PERGAMON

Renewable Energy 25 (2002) 219–234

RENEWABLE ENERGY

www.elsevier.com/locate/renene

Saudi Arabian solar radiation network operation data collection and quality assessment

N.M. Al-Abbadi [a], S.H. Alawaji [a], M.Y. Bin Mahfoodh [a], D.R. Myers [b,*], S. Wilcox [b], M. Anderberg [b]

[a] King Abdulaziz City for Science and Technology P.O. Box 6086, Riyadh 11442, Saudi Arabia
[b] National Renewable Energy Laboratory 1617 Cole Blvd, Golden, CO 80401, USA

Received 21 November 2000; accepted 16 January 2001

Abstract

From 1993 to the present (2000), King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia and the US National Renewable Energy Laboratory (NREL) conducted a joint solar radiation resource assessment project to upgrade the solar resource assessment capability of the Kingdom of Saudi Arabia. KACST has deployed a high quality 12-station network in Saudi Arabia for monitoring solar total horizontal, direct beam, and diffuse radiation. One- and 5-min network data are collected and assessed for quality. 80% or more of the network data fall within quality limits of ±5% for correct partitioning between the three radiation components. We describe the network, quality assessment procedures, data formats and availability.

1. Introduction

From 1993 to the present (2000), the National Renewable Energy Laboratory's (NREL) Center for Renewable Energy Resources and the King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia, conducted a joint solar radiation resource assessment project to upgrade the solar resource assessment capability of the Kingdom of Saudi Arabia [1]. The project is operated under Annex II, Solar Radiation Resource Assessment, to the Joint United States–Saudi Arabian

* Corresponding author. Fax: +1-303-384-6768.
E-mail address: daryl_myers@nrel.gov (D.R. Myers).

0960-1481/02/$ - see front matter
PII: S0960-1481(01)00055-6

Technical Agreement on Renewable Energy Research, and is called the New Energy Project.

The goals of the project were to improve the monitoring of solar radiation resources for alternative energy within the Kingdom, exchange technical expertise with KACST scientists in the principles of solar radiation measurements, instrumentation, network operations, data quality assessment and management, solar radiation modeling, and to generate a solar radiation atlas for the Kingdom. The meeting of the goals of the New Energy Project has resulted in deployment and operation of a high-quality 12-station network for monitoring solar total horizontal, direct beam, and diffuse radiation in the Kingdom, and a new edition of a solar radiation atlas for the Kingdom. Furthermore, the project is working on establishing a national solar radiation data base for the Kingdom. NREL has applied techniques for estimating the total column water vapor and aerosol optical depth from the measured meteorological and radiometric data to support the data base project.

2. Network design

Under the KACST New Energy Project, NREL assisted KACST with the design of a solar radiation monitoring network including selection of sensors, data loggers, instrument platform design, data collection, quality assessment, and management. An Absolute Cavity Pyrheliometer [2] was obtained by KACST to serve as the calibration reference instrument. A central calibration facility for solar radiometers was established at the KACST Solar Village site 40 km northwest of Riyadh. KACST participated in the World Meteorological Organization (WMO) 1995 International Pyreheliometric Comparison (IPC) [3] in order to obtain traceability of their radiometer calibrations to the WMO World Radiometric Reference, or WRR [4].

NREL and KACST evaluated METEOSAT satellite images of the Kingdom, and KACST personnel performed site visits to select sites representing the various climate, topographical, and albedo regimes in the Kingdom. Fig. 1 is a map of the selected sites. Note that the sites represent a coarse $5°\times5°$ grid over the country. The Kingdom is approximately the size of Alaska and Texas combined, or roughly the eastern half of the United States. Riyadh is indicated on the map as the capital, but is not one of the monitoring network sites.

3. Network instrumentation

Instrumentation for the measurement of total solar radiation from the sky dome on a horizontal surface (global horizontal), direct beam radiation in a 5.7° field of view centered on the solar disk, and diffuse sky radiation on a horizontal surface as well as ambient temperature and relative humidity were selected as shown in Table 1.

