Solar and Wind Energy Resource Assessment (SWERA)

High Resolution Solar Radiation Assessment for Kenya

Final country report prepared by DLR

Christoph Schillings[1]

Richard Meyer[2]

Franz Trieb[1]

[1] Deutsches Zentrum für Luft- und Raumfahrt, DLR-Stuttgart, Institut für Technische Thermodynamik, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany

[2] Deutsches Zentrum für Luft- und Raumfahrt, DLR-Oberpfaffenhofen, Institut für Physik der Atmosphäre, D-82234 Weßling, Germany

submitted to UNEP / GEF

October 2004

Content

Notice

This report is electronically available at http://swera.unep.net

Contact the responsible author:

Christoph Schillings
DLR - Deutsches Zentrum für Luft- und Raumfahrt, e.V.
Pfaffenwaldring 38-40
D - 70569 Stuttgart

tel ++49(0)711/6862-784
fax ++49(0)711/6862-783
mail christoph.schillings@dlr.de
www http://www.dlr.de/system

1 Method description

Satellite Data

The high resolution solar radiation assessment is based on data of the geostationary satellite Meteosat. Due to the location of the participating SWERA countries, data of Meteosat 7 (M-7) for the years 2000, 2001 and 2002 (for Ghana, Kenya and Ethiopia) and data of Meteosat 5 (M-5) for the years 2000, 2002 and 2003 (for Bangladesh, West-China, Nepal and Sri Lanka) are used. M-5 has its position at 0° latitude and 63° East longitude, M-7 is located at an orbit at 0° latitude and 0° longitude. Figure 1 gives the field of view of both satellites which scans the specific area every 30 minutes with a spatial resolution of 5x5 km².

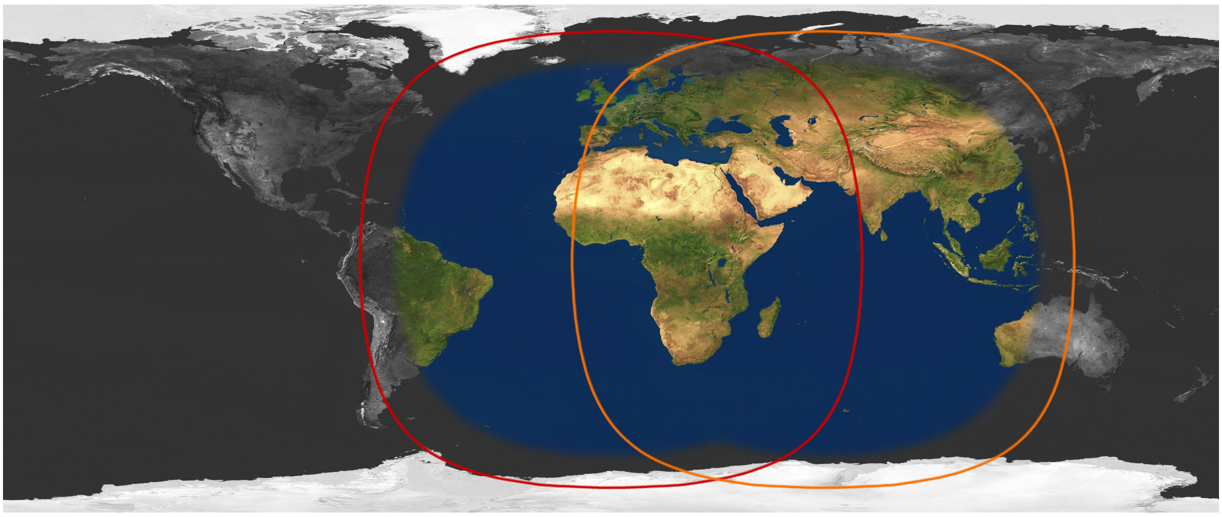

Figure 1: The solar irradiance data is derived from Meteosat a 0° (red circle) and at 63° East (orange circle). The brightened area marks the quantitatively analyzable region. (Meyer et al., 2004).

Data of the visible (VIS) channel, which gives the reflection of the system earth/atmosphere (including clouds) and data of the infrared (IR) channel, which represents the temperature of the surface and atmosphere, are used for gathering information about the clouds. Both are used in a different way to assess the global horizontal (*GHI*) and the direct normal radiation (*DNI*) at ground. Additionally, data of the most important atmospheric components that attenuate the radiation, namely ozone, water vapor and aerosols, are used to take into account the clear-sky conditions of the atmosphere. In the following, the method for deriving *DNI* based on the DLR method and the method for deriving *GHI*, based on a combined method of DLR and SUNY, is described.

Method for Direct Normal Radiation (*DNI*)

The calculation of *DNI* bases on the clear-sky model of Bird and Hulstrom (1981) as described in Iqbal (1983) which was modified by Schillings et al. (2004) for taking into account cloudy conditions with

$$DNI = 0.9751 \cdot I_0 \cdot \tau_R \cdot \tau_{Gas} \cdot \tau_{Ozon} \cdot \tau_{WV} \cdot \tau_{Ae} \cdot \tau_{vis} \cdot \tau_{ir} \qquad (1)$$

Each atmospheric transmittance coefficient τ_i is calculated separately using atmospheric input data. All equations for calculating the clear-sky transmittances are described in Iqbal (1983).

Transmittance for Rayleigh scattering

$$\tau_R = \exp\left[-0.0903 m_a^{0.84}\left(1.0 + am_p - am_p^{1.01}\right)\right] \qquad (2)$$

Transmittance for equally distributed gas (mainly O_2 and CO_2)

$$\tau_{Gas} = \exp\left(-0.0127 am_p^{0.26}\right) \qquad (3)$$

Transmittance for ozone

$$\tau_{Ozon} = 1 - \alpha_{Ozon} \qquad (4)$$

$$\alpha_{Ozone} = 0.1611\chi(1.0 + 139.48\chi)^{-0.3035} - 0.002715\chi\left(1.0 + 0.044\chi + 0.0003\chi^2\right)^{-1} \qquad (5)$$

$\chi = u \cdot am$, with the vertical ozone layer thickness *u* in cm[NTP] and the airmass *am*.

