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Master Level Thesis

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Discrepancies in solar irradiation data for Stockholm and Athens

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Abstract

The aim of this study is to evaluate the variation of solar radiation data between different data sources that will be free and available at the Solar Energy Research Center (SERC). The comparison between data sources will be carried out for two locations: Stockholm, Sweden and Athens, Greece. For the desired locations, data is gathered for different tilt angles: 0°, 30°, 45°, 60° facing south. The full dataset is available in two excel files: “Stockholm annual irradiation” and “Athens annual irradiation”.

The World Radiation Data Center (WRDC) is defined as a reference for the comparison with other datasets, because it has the highest time span recorded for Stockholm (1964–2010) and Athens (1964–1986), in form of average monthly irradiation, expressed in kWh/m^2. The indicator defined for the data comparison is the estimated standard deviation. The mean biased error (MBE) and the root mean square error (RMSE) were also used as statistical indicators for the horizontal solar irradiation data.

The variation in solar irradiation data is categorized in two categories: natural or inter-annual variability, due to different data sources and lastly due to different calculation models. The inter-annual variation for Stockholm is $140.4kWh/m^2$ or 14.4% and $124.3kWh/m^2$ or 8.0% for Athens. The estimated deviation for horizontal solar irradiation is 3.7% for Stockholm and 4.4% Athens. This estimated deviation is respectively equal to 4.5% and 3.6% for Stockholm and Athens at 30° tilt, 5.2% and 4.5% at 45° tilt, 5.9% and 7.0% at 60°

NASA’s SSE, SAM and RETScreen (respectively Satel-light) exhibited the highest deviation from WRDC’s data for Stockholm (respectively Athens). The essential source for variation is notably the difference in horizontal solar irradiation. The variation increases by 1-2% per degree of tilt, using different calculation models, as used in PVSYST and Meteonorm. The location and altitude of the data source did not directly influence the variation with the WRDC data.

Further examination is suggested in order to improve the methodology of selecting the location; Examining the functional dependence of ground reflected radiation with ambient temperature; variation of ambient temperature and its impact on different solar energy systems; Impact of variation in solar irradiation and ambient temperature on system output.

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Contents

Nomenclature

T_a - Ambient temperature;
ρ - Ground reflectance;
S - Estimated standard deviation;
S_a - Annual estimated standard deviation;
S_n - Estimated standard deviation taking into account the natural variation of data (for the time span available);
MBE - Mean Biased Error;
rMBE - Relative mean biased error;
RMSE - Root mean square error;
rRMSE - Relative root mean square error;
PV – Photovoltaic;
Albedo – Ground reflected solar radiation;

1 Introduction

According to the U.S Energy Information Administration report DOE/EIA-0484(2010), the total world's energy demand in 2015 will be 543 quadrillion BTU's or approximately 159,282 TWh. Presuming a surface can receive average solar irradiation of 1,200kWh/m^{2}per year (equivalent solar irradiation for Hungary). With system efficiency of 15% an area of 885 km^2[1]would be required to cover the world energy demand. Although the real area will increase due to the varying availability and efficiency of solar system technologies (efficiency can range from 5% – 40% from amorphous PV systems to parabolic dishes and thermal plants) and also due to daily and seasonal variations of solar radiation. Solar energy is thus one of the renewable energy sources that could potentially replace nuclear and coal energy in the future.

Solar simulation softwares are tools used for the promotion, development and planning of solar energy projects. Many governmental incentives and policies for the stimulation of alternative energies, including solar energy, are based on estimated energy values, such as the REIP - Renewable Energy Incentive Program and the NJCEC Clean Energy Credits in New Jersey. They are based on calculations from PVWATTS. According system size and energy production provides certain price per watt to solar system owners, thus making solar energy more cost efficient and competitive. Models and calculations used in simulation software can be complex and delicate items in which all inputs play an important role, which could influence the system output to a certain extent.

Variations in energy data is observed when using different softwares, even more when using the same software with a different input set. As a result, over/underestimate of the real system values can happen. Minimization of these differences should be the aim of every solar design engineer and solar system simulation software. Over time, solar simulation software become more and more advanced regarding calculation algorithms, and system simulations, thus providing more efficient designs.