All but Solar Village instrumentation is mounted 0.5 m above ground level on identical platforms. At sites with sandy soil, platforms are mounted on concrete pads. The Solar Village platform is located 4 m above ground on the building roof. The

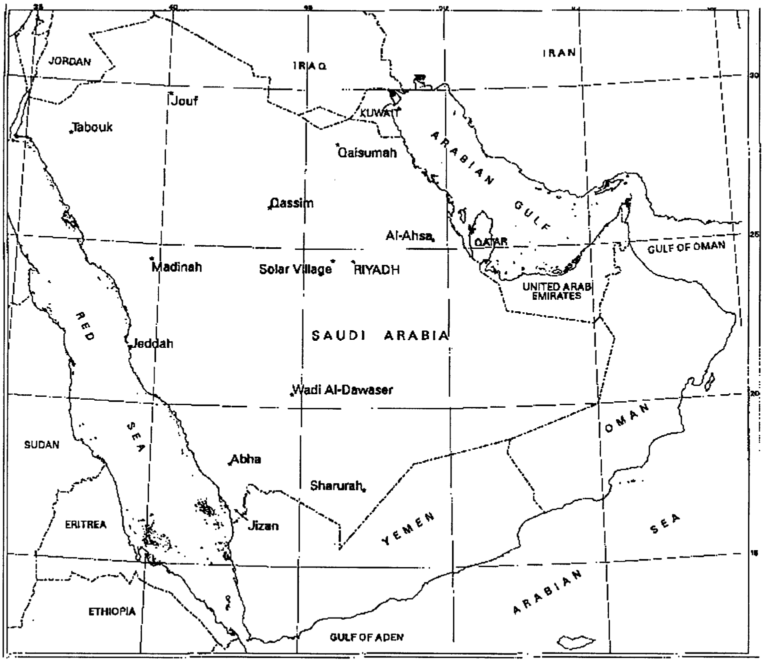


Fig. 1. Map of solar radiation network stations in KSA.

data sample period is 10 s (0.1 Hz), and 5-min averages of the 10-s data are computed and archived. The clock accuracy for the data logger is ± 2.0 s/day. The clocks at all sites are set nightly with respect to national time standards. All network data are downloaded nightly to the data collection center at the Solar Village site. Fig. 2 is a photograph of the instrumentation installed at all 12 stations.

4. Calibrations and instrument characterizations

The radiometers installed in the network are calibrated against the KACST reference absolute cavity pyrheliometer that participated in the 1995 WMO IPC at Davos, Switzerland. Thus, all calibrations are traceable to the WMO WRR.

NREL developed Radiometer Calibration and Characterization (RCC) software to automatically collect calibration data, generate calibration reports, and archive calibration results. The calibrations are derived from the measurement of the direct beam radiation by the absolute cavity radiometer, measurement of the diffuse sky radiation by a pyranometer under a tracking shading disk, and computation of the reference (global horizontal) irradiance using:

$$I_{ref}=I_{dn}\cos(z)+I_{diff},$$

where I_{dn} is the direct beam, I_{diff} is the sky diffuse radiation, and z is the zenith

Table 1
Instrumentation common to all 12 network stations

Parameter	Unit	Sensor	Manuf.	Model	Uncertainty	Comments
Ambient Temperature	°C	1000 Ω Plat. resistance thermometer	Vaisala	50Y	±0.5°C	Combined temperature and RH sensor
Relative humidity (RH)	% RH	Capacitive	Vaisala	50Y	±2.5%	0–100% range
Global horizontal solar irradiance	W/m^2	Type-T thermopilepyranometer	Eppley Laboratory	PSP	±3.0%@1 kW/m^2	Using single calibration factor
Direct beam solar irradiance	W/m^2	Type-T thermopilepyrheliometer	Eppley Laboratory	NIP	±2.0%@ 1 kW/m^2	5.7° field of view
Diffuse horizontal solar irradiance	W/m^2	Type-T thermopilepyranometer	Eppley Laboratory	PSP	±3.0%@ 1 kW/m^2	Under tracking shading disk subtending 5.7°
Solar tracker: direct beam	n/a	Synchronousmotor drive	Eppley Laboratory	ST-1	±3.0° per day	Manual alignment daily
Solar tracker:shade disk	n/a	Synchronousmotor drive	Eppley Laboratory	RSD-2	±3.0° per day	Manual alignment daily
Data logger	V	Analog to digital sample and hold	Campbell ScientificInc.	CR-10	0.2% full-scale	Full-scale: 25 MvResolution 3.33 MvTime±4 msnoise <0.8 μVRMS

Fig. 2. NREL-designed platform and instrumentation for monitoring total and diffuse global radiation on a horizontal surface, direct beam solar radiation, ambient temperature, and relative humidity. The platform is aligned along the meridian of longitude for the site, with the tracking shade disk mechanism to the south (NREL photo by Steve Wilcox).

angle (complement of the solar elevation angle), which, for horizontal surfaces represents the incidence angle for the solar direct beam.

