Comparison of Direct Normal Irradiation Maps for Europe

Suri, Marcel; Remund, Jan; Cebecauer, Tomas; Hoyer-Click, Carsten; Dumortier, Dominique; Huld, Thomas; Stackhouse, Paul; Ineichen, Pierre

Solar Paces 2009
Conference, Berlin, Germany, 2009.

Comparison of Direct Normal Irradiation Maps for Europe

Marcel Šúri[1,2], **Jan Remund**[3], **Tomáš Cebecauer**[1,2], **Carsten Hoyer-Klick**[4], **Dominique Dumortier**[5], **Thomas Huld**[2], **Paul W. Stackhouse, Jr.**[6], **and Pierre Ineichen**[7]

[1] GeoModel, Pionierska 15, 83102 Bratislava, Slovakia, Phone: +421 2 492 12491, Fax: +421 2 492 12499, E-mail: suri@geomodel.eu

[2] European Commission, Joint Research Center, Institute for Energy, TP 450, I-21027 Ispra, Italy.

[3] Meteotest, Fabrikstrasse 14, CH-3012 Bern, Switzerland.

[4] German Aerospace Center, Institute of Technical Thermodynamics, Pfaffenwaldring 38-40, D-70374 Stuttgart, Germany.

[5] Ecole Nationale des Travaux Publics d'Etat, Département Génie Civil et Bâtiment, URA CNRS 1652, rue M. Audin, F-69518 Vaulx-en-Velin, Cedex, France.

[6] Science Mission Directorate, NASA Langley Research Center, Hampton, VA, 23681, USA.

[7] University of Geneva, Battelle Bat D-7 rte de Drize, CH-1227 Carouge, Switzerland.

Abstract

This study provides an insight into the spatial distribution of uncertainty of Direct Normal Irradiation (DNI) as estimated from the relative cross-comparison of five data sources offering solar resource and climate data for Europe: Meteonorm, Satel-Light, NASA SSE, SOLEMI, and PVGIS. The results show that within 90% of the study area the uncertainty of DNI expressed by relative standard deviation may go up to 17%. This high value indicates a need for further improvement of the data inputs and solar radiation models.

Keywords: Direct Normal Irradiation, maps, Europe, relative cross-comparison.

1. Introduction

Several spatial databases of solar resource information are available as a result of international and national projects. They were developed from various data inputs (satellite or ground measurements), covering different time periods, and diverse approaches have been applied. These data are used by the solar energy community in pre-feasibility studies, and for development of projects. Although quality assessment was performed for each database within its development, and also within the MESoR project [1], when comparing them, differences show up as a result of various sources of uncertainty.

This study provides relative comparison of maps of annual sum of Direct Normal Irradiation (DNI) from five solar databases available for Europe: Meteonorm [2], Satel-Light [3], NASA SSE [4], SOLEMI [5], and PVGIS [6].

2. DNI databases and underlying methods

2.1. General characteristics

Spatially-distributed (map) databases can be characterised according to several criteria, e.g. [7]:

Input data from which the databases were created: (i) observations from the meteorological stations - typically global and diffuse measurements are used on the input, rarely also direct radiation; (ii) satellite images, and (iii) by combination of both. Important for DNI modelling are input atmospheric data: (i) integrated in the atmospheric turbidity factor or (ii) individual datasets representing the atmospheric components - water vapour, ozone and aerosols.

Spatial resolution represented by geographical distribution of the meteorological sites, and spatial (grid) resolution of the satellite data and the output grid databases;

Time resolution, which characterizes periodicity of the measurement of the input data and of the resulting parameters. Thus a database may include time series with periodicity of a 15 or 30 minutes (instantaneous or time-aggregated values) up to hourly and daily averages, or it may contain only monthly averages.

Period of time (typically a number of years) which is represented in the output data. Length of time period determines mode of use of the output parameters that can be: (i) estimation of long-term technology performance or (ii) frequency analysis.

Method used for computation of the primary database: (i) solar radiation models, interpolation methods (e.g. geostatistical methods or splines), in case that ground observations are used, or (ii) algorithms for satellite data processing (e.g. Heliosat scheme, radiative-transfer approaches).