1.1 Aims

The goal of the study is to examine the extent of variation in solar irradiation data, between different softwares for two locations: Stockholm (Sweden) and Athens (Greece). This study will considers solar irradiation at different tilt angles: horizontal, 30°, 45° and 60° (facing south) and the solar irradiation will be expressed both on a monthly and annual basis in kWh/m^2.

1.2 Method

The first step is to list free available solar irradiation data sources. Every data source is examined for climate data availability i.e. solar irradiation and classified in tables. Data from WRDC is used as a reference for the comparison between different sources. It is also the dataset with the largest time span, thus most accurately describing natural variation of solar radiation due to seasonal effects. Data on tilted surfaces is calculated for surface facing south with fixed tilts of 30°, 45° and 60° and a fixed ground reflection (or albedo) value of 0.20.

The different steps followed for obtaining and processing solar irradiation data are summarized on the next page:

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[1] The number will be higher due to system availability and maintenance issues.

- Data is obtained from different sources and then compared;
- Data on tilted surfaces (30°,45° and 60°) is calculated using original sources, evaluating multiple transposition models if available;
- Data is formatted into appropriate tables. Comparisons are made using statistical indicators such as estimated standard deviation, MBE, rMBE, RMSE and rRMSE.
- Data on tilted surfaces is calculated with Meteonorm and PVSYST using data sources that exhibit maximum difference in terms of RMSE and MBE from WRDC.
- Analysis of the data for the eventual source of variation.

1.3 Previous work

S. Labed & E.Lorenzo (2003) examined discrepancies in solar simulations for 22 sites in Algeria. Data sources are NASA SSE, Capderou, Censolar and Meteonorm. PVSYST and PV Design PRO software are used. The conclusion is that a variation of up to 15% was noted in the irradiation data; also the impact on sample PV systems, grid connected and stand-alone has been examined in some details.

M. Adsten, B. Perers, E. Wackelgard (2002) investigated energy variations for three locations in Sweden including Stockholm with surface tilt of 45°. Important is that they examine the impact in variation in solar input on the energy output. In Stockholm, for a tilt of 45°, a variation in solar irradiation data of 7% can yield difference in collector energy output of 12% on average for flat plate collectors and 9% for vacuum collectors.

Mesor Training Seminar (2009) is a good overview on solar resource products, such as instruments and solar radiation data sources. Information on solar irradiation variation is given in terms of seasonal and inter-annual variability, showing a maximum deviation of ~5% for 10 years and ~2.5% for 20 years.

PVSYST (2011) shows a comparison of irradiation data for 12 locations using different sources and using Meteonorm data as a reference. The inter-annual variability in solar irradiation is also studied for different locations between 1996 and 2000. Finally measurements are shown for Geneva (Switzerland) between 1982-2007 with annual difference of 5%, although this difference tends to increase since 2003.

C.A. Guyemard (2009) examines ten transposition models and four direct/diffuse separation models, for fixed tilt south facing planes (40° and 90°) and 2-axis tracker at NREL's laboratory in Golden, Colorado. Performance of all transposition models is observed to decrease when only global irradiance is given as an input, due to the dependence on direct/diffuse separation models. For 90° tilt, the albedo value becomes a significant factor and it influences the overall model performance.

P.Ineichen (2011) examines seven hourly models that calculate irradiation on tilted surface(s) for Geneva and Denver. 30°, 45° and 60° tilt angles are examined for south facing surfaces. The main conclusion is that a precision of 11% is estimated for the best model. The bias was not dependent from the direct/diffuse separation model, and knowledge of reflected irradiance has big impact on overall model's bias, as the surface's tilt increases.

S.K. Srivastava, O.P. Singh & G.N. Pandey (1995) examine empirical models for calculating hourly solar irradiation based on known daily/monthly values. It is shown that Collares-Pereira and Rabl models exhibit the best results, in comparison to (Liu and Jordan) and (Garg and Gang) correlations.