Calibrations are accomplished with the radiometers mounted on specially designed platforms on a roof at the Solar Village site. Data are taken from sunrise to sunset on several clear days. Silicon diode radiometers monitor atmospheric stability during the calibrations. Any variation in direct or global irradiance of >0.5% between 30-s readings results in their being excluded from the analysis.

The RCC software generates a report of each individual instrument's departure from true lambertian (cosine) response in 10°-wide bins of zenith angle from 0 to 90°. Fig. 3 shows the graph of the responsivity of an individual instrument as it is generated in the calibration report. Table 2 is a report of the zenith angle dependence of the responsivity generated by the RCC report generator.

The uncertainty in the responsivity is computed from the range of the calibration data in each zenith angle bin, root sum squared with a base level of uncertainty of 1.3%. The base uncertainty level was determined through a detailed uncertainty analysis of the transfer of the WRR scale to the cavity pyrheliometer, time-uncertainty in the diffuse measurements, time keeping and location data, and specifications and testing of the data logger used.

The instrumentation for performing the calibrations consists of an Eppley laboratories Automatic Hickey–Frieden (AHF) absolute cavity pyrheliomter, two shaded pyranometers that are averaged to produce the diffuse sky irradiance, and silicon cell pyranometers and pyrheliometers to measure the sky stability. Data are recorded on a John Fluke Model 2287A Helios data logger with 100 μV resolution, <50 nV of noise, and 0.05% of full-scale accuracy. The full-scale used is 25 mV.

All calibration data and results are archived into a calibration history database that is an integral part of the RCC software. Given the calibration and deployment history

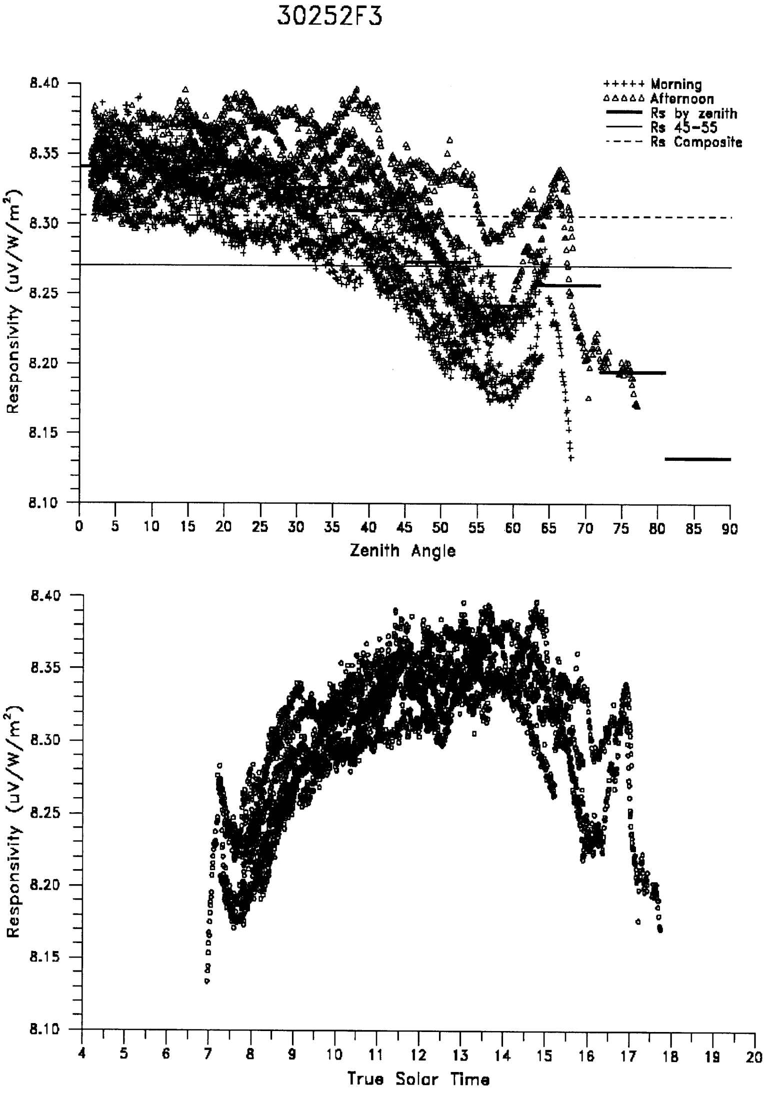


Fig. 3. RCC Graphical report of pyranometer responsivity (μV/W/m^2) —vertical axis — as a function of zenith angle (top) and true solar time (bottom) for a Saudi-network pyranometer.

of a particular radiometer we are able to correct data collected using a single calibration factor (the composite result) to account for individual radiometer cosine responses. These corrections reduce the uncertainties in radiometric data at high zenith angles by at least a factor of 2.