Simulation models used for calculation of derived parameters, such as clear-sky and atmospheric transmittance models, transposition of data to inclined and tracking surfaces, calculation of terrain effects, derived statistical products (long-term averages, synthetic time series, etc.), see [8].

The resulting databases are (in optimal circumstances) benchmarked by comparing the modelled values with independent quality controlled datasets according to strict rules, where the first order statistics are calculated (bias, mean absolute deviation, root mean square deviation, standard deviation, correlation coefficient) and the frequency distributions are analysed.

In our case, due to differences between methodical approaches, time and spatial resolutions of compared databases and limited availability of reliable independent data, it is not possible to make unbiased comparison of all five databases. Instead, we here focus on a relative map based cross-comparison of the DNI spatial products. Such comparison provides means for improved understanding of the regional distribution of uncertainty by combining all existing resources (calculating the average of all) and quantifying the multi-database uncertainty (by the means of standard deviation).

2.2. Analysed databases

Each of the databases analysed here is integrated within a system (software setup) that provides additional tools for search, query, map display, and calculation of derived parameters. In Tables 1 and 2 we summarize the main characteristics of each database/system including the quality indicators Root Mean Square Difference (RMSD) and Mean Bias Deviation (MBD) where possible. While NASA, Satel-Light, and PVGIS are free data sources, access to SOLEMI and Meteonorm are on a commercial basis.

PVGIS (the European section), includes a solar radiation database developed by combination of a solar radiation model and interpolated information from ground observations. The Linke atmospheric turbidity factor [9] represents the atmospheric input parameter in the solar radiation model. Unlike other data, DNI is not directly available in the online version, even though it is used by several PVGIS tools for PV production assessment. For this study the direct normal component was derived from integration of instantaneous values of global and diffuse components calculated using the PVGIS approach that incorporates also terrain effects using high resolution SRTM-3 Digital Elevation Model (DEM).

Primary data incorporated in **Meteonorm version 6.1** are developed by interpolation of ground observed data (mostly global and diffuse radiation) with support of satellite images (MSG and four other geostationary satellites). The new version of Linke atmospheric turbidity factor [10] is used in solar radiation modelling. High resolution SRTM-3 DEM is also applied in the calculation of the terrain effects.

The datasets **Satel-Light** and **SOLEMI** are developed from Meteosat First Generation satellite images. While Satel-Light uses Linke atmospheric turbidity factor [9] in the calculations, in the SOLEMI database the atmospheric transmissivity is treated separately from parameters characterizing effect of aerosols, water vapour and ozone. The spatial resolution of both is determined by the Meteosat geometry.

NASA SSE release 6 (accessible also through RETScreen software, http://www.retscreen.net/) provides access to NASA GEWEX/SRB release 3.0 database that has been calculated from satellite-derived parameters as listed in the Table 1. The output data are at a resolution of 1 arc-degree.

Database	Extent	Spatial resolution	Data inputs	Time period	Time resolution	Overall accuracy
Satel-Light (ENTPE)	West and Central Europe	Meteosat MFG; grid size 5.3-9.6 km	Meteosat First Generation; Linke turbidity [9]	1996-2000	30-minute	Bias 1%, RMSD 48% (based on **hourly** data from 2000 [11])
SOLEMI (DLR)	Europe, Africa, Asia	Meteosat MFG; grid size 5.3-9.6 km	Meteosat First Generation, NASA GISS aerosols, NCAR/NCEP water vapour, TOMS ozone	1991-2005	hourly	Bias 1%, RMSD 48% (based on **hourly** data from 1996-2000 [1])
NASA SSE version 6 (NASA)	Global	1 arc-degree	NASA ISCCP & CERES MODIS irradiance, clouds and surface parameters; NCAR MATCH aerosols; TOMS/TOVS ozone; NASA/GMAO GEOS-4 surface parameters	1983-2005	3-hourly, daily and monthly averages, simulation of daily average profile	Bias 2.4%, RMSD 21% (based on **monthly** averaged data from 1983 to 2006 [4])
Meteonorm version 6.1 (Meteotest)	Global	Meteosat MSG grid size + interpolation + terrain	Meteorological observations (mostly GEBA) and MSG satellite data (2006-2008); Linke turbidity [10]	1981-2000	Monthly averages; hourly synthetic time series	RMSD 5.4% (based on **yearly** values of 10 BSRN stations [12])
PVGIS Europe (EC JRC)	Europe	1 km + terrain	Meteorological observation (G & D measured & estimated); Linke turbidity [9]	1981-1990	Monthly averages; simul. of daily average profile	Not available

Table 1. Technical parameters of the DNI databases. Note: Root Mean Square Difference (RMSD) is based on different data comparisons, therefore the hourly data show much higher difference compared to monthly and yearly averages.

