enable effective agency-wide communication and cooperation. Unlike "top-down" programs, the Solar Initiative will depend on "bottom up" individual initiative and creativity of EPA staff nationwide to align existing resources and create new partnerships (with the building industry, other federal agencies, local and state governments, utilities, the solar energy industry, financial institutions and non-governmental organizations) to remove market barriers and develop and strengthen demand for solar energy products and applications. Financial support will come from a variety of sources, including state-specific funds for renewable energy being created through electric utility restructuring. California, for example, has a $3 per watt subsidy for rooftop installation of photovoltaics, which can cover up to half of system costs.

Solar Energy System Costs

A residential solar hot water system may cost anywhere from $1,800 to $3,500, cost-effectively replacing electric water heating in

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SILICON CELL PYRANOMETERS: THE COST OF ACCURACY

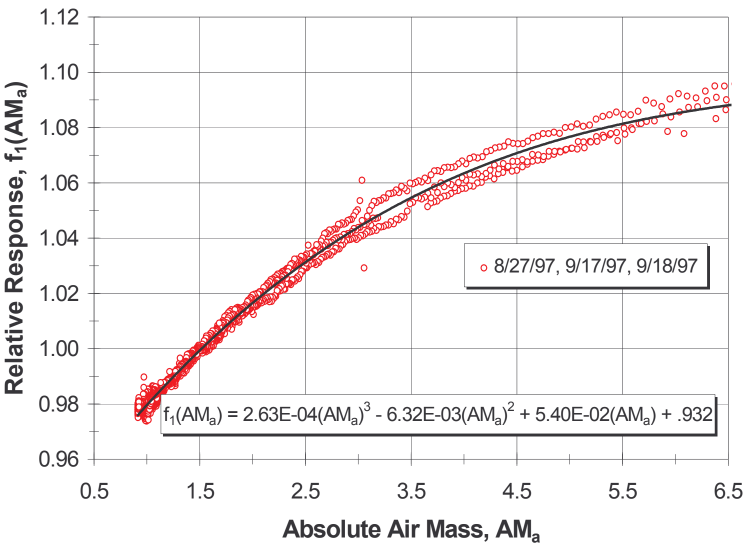

Figure 2. Relative response (Si to Thermopile ratio) as a function of air mass. Empirically derived cubic 'spectral mismatch' correction polynomial.

(Continued from page 1)

full terrestrial solar spectrum deposits measurable energy at the earth's surface in the range from 287 nanometers (nm) to beyond 4000 nm, or 4 micrometers. However, the typical silicon solar cell generates a current derived from absorption of photons in the wavelength region from 350 nm to 1100 nm, as shown in Figure 1.

The figure shows a the terrestrial full sun spectrum at three different air mass (or path lengths through the atmosphere) and the relative spectral response of a typical silicon cell pyranometer (triangular shaped curve).

Note that in the region of the relatively straight, sloping section of the spectral response, the solar spectral shapes vary considerably as air mass (path length) increases. This implies that the signal from the pyranometer will not be the same for similar solar spectral integrated powers at different air masses. The spectral response of a thermopile pyranometer over the 285 nm to 3000 nm range is basically flat. Thus there is a variable **spectral mismatch** between a silicon cell pyranometer and a thermopile pyranometer under different spectral distributions. In addition, the silicon cell does not 'see' changes in the wavelength region beyond 1200 nm. Changes in the longwave spectral distribution can also be the result of variations in the amount of atmospheric water vapor. In any case, the silicon cell is insensitive to the longwave radiation, which a thermopile radiometer will respond to. Thus when the two types of pyranometers are set side by side, the **relative** response of the two will be **different** under different spectral conditions (e.g., as the air mass varies from sunrise to sunset, or if spectral distributions are different under clear versus partly cloudy or overcast conditions).

Sandia National Laboratories has investigated an empirical approach to approximate the above mentioned spectral mismatch by recording the ratio of silicon cell radiometers to thermopile radiometers as a function of air mass under clear sky conditions (2). The derived empirical relationship is shown in figure 2.