Table 2
RCC responsivity report format[a]

Instrument *N*/SD Bin	Rs	Uncert	30252F3 7383/0.041 Pct
45–55	8.27	0.27	2.4
Composite	8.30	0.25	3.3
Zen 00–-09	8.34	0.12	1.9
Zen 09–-18	8.34	0.12	1.9
Zen 18–-27	8.33	0.13	2.0
Zen 27–-36	8.32	0.11	1.9
Zen 36–-45	8.30	0.14	2.1
Zen 45–-54	8.27	0.17	2.4
Zen 54–-63	8.24	0.15	2.2
Zen 63–-72	8.26	0.20	2.8
Zen 72–-81	8.19	0.20	2.8
Zen 81–-90	8.13	0.25	3.3

[a] Key to table entries: *N*/SD, *N*, sample size entire data set; SD is standard deviation in $\mu V/W/m^2$; Rs, responsivity ($\mu V/W/m^2$) in zenith angle bin; Uncert, uncertainty in mean for bin($\pm\mu V/W/m^2$); Pct, uncertainty in mean for bin as ±percent of Rs; 45–55, mean responsivity in 45–55 zenith angle range ($\mu V/W/m^2$); composite, mean responsivity computed from all cosine (bin center) weighted responsivities; zen nn-nn, Zenith angle bin boundaries.

5. Network operations

5.1. Station locations

Table 3 shows station name and location information for the entire 12-station network. See Fig. 1 above for a map of station locations. All stations are configured with instrumentation as described in Section 3 above, and shown in Fig. 2.

Table 3
Saudi Arabian solar monitoring network stations

Station	Latitude (°N)	Longitude (°E)	Elevation (m)
Abha	18.23	42.66	2039
Al-Ahsa	25.30	49.48	178
Gizan	16.90	42.58	7
Qassim	26.31	43.77	647
Jeddah	21.68	39.15	4
Madinah	24.55	39.70	626
Qaisumah	28.32	46.13	358
Sharurah	17.47	47.11	725
Jouf	29.79	40.10	669
Solar Village[a]	24.91	46.41	650
Tabouk	28.38	36.61	768
Wadi Al-Dawaser	20.44	44.68	701

[a] Northwest of Riyadh.

5.2. Baseline surface radiation network station upgrade for the solar village site

In addition to the regular network installation described in Section 3 and shown in Fig. 2, KACST took the initiative to obtain improved instrumentation to upgrade the Solar Village network station to stringent WMO Global Climate Change Research Program Baseline Surface Radiation Network (BSRN) [5,6] standards. This included the addition of an all weather absolute cavity radiometer for direct beam radiation monitoring, upwelling and downwelling infrared (pyrgeometer) sensors, upwelling shortwave radiation sensor, and a more accurate tracking system for direct beam and shading mechanisms. The upwelling shortwave and longwave sensors are mounted on a tower 33 m above ground. The rest of the BSRN instrumentation is located 1 km to the southwest, on the roof of the calibration facility as seen in Fig. 2. The Solar Village BSRN data are collected and archived as 1-min averages of 2-s samples.

5.3. Data collection and quality assessment

The 12-station Saudi Arabian Solar Monitoring Network 5-min surface flux, temperature, and relative humidity data are collected nightly. Data are downloaded via modem lines from data logger memory to the central Solar Village calibration and data-processing facility. Data collection is unaffected and uninterrupted by this data transfer.

The previous day's data are examined by the network manager to find obvious measurement problems, such as failed trackers or sensors. Then, the data are processed through a Data Quality Management System (DQMS) that performs checks on the relative partitioning of the radiometric data and whether the data exceeds physical limits. Since the total global solar radiation, I_{GH}, is made up of a combination of the direct beam and diffuse sky radiation, namely:

$$I_{GH}=I_{DN}\cos(z)+I_{DF},$$

where I_{DN} is the direct beam, I_{DF} is the sky diffuse radiation, and z is the zenith angle (incidence angle for direct beam on a horizontal surface), the measured data are inserted into this equation, and the quality of the balance between components is used to check the data quality.