Transmittance for water vapor

$$\tau_{WV} = 1 - \alpha_{WV} \qquad (6)$$

$$\alpha_{WV} = 2.4959\gamma\left[(1.0 + 79.034\gamma)^{0.6828} + 6.385\gamma\right]^{-1} \qquad (7)$$

$\gamma = w \cdot am$, with the pressure-corrected relative optical path length of precipitable water *w* in cm[NTP].

Transmittance for aerosols

$$\tau_{Ae} = \exp\left[-k_a^{0.873}\left(1.0 + k_a - k_a^{0.7088}\right)am_p^{0.9108}\right] \qquad (8)$$

$$k_a = 0.2758 k_{a\lambda}\big|_{\lambda=0.38\mu m} + 0.35 k_{a\lambda}\big|_{\lambda=0.5\mu m} \qquad (9)$$

with the aerosol optical thickness $k_{a\lambda}$ at the wavelength 0.38 μm und 0.5 μm.

Transmittance for clouds

using the visible Cloud-Index *CI_vis*

$$\tau_{vis} = e^{\left(-CI_{vis} \cdot 0.1\right)} \qquad (10)$$

and using the infrared Cloud-Index *CI_ir*

$$\tau_{ir} = e^{\left(-CI_{ir} \cdot 0.07\right)} \qquad (11)$$

For the clear-sky atmospheric transmittance, the airmass is needed which is calculated by

$$am = \frac{1}{\left[\cos\Theta_Z + 0.15(93.885 - \Theta_Z)\right]^{-1.253}} \qquad (12)$$

The pressure correction is made by

$$am_p = am \cdot \frac{p}{1013.25} \qquad (13)$$

with

$$\frac{p}{p_0} = \exp(-0.0001184 z) \qquad (14)$$

The clear-sky radiation is calculated each 20 minutes (10,30,50 minutes of each hour) for the maps and each 5 minutes (5,10,15,…,55,60 minutes each hour) for the time series. The influence of the clouds is taken into account hourly, therefore all maps (monthly and annual average daily sums) and time series are based on an hourly calculation of the radiation. The DLR -model output for *DNI* is sampled at a 10km spatial resolution.

Method for Global Horizontal Radiation (*GHI*)

The calculation of *GHI* bases on the method of Perez et al (2002) and Ineichen and Perez (2002). *GHI* is calculated with (Perez et al., 2002)

$$GHI = ktm \cdot Ghc \cdot (0.0001 \cdot ktm \cdot Ghc + 0.9) \qquad (15)$$

with *ktm*

$$ktm = 2.36 \cdot CI^5 - 6.2 \cdot CI^4 + 6.22 \cdot CI^3 - 2.63 \cdot CI^2 - 0.58 \cdot CI + 1 \qquad (16)$$

GHI is calculated using the cloud information based on infrared (IR) and visible (VIS) Meteosat data which lead to a single Cloud-Index *CI* with

$$CI = \max(CI\_vis, CI\_ir) \qquad (17)$$

For the determination of the clear-sky global irradiance G_{hc} the new formulation as described in Perez et al (2002) is used with

$$Ghc = cg1 \cdot I_0 \cdot \cos\Theta_Z \cdot \exp(-cg2 \cdot am \cdot (fh1 + fh2 \cdot (TL - 1)))\exp(0.01 \cdot am^{1.8}) \qquad (18)$$

with

- *cg1* = (0.0000509 * alt + 0.868)
- *cg2* = (0.0000392 * alt + 0.0387)
- I_0 = Solar constant (eccentricity corrected)
- Θ_z = solar zenith angle
- *fh1* = exp(-alt / 8000)
- *fh2* = exp(-alt / 1250)
- *am* = elevation corrected air mass
- *alt* = altitude in meters
- T_L = Linke turbidity

Due to missing values of the Linke turbidity T_L for the parameterization of the clear-sky atmosphere, data of the atmospheric components ozone, water vapor and aerosols are used. These atmospheric data are also used for the *DNI*. To derive T_L from atmospheric data we use the following formulation as described by Ineichen and Perez (2002) with

$$Tl = ((11.1 \cdot \ln(b \cdot \frac{I_0}{B_{ncl}})) / am) + 1 \qquad (19)$$

with $b = 0.664 + (0.163 / fh1)$ (20)

and the clear-sky direct normal irradiance B_{ncl}

$$B_{ncl} = I_0 \cdot \tau_{\mathrm{ra}} \cdot \tau_{\mathrm{ae}} \cdot \tau_{\mathrm{o3}} \cdot \tau_{\mathrm{ga}} \cdot \tau_{\mathrm{wv}} \qquad (21)$$

The calculation of transmittance coefficients τ_i and the used atmospheric input data are described in the method for the *DNI*.

The clear-sky radiation is calculated each 20 minutes (10,30,50 minutes of each hour) for the maps and each 5 minutes (5,10,15,…,55,60 minutes each hour) for the time series. The influence of the clouds is taken into account hourly, therefore all maps (monthly and annual average daily sums) and time series are based on an hourly calculation of the radiation. The DLR/SUNY-model output for *GHI* is sampled at a 10km spatial resolution.

Input Data

<u>Elevation</u>

For the airmass pressure correction, the elevation from the GLOBE database from the USGS U.S. Geological Survey [http://rockyweb.cr.usgs.gov/elevation/dpi_dem.html] is used, (Hastings and Dunbar, 1998).