Database	Primary data calculation	Time series	Parameters
Satel-Light http://www.satellight.com/	Heliosat 2	real 30-minute data	G, B, D, illumin., sky types ext, statistics
SOLEMI http://www.solemi.com/	Bird clear sky model, Heliosat-2, cloud transmission functions	real 60-minute data	G, B
NASA SSE 6 http://eosweb.larc.nasa.gov/sse/	Satellite model by [13]	Simulation of daily average profile by [14] and [15]	G, B, D, extended statistics, cloud data, longwave irradiance
Meteonorm 6.1 http://www.meteotest.ch/	Heliosat 1 for satel. data; interpol. with 3D inverse distan. model by [16] and [17]	Stochastic generation of daily, hourly and minute values from monthly averages by [18] and [19]	G, D, B, terrain shadowing (beam and diffuse)
PVGIS Europe http://re.jrc.ec.europa.eu/pvgis/	3D spline interpolation of ground data + model r.sun [20]	Simulation of daily average profile from monthly averages using diffuse and beam clear-sky coefficients by [20]	G, D terrain shadowing (beam only), B not available online

**G=global, B=beam (direct), D=diffuse radiation*

Table 2. Methods used for calculation of primary parameters

The quality of SOLEMI and Satel-Light datasets was validated within the MESoR project [11] by comparing the hourly values from one year of time series measured at 13 ground stations; however the small amount of validation data allows only a limited insight into their accuracy. The validation of NASA SSE has been done by comparing the monthly averaged data to the measurements of BSRN stations [4]. Meteonorm was validated using data measured from 10 BSRN sites, however only yearly values were tested, which does not allow comparing the data quality with the other datasets. DNI derived from PVGIS was not explicitly validated (accuracy assessment was done only for global and diffuse irradiation [6]).

The geographical extent of the spatial products varies: from global (NASA and Meteonorm) to cross-continental (SOLEMI covering Europe, Africa and Asia) and European (PVGIS and Satel-Light). Here we focus on the subsection of the European continent (Fig. 1) where all the data sources overlap.

3. Method

Map-based comparison, as performed here, is a type of relative benchmarking of solar databases. It does not point to the "best" database, but it gives an indication of the *user's uncertainty at any location within the region*. As the existing spatial products cover different periods of time, this comparison introduces also uncertainty resulting from the interannual variability of solar radiation. Here we perform a cross-comparison of maps of *long-term average of yearly sum of Direct Normal Irradiation*.

The maps from all data providers are integrated into a geographical information system (GIS) with geographic latitude/longitude spatial reference (ellipsoid WGS84) and grid cell resolution of 5 arc-minutes. This resolution represents a rectangle of about 9 km x 7 km in latitude 45°, thus describing the regional differences within the continent. The calculations of the five data sources representing yearly sums of DNI (in kWh/m^2) resulted in three outputs:

Map of overall average gives the user an indication of spatial distribution of solar resource estimated by simple averaging of the five datasets.

Maps of absolute and relative standard deviation provide information on magnitude of differences between the combined data sources, i.e. user's uncertainty. If we assume that the estimates are normally distributed, from standard deviation a confidence interval can be calculated in which the value falls corresponding to a given probability. For example, standard deviation multiplied by 1.95996 would give a range where the DNI value from five combined datasets falls with 95% probability.

Maps of differences between individual databases and the overall average indicate deviation of the values in the particular dataset from the overall average. These maps are not published in this paper.

4. Results

The map of yearly sum of Direct Normal Irradiation in Fig. 1 shows the average of five databases, and Fig. 2 indicates relative standard deviation calculated from these databases.