Quality assessment flags are assigned based on the magnitude and direction of deviations from the balance in the radiation component equation. For convenience, the evaluation is performed after normalization with respect to the extraterrestrial (ETR) solar radiation for the appropriate radiation component. The normalized variables are called 'clearness' indices [7], and we refer to them as '*K*-space' parameters. These *K*-space parameters are defined as

Kt Irradiance from 2-pi steradian (sr) on horizontal surface/[ETR direct beam∗cos(z)]

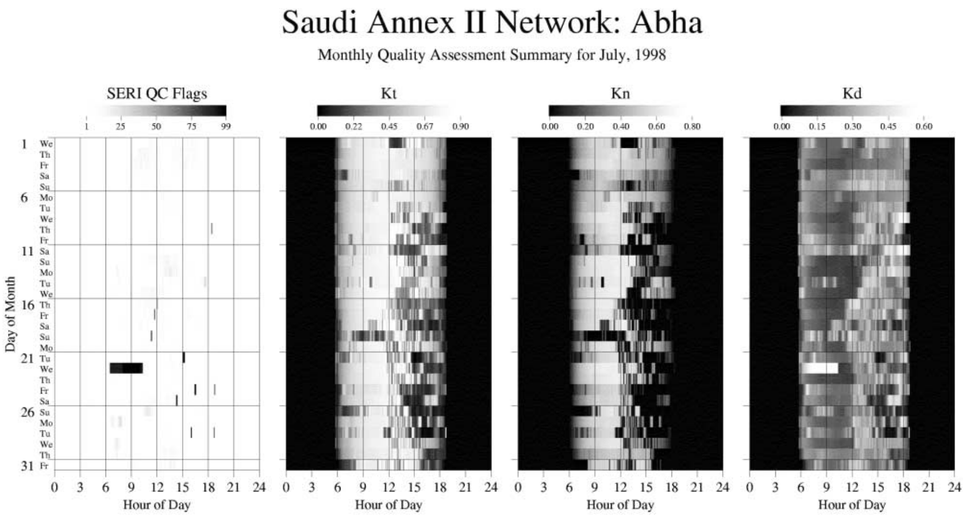
Kn Direct beam irradiance in 5.7° field of view/ETR direct beam

Kd Diffuse (non-direct beam) Irradiance from 2-pi sr on horizontal surface/[ETR direct beam∗cos(z)].

ETR direct beam is computed from the ‘nominal’ solar constant of 1367±7 W/m^2 modified by the inverse square law applied to the daily variation in the earth–sun radius vector caused by the eccentricity of the Earth’s solar orbit.

In *K*-space, the component balance equation reduces to $Kt=Kn+Kd$. *K*-space parameters generally are in the range from 0 to 0.8. Data quality assessment flags in the range from 00 to 99 are assigned that describe both the magnitude and possible source of imbalance in the component equation. Flags in the range from 00 to 09 indicate various low-level failures identified by visual inspection. Flags from 10 to 93 indicate failures in one of four ways. The manner of failure (high or low) is indicated by the remainder of the calculation (flag +2)/4. The magnitude of the test failure (distance in *K*-units) is determined from: d=INT((flag+2)/4)/100. Flags from 94 to 97 indicate that data fall into a physically impossible region where $Kn>Kt$. Flag 98 is not used, and Flag 99 indicates missing data.

A visual interpretation tool developed in conjunction with the DQMS processing allows one to examine the 5-min data and the magnitude of flags associated with the data in *K*-space, as shown in Fig. 4. In the SERI QC Flags section of Fig. 4,



Summary Statistics

Percent of data	Daytime Glo	Daytime Dir	Daytime Dif	Daytime Temp	Daytime RelHum	Nighttime Glo	Nighttime Dir	Nighttime Dif	Nighttime Temp	Nighttime RelHum
Present	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
*Flags <= 5%	99.0	98.8	98.4	100.0	99.9	100.0	100.0	100.0	100.0	99.5
*Flags > 10%	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
*Below empirical limit	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
*Above empirical limit	0.1	0.0	0.5	0.0	0.1	0.0	0.0	0.0	0.0	0.5
*Strange but true	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Site Information
Identifier: AB1
Latitude: 18.23
Longitude: 42.66
Elevation: 2039 meters
Time Zone: 3.0
Data Resolution: 5 min

* Flag statistics indicate percent of present data

Developed by the National Renewable Energy Laboratory

Fig. 4. Visual display of quality assessment (QA) flags and normalized radiation values of one month of 5-min solar data. The dark rectangle of larger QA flags (large errors) on Wednesday 22 July, from 6:30 a.m. to 10:00 a.m. corresponds to a failed diffuse-shade tracker, indicated by the high (white) diffuse value in *Kd*.

the darker the shading, the 'worse' the flags. In the *Kt*, *Kn*, and *Kd* sections, the lighter the shades — the higher the irradiance, and the darker the shades — the lower the irradiance.