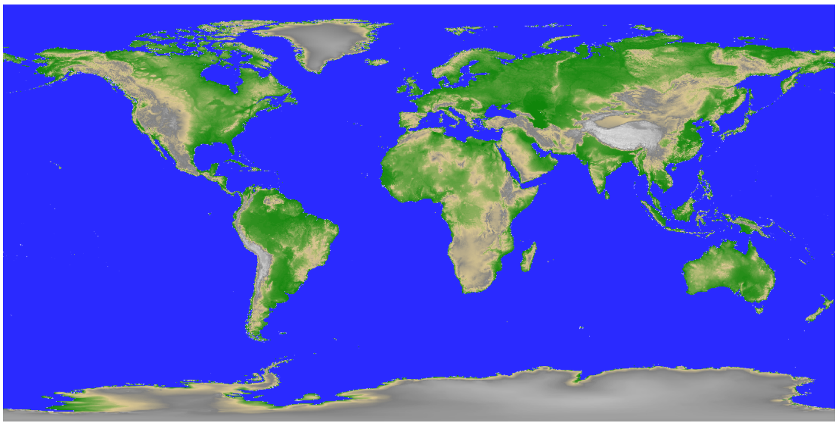

Figure 2: Elevation from GLOBE.

<u>Ozone</u>

The monthly ozone data are taken from TOMS published by the NASA/GSFC TOMS Ozone Processing Team [http://toms.gsfc.nasa.gov/], (McPeters et al., 1998).

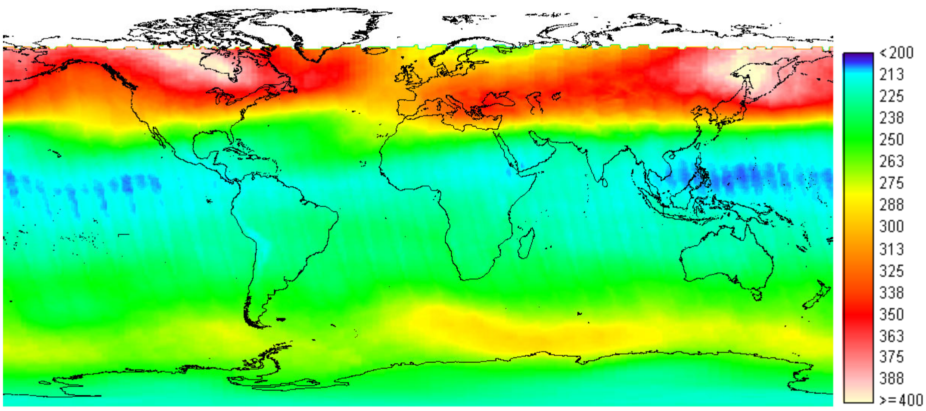

Figure 3: Ozon monthly average for February 2003 in [DU] from TOMS

<u>Water vapor</u>

The daily water vapor data are taken from the NOAA-CIRES Climate Diagnostics Center in Boulder Colorado, USA (NCEP/NCAR) [http://www.cdc.noaa.gov/] (Kalnay et al., 1996).

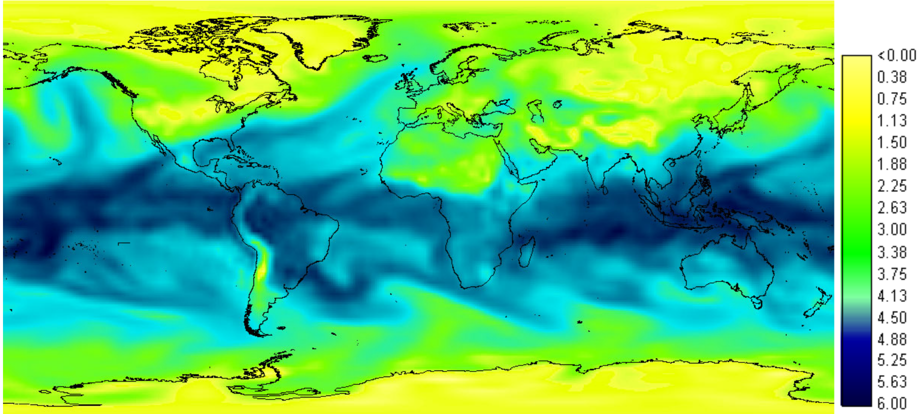

Figure 4: Water vapor daily mean for 7. February 2003 in cm[NTP] from NCEP/ NCAR-Reanalysis

Aerosol

The monthly climatological aerosol optical thickness data are taken from NASA-GACP, [http://gacp.giss.nasa.gov/index.html], (Mishchenko et al, 2002).

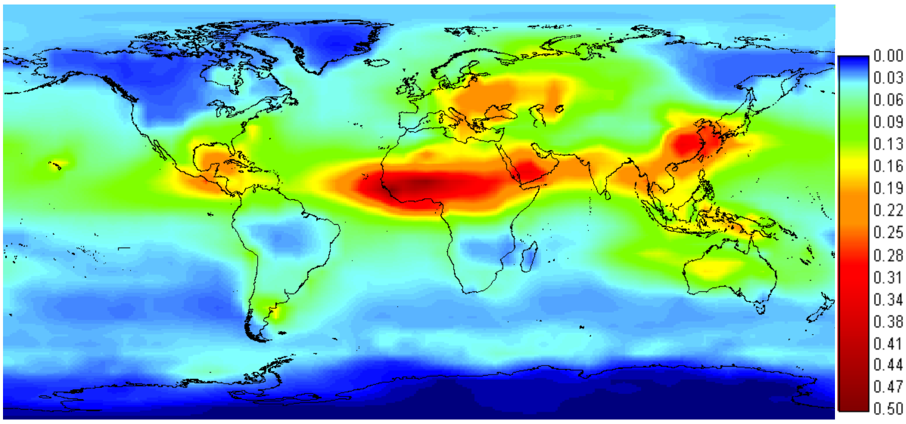

Figure 5: Aerosol optical thickness for February from NASA-GACP.

Clouds

The hourly cloud information are based on half-hourly Meteosat-5 IR and VIS data (© EUMETSAT, 2004). The determination of the cloud indices is described in detail in Mannstein et al. (1999) and Schillings et al. (2004). The basic approach for deriving VIS cloud information is described with

$$CI\_vis = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \tag{22}$$

where ρ is the actual reflectivity measured by the satellite, ρ_{min} corresponds to the surface albedo and ρ_{max} is the maximum reflectivity measured for overcast cloudy conditions. The similar approach is used for IR-data, with the actual, minimum and maximum brightness temperatures T measured by the satellite:

$$CI\_ir = \frac{T_{min} - T}{T_{min} - T_{max}} \tag{23}$$

Figure 6: Field of view of Meteosat (M-7, IR-channel) © 2004, EUMETSAT.