R. Perez, R. Seals, A.Zelenka and P.Ineichen (1990) evaluate global-to-direct conversion models by Erbs et al., Skartveit and Olseth, and Maxwell resulting in Maxwell's algorithm having the best overall performance in means of MBE and RMSE. Also Maxwell's algorithm shown here is the predecessor of Dirint and Dirindex models.

C. P. Cameron, W. E. Boyson, D. M. Riley (2008) examine error in: Perez, Hay and Davies, Reindl and isotropic sky transposition models with measured beam and diffuse radiation. As a result Perez's irradiation model (total to beam and diffuse), yield smallest error. Total+beam yields smaller errors.

J. A. Ruiz-Arias, T. Cebecauer, J. Tovar-Pescador, M. Suri (2010) introduce new topographic correction and use elevation correction on transposition algorithm of Perez et al., (1990b). Resulting in reduced rMBE from 2.4% to 0.4%

G. Notton, C. Cristofari, P.Poggi, M. Muselli (2001) propose linear and extraterrestrial model. This reduces overall variation in solar irradiation calculation, due to stationary hourly values.

P.G. Loutzenhiser, H. Manz, C. Felsmann, P.A. Strachan, T. Frank, G.M. Maxwell (2006) show the effect of using different transposition algorithms. Resulting in Perez's (1990b) model having smallest error. Due to included horizontal brightening and circumsolar diffuse into the diffuse part.

M. Diez-Mediavilla, A. Miguel, and J.Bilbao (2000) assess algorithms for estimation of diffuse irradiation on tilted surfaces comparing with measured values. As a result, Perez's and Reindl's models show as most accurate according to MBE and RMSE indicators.

P.Ineichen (2007) shows new method for estimation of global-to-beam irradiance conversion models. DirIndex which upgrades the existing DirInt (Perez et al., 1992) using relative Linke's Turbidity factor. Note that all the models display increase in RMSE by decreasing timing scale for the solar data, peaking for 5 min data.

J. Tovar, F.J. Olmo, F.J. Batlles, L. Alados-Arboledas (2001) propose dependence on the clearness index for minute values versus hourly averages.

R. Perez, R. Seals, R. Stewart, A.Zelenka (1996) compare hourly solar irradiation between several ground sites and satellite derived images. As a result satellite data becomes more accurate than ground data when distance from local station is greater than 34km from previously reported 50km range for daily irradiances.

R. Perez, R. Seals, R. Stewart, A. Zelenka and V. E. Da-Cajigal (1994) show that satellite data for horizontal irradiation has 20-25% RMSE and negligible MBE, making satellite more suitable to real data acquisition than extrapolation beyond 50km of ground stations.

P.Ineichen (2008) transposition errors are as incorrect as hourly values and splitting of beam and diffuse are different for different algorithms estimated.

C. A. Gueymard (2009) compared various direct/diffuse separation models (hourly radiation) showing Reindl el al. (1990) performing best.

Pierre Ineichen (2008), where DirIndex (Perez et al., 2002) succeeding DirInt - (Perez et al., 1992) was found to have lowest MBE and RMBE.

2 Data gathering, processing and simulation

2.1 Data sources, data tools, simulation software

Concept of free data, available for territory of Europe is brought as free choice for solar engineers, practitioners and anyone interested in designing a solar system. However, it is often difficult to make a distinction between measured data and calculated (software or model)data. This section intends to provide a brief classification of different data sources.

The free available data sources and softwares are listed below in Table 1.

Table1: List of free available data sources and softwares

Source	*Author/Country*
Solar Advisor Model (SAM)	NREL, U.S.A
PVSYST	University of Geneva
PVGIS-ESRA	SOLAREC, European Commission
RETScreen	Natural Resources, Canada
Energy Output Calculator v3.0 (SP EOC v3)	SR Technical Research Institute of Sweden
NASA SSE	NASA
WRDC	WMO, NREL
Satel-Light	Multiple research teams, EU funded

This list can be divided into data sources, data tools and simulation softwares (Table 2). Every item offers different options and different services, but they have in common latitude (°), longitude (°) and elevation (m).Solar irradiation data is typically expressed in form of average daily/monthly values for global horizontal and/or diffuse solar irradiation, measured in kWh/m^2.