In Fig. 4, there is a diurnal pattern for this month of sunny mornings and partly cloudy afternoons. Up until the 22nd of the month, the flags are light (small errors), but there are several hours on the 22nd when the flags are large (dark rectangle from 7 to 9:30 a.m.).

On the same row for the *Kt*, *Kn*, and *Kd* plots, the bright rectangle in the *Kd* segment on the 22nd indicates the tracking shading disk for the diffuse was not shading the pyranometer (high *Kd*). Thus, the component balance equation was not true, and the software flagged the data. By 10:30 a.m., the station operators corrected the problem.

The monthly summary shows that $>$98% of the data were flagged as having errors of $<$5% in the component balance equation, and 0.5% of the data had errors $>$10%. Both KASCT and NREL process all data for the entire network with this product as part of a monthly network performance report.

6. Data formats and availability

6.1. Correcting and internet posting of data

Monthly quality assessed data files, for all 12 stations and the BSRN station at the Solar Village, are forwarded to NREL. NREL post processes the global solar radiation data to correct for zenith angle variations in the responsivity of the pyranometer measuring the total sky radiation. All data then is posted on the NREL supported Web site at http://rredc.nrel.gov/solar/new_data/Saudi_Arabia/. At this site all corrected 5-min network station data from January 1998 to the present is available. The Solar Village 1-min resolution BSRN data are formatted and posted on the above site, and is also reformatted and submitted to the BSRN Archive in Zurich, Switzerland (at http://bsrn.ethz.ch/) in the BSRN Archive format. Data for the entire network is available from the Energy Research Institute of KACST through Dr Al-Abbadi. A CD-ROM release of the first 5 years of measured data is planned for early 2001.

6.2. Network monthly mean daily totals

Table A1 in Appendix A contains monthly mean daily totals in kilowatt-hour per square meter for each station as of July 2000. The 5-min station data were converted to daily totals by integration into watt-hour values which were summed into daily totals. At least six 5-min data values were needed to compute an hourly total. If this criteria was not met during an hour, the hourly total was not computed. For each of the 24 h in a day (1–24) the mean monthly hourly value was computed. Finally the mean monthly hourly values were summed to form the monthly mean daily total. Table A2 displays the percent of possible daylight hours contributing to the monthly mean daily total.

7. Summary

The Energy Research Institute of KACST and NREL conduct a joint solar radiation resource assessment project to upgrade the solar resource assessment capability in the Kingdom of Saudi Arabia. KACST has deployed a high quality 12-station network in Saudi Arabia for monitoring solar total horizontal, direct beam, and diffuse radiation. One- and 5-min network data are collected and assessed for quality. A total of 80% or more of the network data fall within quality limits of ±5% for correct partitioning between the three radiation components. NREL post processes this data to correct for known zenith angle dependence of the calibration factors used to produce the total radiation flux at the ground. The quality assessed and corrected network data are available through an NREL Internet site. One-minute resolution BSRN quality data from the Solar Village site, 40 km northwest of Riyadh, is posted on the same NREL internet site, and reformatted and submitted to the BSRN Archive in Zurich Switzerland. The entire high resolution data set is available through Dr Al-Abbadi at KACST. A CD-ROM release of the first 5 years of measured data is planned for early 2001.

Acknowledgements

Dr Eugene L. Maxwell was the US and NREL project technical leader for the first 4 years of the joint US/Saudi Arabian project on Solar Radiation Resource Assessment. His vision and technical implementation of the project is the foundation of the measurement network success. The diligent work of the Solar Village technicians Abdulaziz Al-Moammer, Abdullah Al-Rubeq, Moawiah Al-Khaledi, and Artemio Medrano to perform network radiometer calibrations and routine station operations is critical to maintaining the quality of the Saudi network data. The efforts of many MEPA technicians at the other 11 network sites also contribute to the high quality of the network data. The Joint New Energy Annex II Solar Radiation Assessment Project was not possible without the co-operation of the US/Saudi Arabian Joint Economic Commission and the US Department of Energy (DOE), particularly Dr Allan Jelacic of DOE Headquarters, and Mr Robert Martin of the DOE Golden Field Office.