2 Model output

The solar radiation is calculated for the complete country for the years 2000, 2001 and 2002. The data are made available in a digital GIS-format (ESRI Vector-Shapefile). Within this report, maps of the annual average daily total sum of *GHI* and *DNI* are presented. The complete database (ESRI-Shapefile and MS-Access database) can be downloaded from the SWERA-homepage (http://swera.unep.net). Within the ESRI Vector-Shapefile, 3 annual and 36 monthly average daily total sums of *GHI* and *DNI* are given for each 10km x 10km georeferenced pixel as shown in the following figures. Additional, hourly time series for the same time period for several interesting sites are delivered in a separate ASCII-File. The output time of the hourly data is UTC.

Time series

For following sites hourly time series of GHI and DNI for three years are calculated:

Stations/Sites	Lat(degree)	Long(degree)	Elevation (m)
Dagoretti	-1.30	36.75	1935
Eldoret	0.53	35.28	2120
Embu	-0.50	37.45	1607
Garissa	-0.48	39.63	138
JKIA	-1.32	36.92	1748
Kericho	-0.48	35.18	1968
Kabete	-1.25	36.73	2089
Kakamega	0.28	34.77	1706
Machakos	-1.58	37.23	1722
Kisii	-0.68	34.78	1837
Kisumu	-0.10	34.75	1236
Kitale	1.02	34.98	1840
Lamu	-2.27	40.90	30
Lodwar	3.12	35.62	544
Makindu	-2.28	37.83	1076
Malindi	-3.23	40.10	21
Mandera	3.93	41.87	356
Marsabit	2.32	37.98	1447
Meru	0.08	37.65	1640
Mombasa	-4.05	39.63	17
Moyale	3.53	39.05	1197
Msabaha	-3.27	40.05	98
Mtwapa	-3.93	39.73	23
Wilson	-1.32	36.82	1804
Nakuru	-0.28	36.07	1976
Nanyuki	0.05	37.03	2034
Narok	-1.10	35.87	1706
Thika	-1.02	37.10	1574
Nyahururu	-0.03	36.35	2558
Voi	-3.40	38.57	603
Wajir	1.75	40.07	262
Nyeri	-0.43	36.97	1935

The hourly time series can be downloaded from the SWERA web-site. All ASCII-files are compressed to one single ZIP-file. The name convention of the ASCII-file name is:

Country_Sitename_Lat_Lon_Z_Year.dat

for example Kenya_Dagoretti_S1.30_E36.75_Z1935_2000

<u>Important notice</u>: The following maps show classified values of *kWh/m²/day* with a common color ramp for all SWERA countries to give a first impression of the solar regime for each country and for easier comparison with other countries. The provided digital GIS data (available at http://swera.unep.net) give the real (and not classified!) values in *Wh/m²/day* for each georeferenced pixel with a signal resolution of 1 Wh/m²/day.