Table 2: Division of solar radiation sources.

Data Sources	*Data Tools*	*Simulation Software*
WRDC	Meteonorm	PVSYST
Satel-Light	PVGIS	SAM
NASA's SSE	Satel-Light	SP EOC v3.0
PVGIS		RETScreen

In strict sense data sources are items that provide measured solar irradiation such as WRDC, Satel-Light, NASA's SEE, PVGIS and Meteonorm. Additionally they are items that provide means for processing solar data. Radiation and transposition models are used as tools for processing data from initial input into radiation on desired surface with desired time step. Data tools act as a binder between data sources and simulation softwares.

Simulation software act as system modeling tools that effectively convert energy input – solar irradiation into energy output of the system. Usually they contain the three parts mentioned above in Table 2, such as SAM, PVSYST, SP EOC v3.0 etc.

Solar irradiation inputs are typically in appropriate format and files, and each software/tool has its own defined rules how to format it. For example SAM uses EPW, TMY2 and TMY3 format. Others such as RETScreen and SP EOC v3.0 do not allow change in solar irradiation input.

Interestingly some sources such as PVGIS, Meteonorm and NASA's SSE have developed interpolation algorithms. They can calculate solar irradiation data for desired location (based on latitude and longitude). Accuracy of such algorithms will not be examined here although such comparison is done by Perez (1996).

Inter-data dependence is noticed between RETScreen and NASA's SSE, NASA's SSE and WRDC, EP EOC v3.0 and Meteonorm. Also only Meteonorm and PVSYST allow user to input own data and process it, using given models. SAM only allows inputs in form of meteo files, recognizable by the program such as: TMY2, TMY3 and EPW.

Solar irradiation data on a global level is being delivered in one of two ways: satellite or ground stations data (Table 3). Satellite stations provide data in form of raw images, while ground stations provide data in already predefined numbering formats typically in ASCII format.

Table 3: Comparison between data from satellite and ground stations.

Satellite data	*Ground stations*
Measured via infra-red and other visual sensors.	Pyranometers, pyrheliometers etc.
Data is for a large image suitable for making energy maps.	Data is for particular location.
Measures only global solar irradiation	Measure beam, diffuse and reflective part of solar irradiation.
Depending on satellite timing in data points can be from 15min to 1h.	Minute and less timing in data points is done.

Typically ground stations are placed in airports, schools or institutes near/in cities. Advantage of ground data is that solar radiation that is diffuse and beam can be measured thus including effects of scatter and diffusion in the atmosphere. Satellite stations provide only global radiation.

In Europe, commonly used databases providing ground measurements for solar irradiation are listed below:

- World Radiation Data Centre Database or WRDC.
- IDMP, International Daylight Measurement Program.
- European Solar Radiation Atlas, ESRA by Mines Paris Tech.
- Meteonorm databases (GEBA, WMO and Swiss database).
- World Meteorological Organization (WMO) stations.
- ESRA – European Solar Radiation Atlas.

All of the data sources provided before will not be used, since they either are not free, or not accessible for the examiner.

Satellite data in form of images cover wider territories. For Europe, typical satellite source is EUMETSAT's MSG satellites or METEOSAT 9 (MSG-2) with 15min resolution. Planned is MSG-3 with 10 min resolution. Typical look of satellite image data is shown below in figures 1 and 2. Notably Europe presents small part on satellites view angle, but still sufficient to provide satellite data for calculation of irradiation.

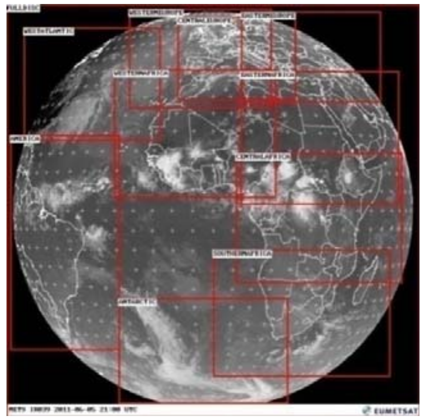

Figure 1: Monochromatic image (copyright 2011, Eumetsat)

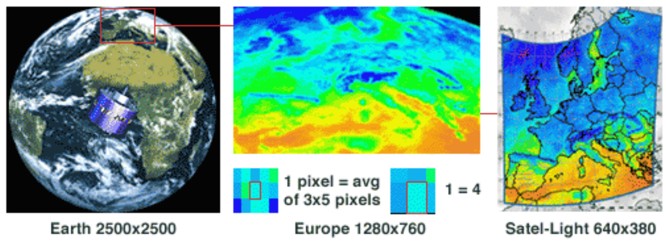

Figure 2: Europe overlay by Satel-Light.