Appendix A. Monthly mean daily totals data summary for the Saudi Arabian network

Table A1
Monthly mean daily total kilowatt-hours by station 1996–July 2000

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abha												
Global	4.906	6.253	6.382	7.049	6.778	6.778	6.219	6.067	6.585	6.215	5.535	5.077
Direct	6.218	8.008	6.562	6.802	6.219	5.812	4.416	4.546	6.674	7.531	7.695	7.458
Diffuse	1.177	1.079	1.611	1.836	1.994	2.275	2.710	2.393	1.821	1.157	0.944	0.878
Ahsa												
Global	3.998	4.915	5.673	6.699	7.432	7.941	7.572	7.258	6.629	5.591	4.564	3.753
Direct	5.252	4.971	4.569	5.521	6.055	7.386	6.314	6.548	6.931	6.202	6.135	5.106
Diffuse	1.342	1.787	2.272	2.604	2.557	2.060	2.531	2.134	1.688	1.395	1.194	1.158
Gizan												
Global	4.574	5.390	5.923	6.800	6.930	6.496	5.702	5.903	6.408	5.883	5.219	4.721
Direct	4.304	4.674	4.564	5.515	5.636	4.532	2.659	3.421	5.131	5.873	5.842	5.198
Diffuse	1.926	2.201	2.473	2.435	2.412	2.710	3.378	2.942	2.303	1.724	1.515	1.641
Qassim												
Global	3.928	4.805	5.712	6.676	7.180	8.014	7.724	7.314	6.544	5.459	4.115	3.544
Direct	5.324	5.585	5.416	5.572	5.969	8.134	7.376	7.429	6.610	6.358	5.074	4.962
Diffuse	1.189	1.608	2.125	2.355	2.550	1.862	2.074	1.769	1.797	1.502	1.371	1.135
Jeddah												
Global	4.343	5.188	6.028	6.881	7.061	7.336	7.034	6.788	6.155	5.576	4.525	4.099
Direct	4.854	5.291	5.203	5.798	5.394	6.036	5.187	5.285	4.451	6.072	5.379	5.066
Diffuse	1.465	1.746	1.975	0.000	2.224	2.238	2.881	2.317	2.399	1.701	1.337	1.385
Madinah												
Global	4.210	5.333	6.091	6.886	7.157	7.856	7.461	7.040	6.302	5.583	4.403	3.943
Direct	6.126	6.767	6.107	6.599	6.217	8.083	7.158	6.784	6.223	6.727	5.956	5.722
Diffuse	1.024	1.248	1.682	1.965	2.180	1.691	1.963	1.852	1.841	1.331	1.146	1.099
Qaisumah												
Global	3.532	4.553	5.483	6.454	7.362	8.026	7.653	7.346	6.497	5.190	3.943	3.278
Direct	4.340	5.074	4.730	4.772	5.678	7.970	6.900	7.588	6.627	5.394	5.066	4.463
Diffuse	1.255	1.593	2.187	2.593	2.860	2.092	2.707	2.032	1.754	1.690	1.333	1.088

(continued on next page)

Table A1 (*continued*)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sharurah												
Global	5.185	6.149	6.540	7.325	7.441	7.349	6.880	6.946	6.924	6.385	5.677	5.200
Direct	6.504	7.167	5.467	6.583	6.662	6.514	4.440	5.165	6.873	8.210	7.363	6.923
Diffuse	1.361	1.566	2.216	2.197	2.151	2.152	3.152	2.472	1.910	1.438	1.146	1.094
Jouf												
Global	3.481	4.536	5.851	7.025	7.599	8.331	7.976	7.316	6.547	5.215	3.794	3.228
Direct	4.923	5.839	6.425	6.816	7.245	9.453	8.380	7.903	7.772	6.725	5.343	4.856
Diffuse	1.149	1.371	1.771	2.176	2.443	1.458	1.638	1.677	1.409	1.314	1.162	1.077
Solar Village												
Global	4.093	5.011	5.769	6.631	7.316	8.006	7.621	7.419	6.730	5.660	4.411	3.794
Direct	5.724	5.600	5.196	5.638	6.172	8.113	7.119	7.533	7.339	7.088	6.045	5.632
Diffuse	1.147	1.659	2.226	2.435	2.590	1.945	2.228	1.842	1.625	1.312	1.201	1.090
Tabouk												
Global	3.861	4.899	6.132	7.141	7.468	8.049	7.882	7.334	6.520	5.262	4.153	3.509
Direct	5.920	6.722	7.038	7.296	7.202	9.151	8.329	8.089	7.698	6.997	6.048	5.523
Diffuse	1.015	1.252	1.398	1.682	2.229	1.288	1.858	1.396	1.247	1.036	1.087	0.930
Wadi Al-Dawasser												
Global	4.569	5.774	6.149	7.167	7.435	7.660	7.237	7.090	6.862	6.083	5.166	4.562
Direct	5.871	6.777	5.287	6.163	6.317	6.880	5.676	6.099	6.578	7.238	7.026	6.536
Diffuse	1.356	1.551	2.323	2.418	2.521	2.348	2.742	2.410	1.735	1.297	1.175	1.130