Global Horizontal Radiation

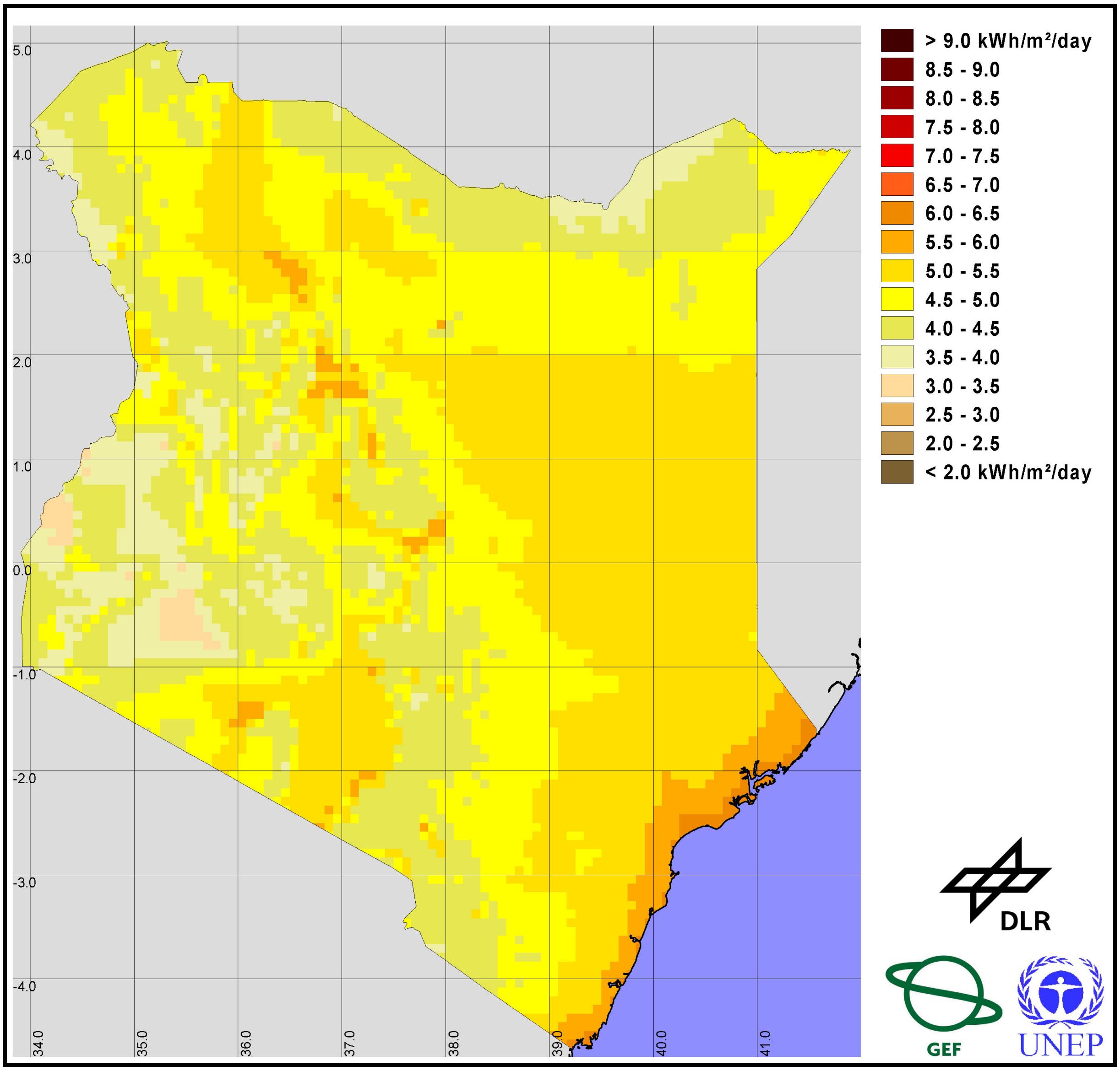

Figure 7: Annual average daily total sum of *GHI* kWh/m²/day for Kenya 2000

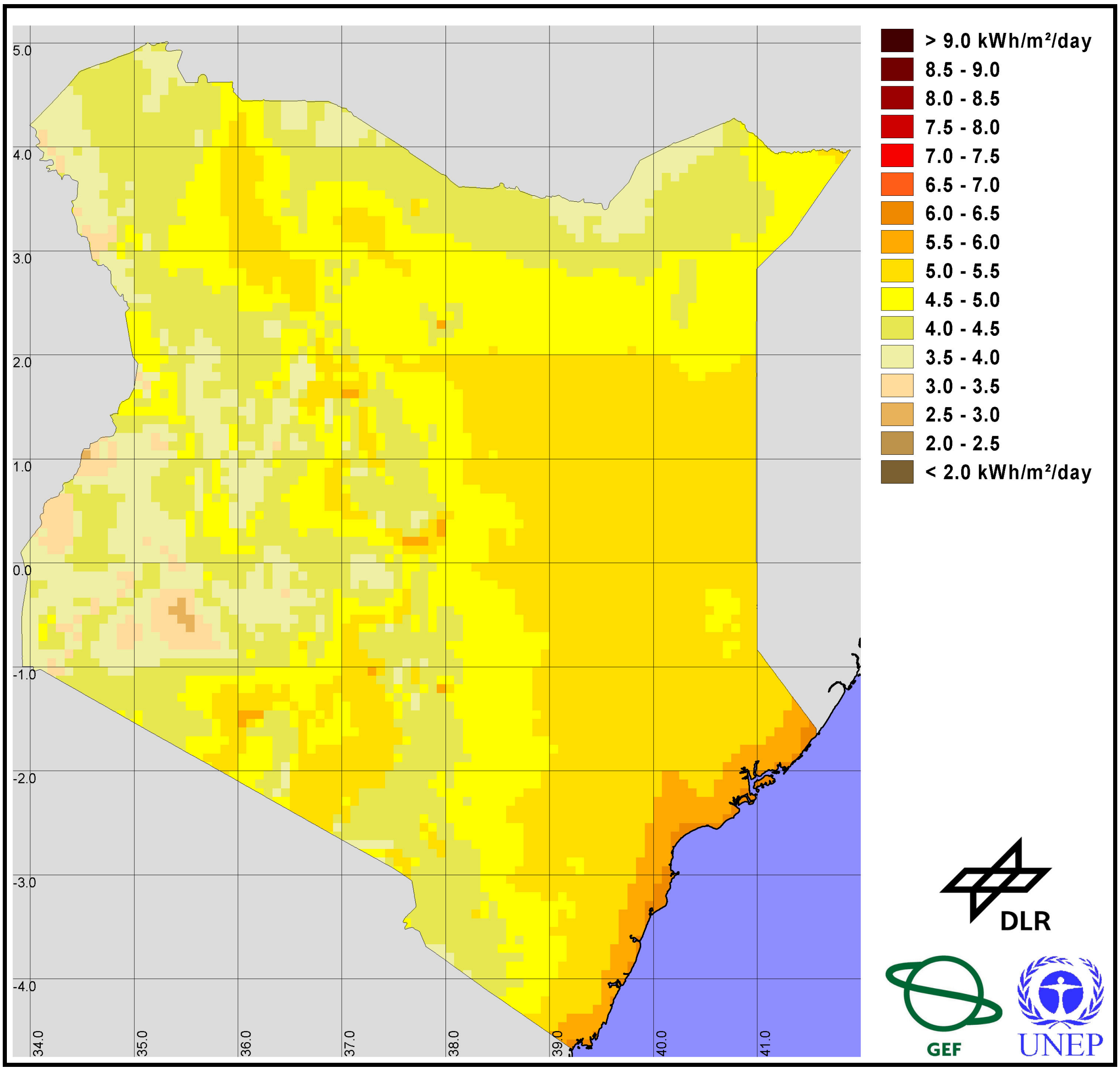

Figure 8: Annual average daily total sum of *GHI* in kWh/m²/day for Kenya 2001

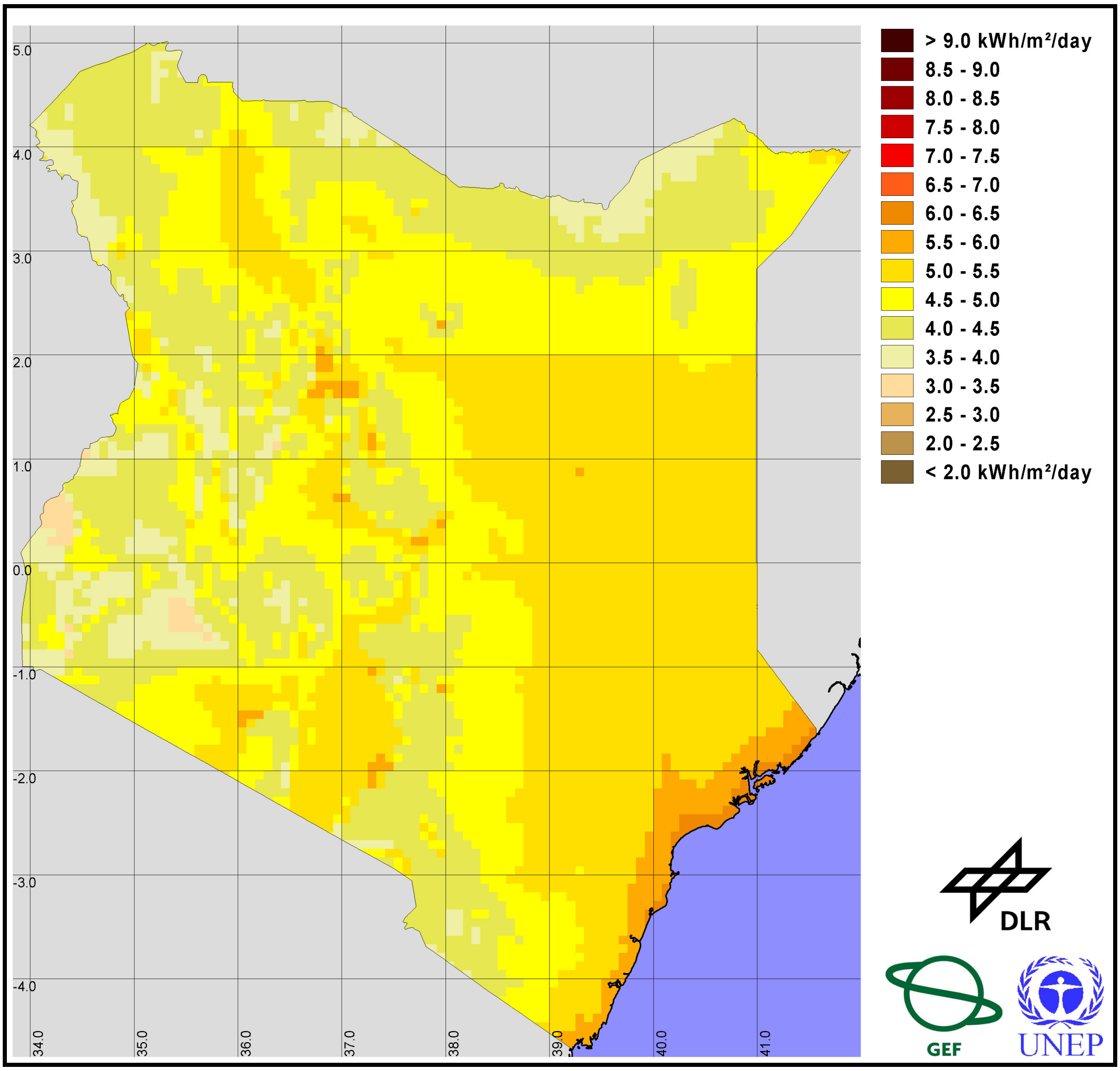

Figure 9: Annual average daily total sum of *GHI* in kWh/m²/day for Kenya 2002

Direct Normal Radiation

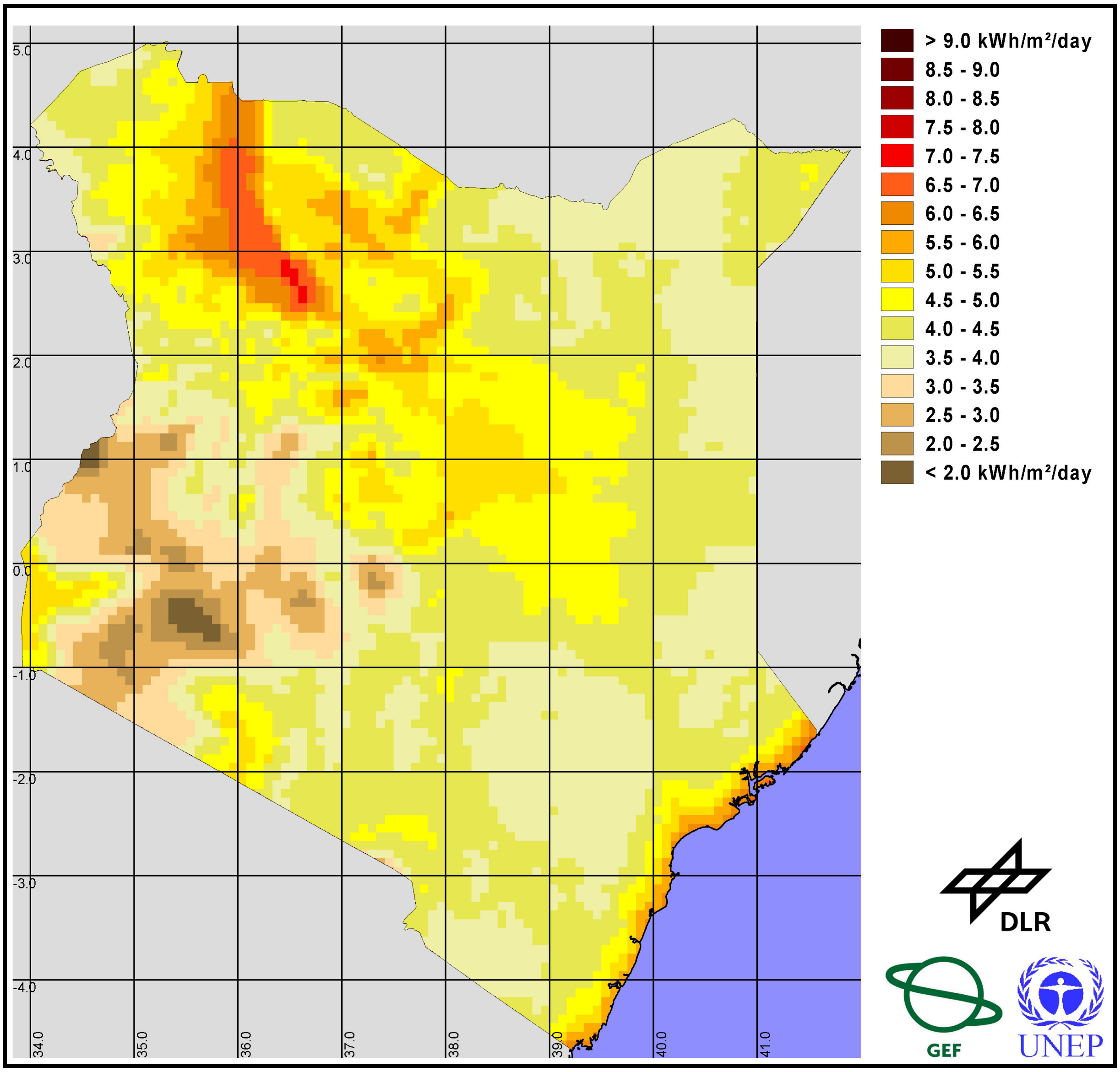

Figure 10: Annual average daily total sum of *DNI* in kWh/m²/day for Kenya 2000

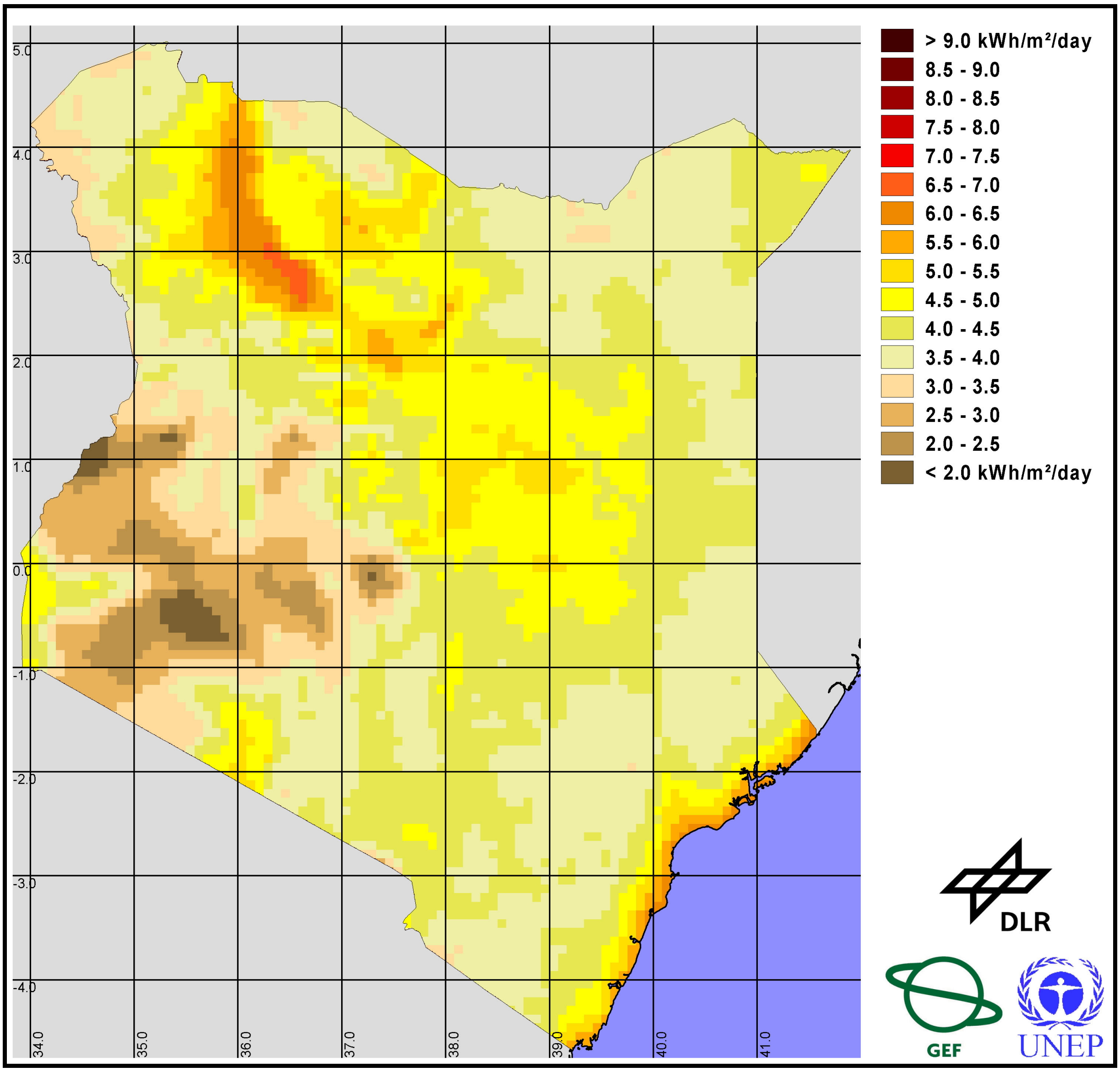

Figure 11: Annual average daily total sum of *DNI* in kWh/m²/day for Kenya 2001

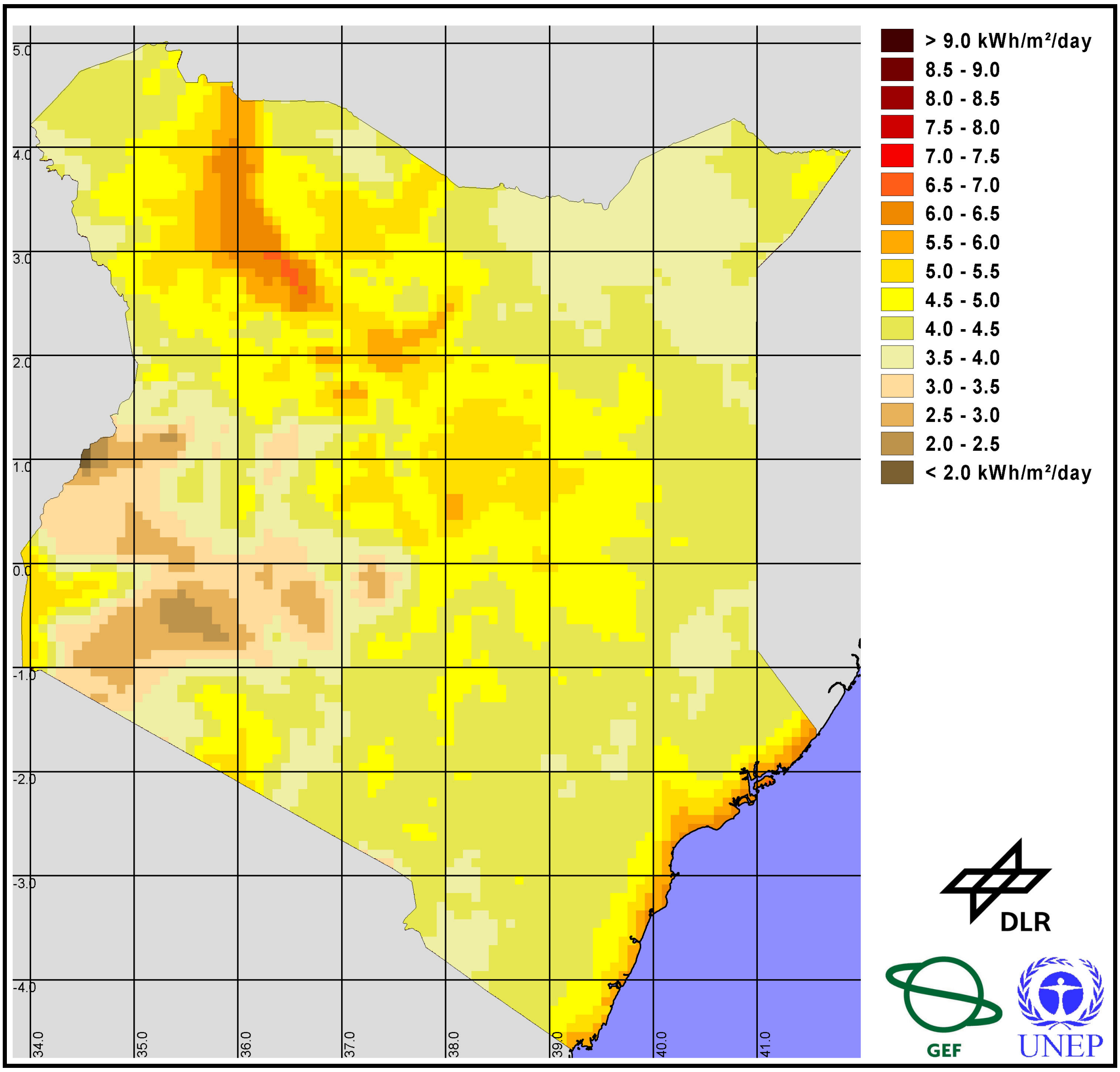

Figure 12: Annual average daily total sum of *DNI* in kWh/m²/day for Kenya 2002

3 Comparison with ground measurement in Kenya

No comparison was performed due to missing ground measurement data.

Acknowledgement:

All Meteosat data is under copyright of EUMETSAT (© 2004), Darmstadt, Germany. Many thanks for access to the data set go to the crew of the MARF (Meteosat Archive and Retrieval Facility, Darmstadt) and to our colleagues from DLR-DFD (Deutsches Fernerkundungs-Datenzentrum). Data on aerosol is provided by NASA-GACP Global Aerosol Climatology Project. We also acknowledge the use of the water vapor data from the NCEP Reanalysis by NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, US and the use of the TOMS ozone data provided by the NASA-Goddard Space Flight Center (GSFC), Washington, DC, USA. Special thanks to Rüdiger Buell and Hermann Mannstein at the Institut für Physik der Atmosphäre for doing the archive logistics and cloud data processing of the Meteosat 5 and Meteosat 7 data.

4 References

Bird R.E. and R.L. Hulstrom (1981): Review, evaluation and improvement of direct irradiance models. *J. of Sol. Energy Engineering* **103**, 182-192.

Hastings D.A. and P.K. Dunbar (1998): Development & Assessment of the Global Land One-km Base Elevation Digital Elevation Model (GLOBE). *International Society of Photogrammetry and Remote Sensing (ISPRS) Archives* **32** (4), 218-221. (http://www.ngdc.noaa.gov/seg/topo/globe.shtml)

Ineichen P. and R. Perez (2002): A new airmass independent formulation for the Linke turbidity coefficient. *Solar Energy*, **73** (3), 151-157.

Iqbal M. (1983): An introduction to solar radiation. Academic Press, Toronto.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, R. Jenne and D. Joseph (1996): The NMC/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society **77** (3), 437–472.

Mannstein H., H. Broesamle, C. Schillings and F. Trieb (1999): Using a METEOSAT cloud index to model the performance of solar-thermal power stations. *Procs. of Eumetsat Conference Copenhagen*, 239-246.

McPeters R.D. , P. K. Bhartia, A. J. Krueger, J. R. Herman, C. G. Wellemeyer, C. J. Seftor, G. Jaross, O. Torres, L. Moy, G. Labow, W. Byerly, S. L. Taylor, T. Swissler and R. P. Cebula (1998): Earth Probe Total Ozone Mapping Spectrometer (TOMS) Data Products User's Guide. *NASA Technical Publication* 1998-206895.

Meyer R., C. Hoyer, E. Diedrich, C. Schillings, S. Lohmann, M. Schroedter-Homscheidt, R. Buell and F.Trieb (2004): Solar Energy Mining: A High-Quality Satellite-based Service to Provide Direct Solar Radiation for Europe, Brazil, Africa and Asia. Presentation at SolarPaces 2004, Oaxaca, Mexico.

Mishchenko M., J.E. Penner and D. Anderson (Ed.) (2002): Global Aerosol Climatology Project. Special Issue of Global Aerosol Climate, *J. of Atmospheric Science* **59** (3).

Perez R., P. Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George and F. Vignola (2002): A new operational satellite-to-irradiance model - description and validation. *Solar Energy*, **73** (5), 307-317.

Schillings C., H. Mannstein and R. Meyer (2004): Operational method for deriving high resolution direct normal irradiance from satellite data. *Solar Energy* **76**, 475-484.