Satel-Light uses Meteosat's data, exclusively, as direct input for calculations. As shown single pixel covers 5 km (latitude) x 6 km (longitude) at 34°, and at 64° up to 5km (latitude) x 16km (longitude). This is merely an example how satellite data can be processed. There are many models that deal with these issues and will not be reviewed here. Real data images are provided-worldwide by satellites such as: Meteosat (Europe), GOES (USA) or GMS (Japan) etc.

The solar irradiation data that is calculated and shown is expressed in average monthly irradiation in kWh/m^2. Some softwares/tools such as RETSCREEN, PVGIS and Satel-Light offer average daily irradiation Wh/m^2/daily, which is converted to average monthly irradiation.

2.2 WRDC, basis for comparison data

WRDC is situated in St. Petersburg and the oldest institution that gathers solar irradiation data for territory of Europe. It is known as the Main Geophysical Observatory and serves as a central depository for solar radiation data collected at over 1000 measurement sites throughout the world.

WRDC archive contains the following measurements (not all observations are made at all sites):

- Global solar radiation;
- Diffuse solar radiation;
- Downward atmospheric radiation;
- Sunshine duration;
- Direct solar radiation (hourly and instantaneous);
- Net total radiation;
- Net terrestrial surface radiation (upwards);
- Terrestrial surface radiation;
- Reflected solar radiation;
- Spectral radiation components (instantaneous fluxes);

All data gathered, as defined by the WRDC, has uncertainty defined as: 5% if data is higher than MJ/m^2 and 0.4 MJ/m^2 if lower than 5%. In case of Stockholm and Athens uncertainty is shown in table 4.

Table 4: Data uncertainty for Stockholm and Athens

	Stockholm	*Athens*
Average daily data	9.18 MJ	47.9 MJ
Uncertainty (5%)	0.46 MJ	1.46 MJ

The archive contains data records from 1964-1993. Later inquire for newer data resulted in a dataset available for 1964-2010 only for Stockholm. Archive's system was used as described on the web site. Stockholm and Athens stations identification codes are described below (Table 5).

Table 5: WRDC's identification for Stockholm and Athens databases.

Country	*Station*	*ID Tag*	*Latitude*	*Longitude*	*Elevation*
SWEDEN	STOCKHOLM	024830	5921	01804	0030
GREECE	ATHENS OBS.	167140	3758	02343	0107

Data as obtained can be accessed in the additional files: "Stockholm irradiation" and "Athens irradiation" under sheet's "RAW.DATA". Data is presented in J/cm^2, where 3600 J/cm^2=1 kWh/m^2. WRDC's data for Stockholm 59.35°N and 18.07°E and Athens 38.97°N and 23.72°E.

Inter-annual or natural variability for Stockholm is less than 1% and for Athens less than 2%, according to Mesor Training Seminar (2009).

Tables 6 and 7 show WRDC's data for Stockholm and Athens, including estimated standard variation. Athens exhibits higher energy input, due to the fact it has better geographical location (solar radiation on average falls with lower AM factors).

Table 6: Horizontal global solar irradiation for Stockholm

	Global	*S_n*
Jan	10.2	2.1
Feb	26.2	5.3
Mar	65.4	10.7
Apr	109.8	14.7
May	163.1	15.1
Jun	172.8	23.2
Jul	164.4	31.9
Aug	129.4	16.5
Sep	77.5	10.3
Oct	36.8	5.5
Nov	13.2	3.2
Dec	6.5	1.3
Year	975.8	140.4

*Units in kWh/m^2.