The overall average of the five databases shows three regions of high yearly sum of DNI in Europe (values above 1800 kWh/m^2) – Southern and Central Spain and Portugal, Sicily and Sardinia (Italy), and Provence (France). Although variability of estimates in these areas, given by the relative standard deviation, stays generally within 7 to 8%, it increases in some regions such as the Mediterranean islands. The DNI resource in the rest of Italy and South-Eastern Europe is lower, and on top to this, the user's uncertainty from comparing values in different databases is often high (standard deviation sometimes above 20%).

Higher disagreement between the databases can be found in mountains (the Alps, Pyrenees, Carpathians, Balkan Mountains, etc.), but also along some coastal zones and even in flat regions of South and North-East Spain, around the Baltic and North Seas. High standard deviation shows strong disagreement between databases in Bulgaria and Romania, in Lithuania, South Scandinavia, and in the Po plain in Italy.

Since the PVGIS database was not originally built for providing DNI information, and quality assessment for DNI is missing, we analyzed separately the other four databases (Fig. 3). Meteonorm, SOLEMI, Satel-Light and NASA SSE show slightly higher level of agreement (standard deviation most often less than 7%) in Central Spain, North Africa, Southern France, and parts of Sicily. These are regions where DNI is of highest importance as most of CSP (Concentrated Solar Power) and CPV (Concentrated Photovoltaics) projects focus there.

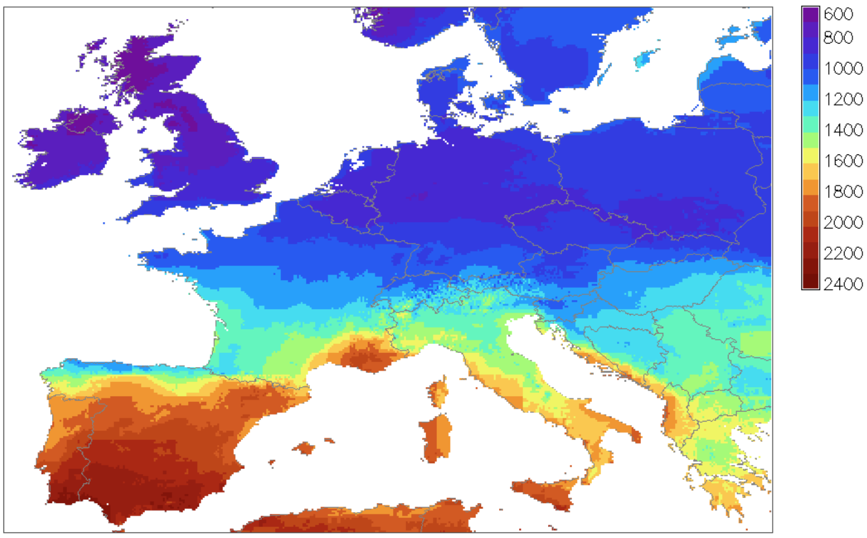


Fig. 1. Yearly sum of Direct Normal Irradiation – average of five databases: Meteonorm, PVGIS, NASA SSE, Satel-Light, and SOLEMI [kWh/m^2].