Table A2
Percent of possible daylight data hours used to calculate monthly mean daily total kilowatt-hours by station 1996–2000 in Table 4

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abha												
Global	99	100	98	100	100	93	100	100	100	99	99	99
Direct	80	96	95	97	100	93	98	76	77	98	97	99
Diffuse	98	100	96	99	98	93	99	98	79	97	99	99
Ahsa												
Global	95	100	100	100	100	99	100	100	100	78	80	100
Direct	76	97	80	62	81	98	100	97	80	77	78	96
Diffuse	94	99	99	97	50	79	97	97	78	39	80	100
Gizan												
Global	100	100	100	100	100	90	100	100	100	100	100	100
Direct	82	99	98	98	98	89	99	99	99	97	97	99
Diffuse	99	100	99	79	60	54	81	95	99	99	100	100
Qassim												
Global	100	98	100	100	100	100	100	100	98	100	100	100
Direct	97	81	65	78	99	83	100	99	96	97	99	98
Diffuse	100	97	99	99	99	100	99	99	97	97	97	99
Jeddah												
Global	74	99	98	96	98	95	97	98	99	97	100	100
Direct	68	93	68	89	81	76	58	23	70	24	96	100
Diffuse	70	92	48	0	36	38	39	45	46	72	73	75
Madinah												
Global	100	100	79	99	100	100	100	99	90	98	100	100
Direct	99	96	58	75	79	97	79	94	87	77	97	99
Diffuse	99	99	97	98	97	60	98	97	89	97	100	100
Qaisumah												
Global	99	100	99	99	100	100	100	97	73	97	100	100
Direct	94	93	93	53	57	97	96	25	45	75	98	76
Diffuse	79	95	77	77	40	75	39	48	70	58	79	79

(continued on next page)

Table A2 (*continued*)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sharurah												
Global	78	98	100	97	98	99	97	98	80	75	97	99
Direct	57	73	75	35	55	46	78	73	53	19	55	54
Diffuse	55	55	74	56	37	28	74	74	57	20	56	73
Jouf												
Global	100	100	100	100	100	100	100	88	100	100	100	100
Direct	80	99	97	99	98	99	98	88	100	99	99	99
Diffuse	100	98	98	78	38	38	78	87	98	99	99	100
Solar Village												
Global	100	100	100	100	100	100	100	100	100	100	100	100
Direct	99	100	99	100	100	100	100	100	100	100	100	100
Diffuse	100	100	99	99	100	99	100	100	100	100	100	100
Tabouk												
Global	99	100	99	99	99	100	100	91	79	80	100	99
Direct	97	99	97	97	99	98	99	89	76	79	79	96
Diffuse	58	73	36	19	19	39	38	66	38	59	75	95
Wadi Al-Dawasser												
Global	100	100	100	97	100	100	100	100	97	98	100	100
Direct	100	100	100	95	98	99	99	96	99	99	100	100
Diffuse	78	97	95	93	82	82	98	79	76	97	99	100

References

[1] Maxwell E, Cornwall C, Wilcox S, Alawaji S, Bin Mahfoodh M. Assessment of solar radiation resources in Saudi Arabia. In: Sayigh AAM, editor. Renewable Energy, Proceedings of World Renewable Energy Conference 15–21 June 1996, vol. III. Oxford: Pergamon, 1996:2135-2139
[2] Kendall J, Berhdahl C. Two black body radiometers of high accuracy. Applied Optics 1970;12:1089–91.
[3] WMO. International Pyrheliometric Comparisons IPC VIII, 25 Sep 13–Oct 1995, Results and Symposium, Working Report No. 188. Switzerland: Swiss Meteorological Institute, Davos and Zurich, 1996.
[4] WMO. Guide to Meteorological Instruments and Methods of Observation, OMM No. 8. Geneva, Switzerland: Secretariat of the World Meteorological Organization, 1983:9.3.
[5] Ohmura A, Dutton E, Forgan B, Fröhlich C, Gilgen H, Hegner H, Heimo A, König-Langlo G, McArthur B, Müller G, Philipona R, Pinker R, Whitlock C, Dehne K, Wild M. Baseline surface radiation network (BSRN/WCRP): New precision radiometry for climate change research. Bulletin of the American Meteorological Society 1998;79(10):2115–36.
[6] McArthur L. Baseline Surface Radiation Network (BSRN) Operations Manual, (Version 1.0), WMO/TD No. 879. Geneva, Switzerland: World Climate Research Program, WMO, 1998.
[7] Liu B, Jordan R. The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation. Solar Energy 1960;4:1–16.