The determination of the empirical mismatch correction function requires the removal of angle of incidence effects (see next paragraph). One method is to mount the silicon cell and thermopile radiometers on a solar tracker, track the sun through the range of air masses encountered during the day, and record the ratio of the indicated irradiances. This method includes variable contributions from the diffuse sky radiation (with it's distinct 'blue' shifted spectrum). Alternatively, the ratio of a solar tracking thermopile normal incidence pyrheliometer (NIP) and silicon cell pyranometer with a 5.7 deg field of view (FOV) collimator (to match the FOV of the NIP) can be monitored. The former method was used for the data presented at left. Note that the relative response is with respect to that at air mass 1.5, corresponding to the direct normal ASTME-892 spectrum.

there is a variable spectral mismatch between a silicon cell pyranometer and a thermopile pyranometer ...

The next most important influence on any pyranometer's response is the **angle of incidence** (sometimes called 'cosine response') dependence of the sensor. In reality this is a combination of departure from true lambertian nature of the detector, and changes in relative proportion of transmitted, reflected and absorbed radiation at the outer surface of the optical detector. Figure 3 shows the relative response of a typical silicon cell radiometer as a function of the angle of incidence.

The data shown were collected by Sandia National Laboratories(2) by mounting the radiometer on a solar tracker and, while monitoring the

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SILICON CELL PYRANOMETERS: THE COST OF ACCURACY

(Continued from page 4)

solar irradiance with a separate solar tracking radiometer, progressively changing the incidence angle between the solar beam and the detector by moving the tracker off of normal incidence to the solar beam. The response falls off by 5% at 70 degrees incidence angle, or an equivalent air mass of 2.92 for a horizontal pyranometer and incidence angle of 70 degrees. The fitted line is a cubic polynomial for the relative response, f(AOI) as function of the incidence angle (AOI):

$$f(AOI)=1+6.07E\text{-}4*AOI+1.367E\text{-}5*(AOI)^2-4.505E\text{-}7*(AOI)^3$$

A third, and less important influence on silicon cell pyranometer accuracy is the **temperature coefficient** of crystalline silicon. The magnitude of this coefficient as measured at Sandia National Laboratories (3) is on the order of 0.1 percent per Degree Celsius (%/C). However, for corrections to be made, some means of measuring and recording or processing the sensor temperature (such as installing thermocouples in the pyranometer body) are required. Alternatively, Sandia Laboratories also reports that pyranometers instrumented in this way seem to operate about 6 deg C above ambient temperatures (3) Note that applying such a correction implies a translation of the irradiance to that measured by a silicon cell held at a specified reference temperature (chosen or specified by the user).

Sandia National Laboratories reported the efficacy of applying the above empirical polynomial corrections to both clear (requiring Air Mass and AOI corrections) and overcast sky (using air mass corrections) conditions as reducing differences between thermopile and a specific make and model (Li-Cor LI 200SB) of silicon cell pyranometer from over 10% to within 1% under clear skies, and from +/-15% to within 5% under overcast skies(3), typical of the relative errors between individual thermopile pyranometers under such conditions(4)

Conclusions

As seen above, there is a significant amount of information available about the sources of errors, and means to correct for these errors, regarding some silicon cell pyranometers. The question of how applicable the empirical spectral mismatch (air mass), angle of incidence, and temperature corrections are to any silicon cell based pyranometer **other than those tested** is still open. We suggest trial application of these correction algorithms to silicon cell pyranometer data and examination of their impact, and especially comparison to concomitant thermopile radiometer data.

In any event, the determination of individual silicon cell correction functions is a time consuming, weather (and possibly site) - dependant, and expensive proposition. The cost of these characterizations may cancel out the presumed 'savings' with respect to the basic cost of 'more costly' thermopile instruments which are much less susceptible (but still imperfect themselves) to these influences, if equivalent accuracies are desired.

NOTES & REFERENCES

[1] The mention of any commercially available instrumentation is made for the convenience of the reader, and no endorsement, implied or otherwise, is intended by the National Renewable Energy Laboratory, Sandia National Laboratory, their operating agents, or the U.S. Department of Energy.