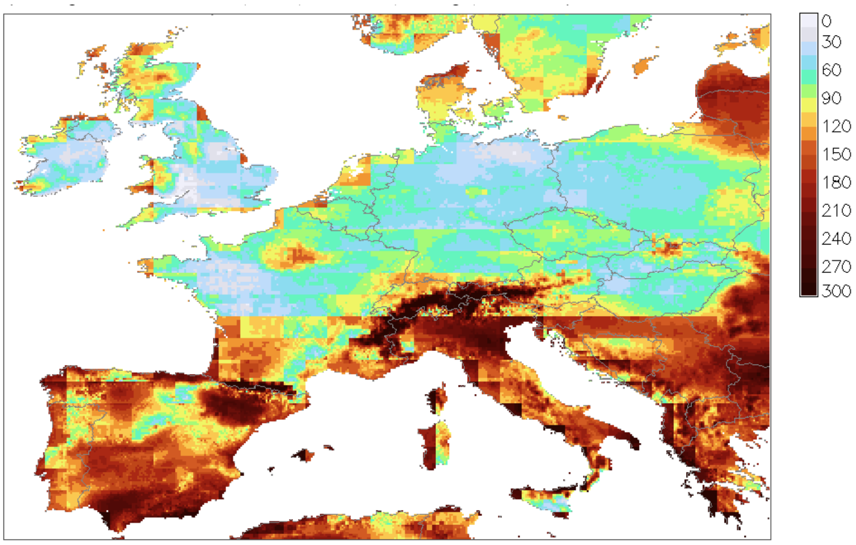
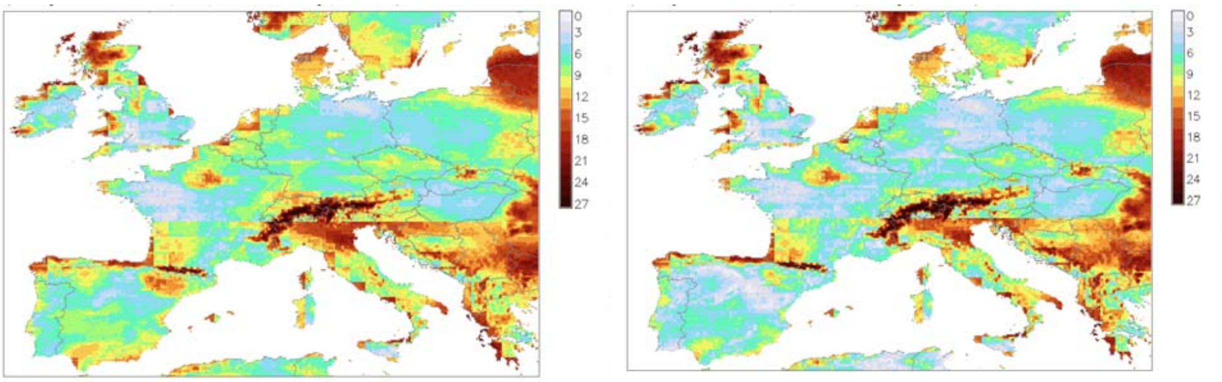


Fig. 2. Yearly sum of Direct Normal Irradiation – standard deviation calculated from five databases [kWh/m^2] as listed in Fig. 1.

In the maps, few features can be observed. In the NASA SSE database, different equations for latitudes North and South from 45 degrees are used, and this results in sudden change in the DNI values. Very high deviations between all databases in the Balkan countries and Lithuania region may result from using different aerosol and atmospheric turbidity climate values and less accurate estimation of clouds by satellite algorithms.

Mountainous regions show high variability due to the fact that the terrain effects are considered at higher spatial resolution only in Meteonorm and PVGIS. In addition, the DNI estimates from satellite datasets result in higher uncertainty in mountains also due to difficulties in separation between clouds and snow as they are based on the older generation satellites. Although SOLEMI and Satel-Light databases use the same type of data inputs (Meteosat First Generation), they still show differences in some regions that may be a result from the use of different aerosol/turbidity databases, and different time covered by the data (interannual variability).



a) b)

Fig. 3. Yearly sum of Direct Normal Irradiation – relative standard deviation: a) calculated from five databases: PVGIS, Meteonorm, NASA SSE, Satel-Light and SOLEMI [%] b) calculated from four databases: Meteonorm, NASA SSE, Satel-Light, and SOLEMI [%].

Cumulative distribution of the map values indicates that in 90% of the study region the relative standard deviation calculated from all five databases does not exceed 17%; however in extreme cases it can be higher than 24%. Compared to the results from previous study [21], the standard deviation for DNI is in general about 2.5 to 3 times higher compared to Global Horizontal Irradiation.

5. Discussion

Differences in the estimates from several solar radiation databases relate to a number of factors.

DNI is sensitive to the determination of cloud index attenuating irradiance reaching the surface. With the older generation satellites (Meteosat First Generation), effects of snow, ice and fog are interfering with cloud detection, which leads often to underestimation of DNI, mostly in mountains. The current satellite instrument MSG SEVIRI, orbiting since 2004, provides high quality calibrated signal with stable and known properties over continents, and with high information potential showing promising improvements in cloud detection.