[2] D.L. King and D.R. Myers, 26th IEEE PV Specialist Conference, 1997, pp 1285-1288

[3] D.L. King, W.E. Boyson, B.R. Hansen, and W.J. Bower, 27th IEEE PV Specialist Conference, 1998

[4] D.R. Myers and T.W. Cannon, 14th NREL/SNL PV Program Review, AIP Conf. Proc. 394, PP 395-403

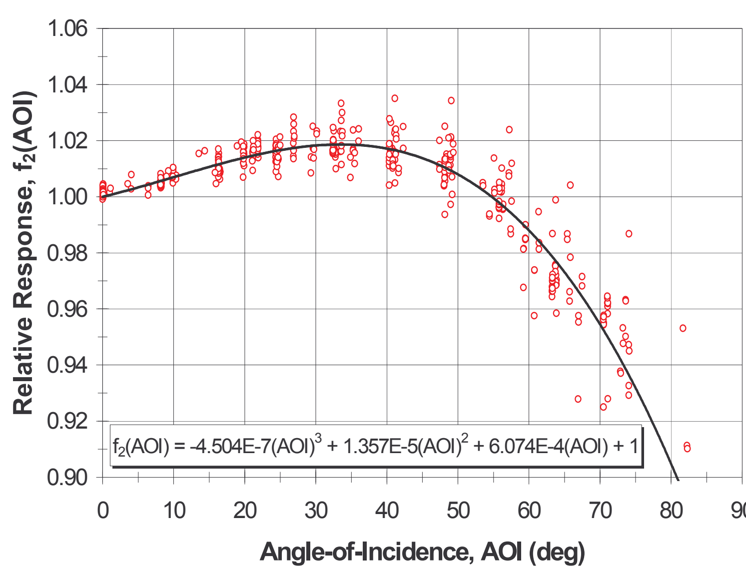


Figure 3. Relative response of silicon pyranometer versus angle of incidence (AOI) between solar beam and normal

ASES - RAD Meeting Minutes for June 16th Meeting, Albuquerque

by Gary Vliet

The meeting was called by Jim Augustyn (Chair) at 5:50 PM Tues., June 16th in the Marriot, during the ASES/ASME/AIA Solar 98 meeting in Albuquerque.

Attendees: Jim Augustyn, Mike Sloan, Frank Vignola, Ross McCluney, Bob Cable, Rob Nelson, Mike Boice, Tim Townsend, Charlie Whitlock, Ann Carlson, Roberta DiPasquale, Cecile Warner, Gene Maxwell, Dave Rennè, Gene Grindle, Lorin Vant-Hull, David Soule, Bill Marion, Ray Bahm, and Richard Perez.

1. There was considerable discussion about the turn-over between the Chair and past Vice-Chair and of the By-Laws. After some confusion about the former, the meeting was turned over to Mike Sloan (past Vice Chair) who presided over the major portion of the meeting. Apparently RAD has a set of by-laws, but not all divisions do. The policy regarding the change-over of the chair will be taken up officially at the ASES BOD meeting on Wed.

2. In any case, it was moved, seconded and passed unanimously that the transition occur at the Summer ASES Annual meeting, that the outgoing Chair preside at the Sat meeting before the Conference and that the past Vice-Chair becomes the presiding chair immediately following and will preside at the scheduled RAD meeting later during the week of the ASES conference. Note that Cecile Warner, current Vice Chair, officially becomes the Chair in Jan. 1999. There was some discussion about 2 year terms for the officers, but no decision was made on this.

3. Session Policy: Richard Perez reported on the session policy for the next June meeting in Portland, Maine. Papers will be solicited in 4 categories: Market Penetration, Technical and Scientific, Applications and Validations, and Environmental and Society. We are to nominate 2 persons to receive/arrange reviews of papers and they will be reviewed by abstract (1-2 pages). October - identify proposed sessions and workshops, etc., and January - program will be finalized.

4. Review of Current Meeting: - Workshops (Sun): Augustyn reported that the combined effort with the local group went well, but that the confusion over the day (Sat or Sun) and the late rescheduling impacted the attendance, the actual being 8 persons. However, the workshop generally went pretty well. Suggestion that the workshops be on Sunday if at all possible to increase attendance. Discussion about holding a similar workshop at each of the next couple of annual meetings.