Compared to global horizontal irradiation, DNI is also more sensitive to the atmospheric parameters. The quality and the spatial detail of output databases are determined by input data used in the models, mainly parameters describing the optical state of the atmosphere, such as Linke atmospheric turbidity, or the analytical datasets (ozone, water vapour, and aerosols). Effect of aerosols represented by Atmospheric Optical Depth (AOD) is, after cloudiness, the most important variable affecting DNI [22].

Like cloudiness, AOD is highly variable over time and space. Its measurement requires sophisticated instrumentation and complex satellite models. The numerous datasets available to solar radiation modelling community come from various sources: AERONET, AEROCOM, GADS, TOMS, GOCART, NASA/GISS, MATCH, GEMS, etc. (see [23]). However, except AERONET, they represent only climate (averaged) values for a limited period of few years, which does not allow dealing with high-frequency changes.

There is an inherent difference between in situ (ground) and satellite observations, and the methods how these data are processed. Databases relying on the interpolation of ground observations (PVGIS Europe, and partially also Meteonorm) are sensitive to the quality and completeness of ground measurements (especially those from older time periods) and density of the measuring stations (which is not satisfactory in many regions).

PVGIS and Meteonorm primary databases include only long-term statistical averages and some geographical regions may show higher uncertainty due to lower concentration of measured sites with varying consistency. The satellite-derived databases (NASA SSE, SOLEMI and Satel-Light) offer time series with high time resolution (three-hourly, hourly, and half-hourly data, respectively) and they provide spatially-continuous coverage, but the results are affected by higher uncertainty of the cloud cover assessment when the ground is covered by snow and ice and for low sun angles.

Terrain effects (differences in airmass, shadowing by surrounding terrain) play an important role in solar radiation modelling in hilly and mountainous regions. Spatial resolution of the input data and DEM has a direct impact on the accuracy of the estimates. Using coarse DEM resolution (compared to high-resolution data) results in a smoother spatial pattern of solar irradiance, which changes also the regional mean of the irradiation. High-resolution DEM is presently considered only in Meteonorm and PVGIS. Databases with coarser spatial resolution (e.g. NASA SSE) provide good regional estimates, however for studies at local level they may show higher deviations as they smooth out local climate and terrain features.

There is potential for improvements in the cross-comparison methodology. The presented approach assumes that each database has an equal weight. Uncertainty can be reduced by weighting each contribution based on indicators of **(i)** quality, **(ii)** number of data-years included, **(iii)** spatial resolution and **(iv)** incorporation of terrain effects. These improvements are possible, providing support information is calculated from long-term observations and from terrain analysis.

6. Conclusion

This study provides an insight into the spatial distribution of uncertainty of the estimates of Direct Normal Irradiation by relative cross-comparison of five data sources. Due to limited information, at this stage, all databases are assumed to give an equal contribution to the overall average. The map of standard deviation from the average indicates the combined effect of differences between the databases, and in this study it is used as an indicator of the user's uncertainty.

The choice of primary inputs (ground-measured vs. satellite) for building spatial databases depends on the availability of the data in the region of interest. Due to limited number of high-quality ground instruments, and high potential of numerical modelling, the satellite-derived databases may provide more consistent information in most regions across the continent.

The accuracy of estimates of Direct Normal Irradiation is sensitive to the effect of clouds, aerosols, water vapour, and terrain features. It is assumed that clouds and aerosols are the main drivers of the differences between the estimates due to their large spatial and temporal variability and complexity of the modelling.

The results show that within 90% of this study area the uncertainty of estimates of long-term yearly sum of Direct Normal Irradiation, expressed by relative standard deviation, may be as high as 17%. Converted to the user's uncertainty at 95% confidence level this means that based on the comparison of the five data sources, the DNI estimate may deviate in some regions up to +/- 33% from what is considered here as the overall average.

As shown on the maps of standard deviation (Fig. 2 and 3), there are regions where solar industry has to expect higher differences in the outputs from the analysed databases. Mainly in complex climate conditions of mountains, some coastal zones and in areas where solar radiation modelling cannot rely on sufficient density and quality of input data. Significant differences are also observed in some regions, such as Balkan, Greece, parts of Iberian Peninsula and Italy, Carpathians, Southern Scandinavia, Scotland, Ireland, and the region around Lithuania.

From this study, a few preliminary conclusions can be derived:

- In satellite models the potential of high resolution multispectral Meteosat MSG data for improvements of cloud/ice/snow detection at the operational level has to be fully exploited.
- High uncertainty indicates a need for further improvement of the atmospheric data inputs, mainly Aerosol Optical Depth. The initiatives for data intercomparison and assimilation such as AEROCOM and GEMS should bring promising results.
- High resolution modelling of terrain effects (shadowing and elevation in case of DNI) needs to be incorporated into the satellite models especially for the needs of solar concentrator technology. The MSG satellite, SRTM DEM, and high-performance computer technology offer all the means for the implementation of computing-power demanding complex models exploiting full data resolution.

This study gives only a preliminary outline of the state of the art of current knowledge of DNI in Europe. It is understood that such a simple data comparison does not answer the needs of the solar energy industry and therefore further work is in progress to improve this knowledge (i.e. decrease the uncertainty). However, finding proper measures for weighting the factors mentioned above and attributing them to each of the database is found to be a non-trivial task.

Acknowledgement

This work was realized in the framework of the program of the International Energy Agency, Solar Heating and Cooling, Task 36 *Solar Resource Knowledge Management*, and the European Union’s FP6 project *Management and Exploitation of Solar Resource Knowledge*, contract No. 038665.

References

[1] C. Hoyer-Klick et al., SolarPACES 2009 Conference, Berlin, 2009.

[2] J. Remund, S. Kunz, C. Schilter, Handbook of METEONORM Version 6.0, Meteotest, 2007.

[3] D. Dumortier, M. Fontoynont, D. Heinemann, A. Hammer, J.A. Olseth, A. Skartveit, P. Ineichen, C. Reise, CIE Conference 24th Session, Warsaw, 1999, 277-281.

[4] NASA SSE, Surface meteorology and Solar Energy Release 6.0 Methodology, version 2.4, 2009.

[5] C. Schillings, H. Mannstein, R. Meyer, Solar Energy, 76 (2004), 475-484.

[6] M. Šúri, T. Huld, T. Cebecauer, E.D. Dunlop, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 1 (2008), 34-41.

[7] C. Gueymard, D.R. Myers, Modeling Solar Radiation at the Earth's Surface: Recent Advances. Springer, 479-504.

[8] MESoR project. D 1.1.1 Handbook on Benchmarking, 2009

[9] J. Remund, L. Wald, M. Lefèvre, T. Ranchin, J. Page, Proceedings of ISES Solar World Congress, Göteborg, 2003.

[10] J. Remund., IEA SHC Task 36 meeting, Wels, Austria, 2008.

[11] P. Ineichen., IEA SHC Task 36 meeting, Baeza, Spain, 2009.

[12] J. Remund, Proceedings of 10th World Renewable Energy Conference, Glasgow, 2008.

[13] R.T. Pinker, I.J. Laszlo, J. Appl. Meteor., 31 (1992), 194-211.

[14] M. Collares-Pereira, A. Rabl, Solar Energy, 22 (1979), 155-164.

[15] B.Y.H. Liu, R.C. Jordan, Solar Energy, 4 (1960), 1-19.

[16] A. Zelenka, G. Czeplak, V. D'Agostino, J. Weine, E. Maxwell, R. Perez, M. Noia, C. Ratto, R. Festa, IEA Report No.IEA-SHCP-9D-1, 1992.

[17] J. Remund, E. Salvisberg, S. Kunz, Solar Energy, 62 (1998), 5.

[18] R. Aguiar, M. Collares-Pereira, Solar Energy, 40 (1988), 269-279.

[19] R. Aguiar, M. Collares-Pereira, Solar Energy, 49 (1992), 167-174.

[20] M. Šúri, J. Hofierka, Transactions in GIS, 8 (2004), 175-190.

[21] M. Šúri, J. Remund, T. Cebecauer, D. Dumortier, L. Wald, T. Huld, F. Blanc, Proceeding of the EUROSUN 2008, 1st International Conference on Solar Heating, Cooling and Buildings, Lisbon, 2008.

[22] C. Gueymard, R. George, Proceedings of Solar World Congress, International Solar Energy Society, Orlando, USA, 2005.

[23] C. Hoyer-Klick, Comparison of different Clear Sky Models and Atmospheric Input Data Sets, manuscript, 2008.