- Forum (Tues.): Sloan reported that it went pretty well but was not really a "forum" - more like a regular session. Discussion that forums in future have a format that is more consistent with the intent of a "forum".

- Session (Tues.): Ray Bahm reported it went well but 6 or 7 papers (only 6 of the 7 showed up) were possibly too many papers.

5. Discussion of division name. After brief discussion it was agreed to leave the name as "Renewable ....." rather than "Solar...." even though the overwhelming coverage is allocated to solar and not wind, biomass, etc. [*Secretary's comment: Besides I think RAD is much preferred over SAD !!*].

6. Newsletter: Frank Vignola indicated the deadlines for articles is October for the late fall issue and February for the Spring issue. Frank asked for more persons to submit articles. The was discussion that some cartoons, anecdotes, statistics on the number of recording stations, etc. be included. Also, it was suggested that the Vice-Chair take on as one of the duties of getting articles for the newsletter. Finally, those in attendance expressed their appreciation to Frank for his constructive effort at getting out an informative publication.

7. Dave Rennè made a statement regarding Gene Maxwell's long effort in the solar resource assessment area and those in attendance expressed their appreciation for his accomplishments. We all wish him well in his retirement, and hoped that he would continue his association with our division.

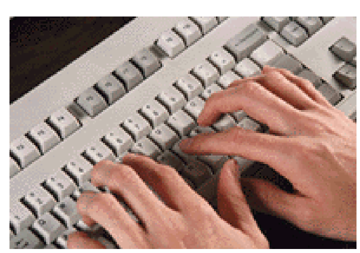
It was moved, seconded and passed unanimously that the transition from Vice-Chair to Chair takes place at the beginning of the annual division

8. Committee Assignments:

Program: Rennè (Chair), Vignola, and DiPasquale.

Reviews: Marion, Vliet

Nominating: Augustyn (Chair), Townsend, and Maxwell.



NREL's Solar Resource Activities

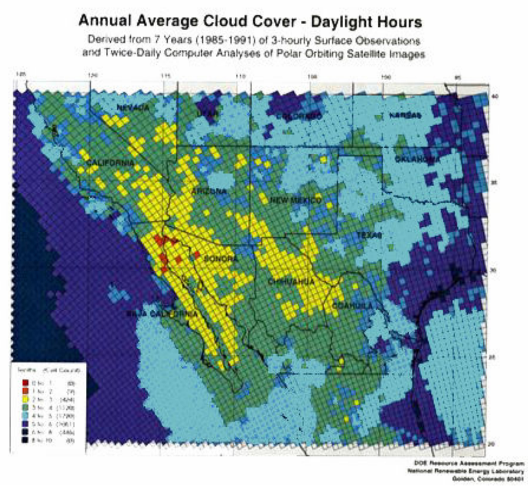
by Dave Renné

This past year, NREL's solar resource assessment team has continued to focus its efforts on basic and applied research, information dissemination, and field measurements. Our primary DOE funding source has been and will continue to be from NREL's Photovoltaics Program, which is managed by the National Center for Photovoltaics. We also receive support from DOE's Concentrating Solar Power (CSP) Program and the Atmospheric Radiation Measurement (ARM) Program, and non-DOE funding from NASA and from the government of Saudi Arabia.

A major area of activity for us is the development and validation of high resolution maps of solar resources using a variety of satellite and surface data sources. NREL's team has been using a cloud cover data set that covers the entire globe, and provides monthly average cloud cover at a 40-km resolution from historical surface records and satellite data. Gene Maxwell pioneered the development of a model to convert these cloud cover data into solar resource estimates. He has continued with this work even after his retirement from NREL, and will soon have several important papers published. This task is now being led by Dave Renné, Ray George, and Liz Brady. Recently, with support from the CSP Program, we have produced direct normal solar maps of northern Africa and southern Europe.

We are also supporting Richard Perez' pioneering work of converting GOES-8 and GOES-9 weather satellite imagery into very high resolution time and space solar resource data for parts of North America. He will help us host the Second International Satellite Data Users Workshop, which will be held in Golden, Colorado on February 3-4, (see separate announcement in this Solar Spectrum).

Our fruitful collaborations with NASA's Langley Research Center, or LARC, (Charlie Whitlock, Roberta DiPasquale, Paul Stackhouse, and Ann Carlson) are continuing through a formal interagency agreement that has been established between DOE and LARC. They are now working on a second generation data set of world-wide satellite-derived solar energy estimates, and are actively involving industry in the design of this new data base.



Satellite Map from Gene Maxwell

In other activities, Bill Marion has been evaluating to what extent a world-wide surface station meteorological data base, known as DATSAV2 (available from the National Climatic Data Center) can be used to develop hourly TMY data sets from the METSTAT model. This coming year, Bill will develop a web site that will allow users to access information from the internet to develop quick estimates of the a.c. energy production of PV systems located anywhere in the U.S. and its territories. The estimates will include monthly and yearly energy production and cost savings. The 239 station TMY2 data base will be the resource data used as input to these estimates.

Liz Brady continues to expand our Geographic Information Systems capabilities with the development of striking color maps depicting a variety of analyses that include resource data. Pam Gray-Hann has joined Liz' team to lend assistance to this growing work, which is also supported by NREL's Federal Energy Management and Wind Energy Programs. Recently Liz completed a demonstration version of the Map Server, which allows interactive internet access to NREL's maps and data products so that the user can customize their own maps on-line.

Martin Rymes continues to tackle significant technical problems at the lab. He recently undertook a task to develop a computerized 3-dimensional global depiction of renewable energy resources, so that world-wide maps can be produced with no significant map transformation errors. He also has evaluated the MeteoNorm data disk that was developed by the Swiss, to better understand how this product can assist industry, and how it can be merged with the other products being developed at NREL and elsewhere.

In the next Solar Spectrum we will summarize our current measurement programs, including activities at our own Solar Radiation Research Laboratory, the Cooperative Network for Renewable Resource Measurements (which now includes the Historically Black Colleges and Universities network of stations in the southeast U.S., the ARM Program, and the Saudi Project.

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NOTES FROM

Off the SEIA Web Page:

A last minute surprise has added more funding for renewables. The President has signed a giant $487 billion funding bill which has directed an additional $60 million for renewable energy programs within the U.S. Department of Energy. However, $42 million of these funds cover uncosted balances (funds obligated but not yet spent down) leaving $18 million in unspecified funds for DOE's renewable energy programs. The breakdown of how the $18 million is to be directed will be decided by Assistant Secretary Reicher in October 1998.

The FY'99 solar appropriations are $66.8 milliion for Photovoltaics RD&D, $17.1 million for Solar Thermal RD&D and $2.9 million for Solar Buildings RD&D.

EPA'S SOLAR INITIATIVE

(Continued from page 3)

areas where electricity costs more than eight cents per kilowatt-hour. Solar thermal space heating is effective in most areas of the country. For example, the cost of a 100 square foot transpired collector installation can range from $1,000 for retrofits on existing buildings and $500 - $700 for new systems, but can produce energy savings to offset the entire cost of the system in five years or less. Photovoltaic costs are more complicated because system size, features and net cost to the users depend on the financing terms and interest rates, available incentives and access to low cost hardware and installation through bulk purchasing programs. Residential photovoltaic systems recently installed in Sacramento cost under $7,000 per kilowatt. Solar technologies are most cost-effective at remote installations that are independent of the power grid. System costs can also be rduced by federal and state tax incentives and other financial support. Additional cost reductions are possible through the use of net metering.

EPA support for other renewable energy technologies may be developed in the future in response to new Administration sustainable energy efforts, or in response to the environmental opportunities being created by electric utility restructuring. Because of utility deregulation, renewable energy is becoming increasingly available on a retail level. If a significant percentage of people choose renewable energy, the result will be cleaner air, a stronger U.S. renewable energy industry and lower U.S. greenhouse gas emissions. Numerous studies have shown that consumers prefer clean, renewable energy, although most people do not realize where electricity comes from. EPA may have a role to play in increasing public availability of information on the environmental impacts of electricity generation, and in developing new efforts to encourage purchases of renewable energy by consumers, government and businesses.