Table 7: Horizontal global solar irradiation for Athens.

	global	*S_n*
Jan	58.8	8.3
Feb	73.9	8.2
Mar	116.9	12.9
Apr	153.4	12.9
May	193.9	10.5
Jun	209.4	14.6
Jul	216.2	10.0
Aug	194.4	11.6
Sep	150.5	10.6
Oct	107.3	9.9
Nov	68.6	8.7
Dec	53.9	5.5
Year	1597.7	124.3

*Units in kWh/m^2.

2.2.1. NASA's SSE

NASA's SSE or Surface Meteorology and Solar Energy is a dataset aimed to help the development of solar photovoltaic energy. It dates from 1983-2005 originating from ground mounted stations. It measures global horizontal irradiation on hourly basis and reports in monthly/daily averages in kWh/m^2. Uncertainty is not known, but it's estimated somewhere of 6-12%, depending on station.

Below (Table 8) show is the solar irradiation data for Stockholm, while Athens's data is available in the appendix section. The NASA's SSE data is notably higher than WRDC's data, but S_n is lower, due to the fact that less years are taken into account, for calculation of the deviation.

Table 8: Horizontal global solar irradiation and S_n for Stockholm, NASA's SSE.

	Global	*S_n*
Jan	12.5	0.9
Feb	30.0	3.1
Mar	75.5	8.0
Apr	122.3	10.3
May	173.6	15.7
Jun	175.6	19.2
Jul	173.4	19.4
Aug	135.6	14.8
Sep	85.3	9.7
Oct	41.4	3.6
Nov	16.5	1.2
Dec	7.6	0.5
Year	1,049.9	106.8

*Units in kWh/m^2.

2.2.2. Satel-Light

Satel-Light acts as data source and tool, since it calculates data on surface with desired azimuth and slope. Ground reflectance is entered as annual value. Data is obtained online and it use satellite images from Meteosat, MSG-2.

The database contains images from 1996 to 2000. Data is delivered in form of daily/monthly data kWh/m^2 for global and diffuse horizontal solar irradiation. Comparison is made with ground measurements and on annual basis MBE difference is -1% to 3% and RMSE 20% for Southern Europe and 40% Northern Europe. For calculation of solar irradiation on tilted surface Skartveit (1998) is used.

Solar Irradiation data, as given by the database is shown below in Table 9. Unlike NASA's SSE and WRDC's data it offers diffuse solar irradiation. The global solar irradiation is higher than the one WRDC provides.

Table 9: Satel-Light - horizontal solar irradiation for Stockholm.

	global	*diffuse*
Jan	10.1	7.2
Feb	28.9	16.1
Mar	72.1	34.4
Apr	112.3	52.9
May	160.9	70.5
Jun	164.3	76.2
Jul	161.5	78.7
Aug	136.0	64.9
Sep	83.0	41.8
Oct	38.0	23.4
Nov	14.8	9.7
Dec	6.4	4.7
Year	988.9	481.1

*Units in kWh/m^2.

Clear factor for uncertainty is not provided, but it shows percentage that accounts for actual measured or assumed data. Stockholm-73% (measured) and Athens-82% (measured).

Table 10 gives solar irradiation on tilted surfaces, delivered by Satel-Light. It is worth observing that solar energy rises as tilt increases, up to 45°, than it decreases slightly.

Table 10: Satel-Light – solar irradiation for tilted surfaces for Stockholm.

	30°		*45°*		*60°*	
	global	*diffuse*	*Global*	*Diffuse*	*global*	*Diffuse*
Jan	19.9	8.8	23.3	9.1	25.3	9.0
Feb	53.3	19.7	61.3	20.4	65.7	20.3
Mar	104.0	38.3	111.8	38.3	113.1	37.0
Apr	135.3	54.9	136.5	53.3	130.5	50.1
May	173.0	70.5	166.7	67.5	152.4	62.7
Jun	168.0	74.6	158.6	70.7	142.1	65.0
Jul	168.9	77.6	161.0	73.7	145.7	67.8
Aug	155.8	66.6	154.1	64.5	144.6	60.3
Sep	109.8	45.1	114.7	44.4	113.3	42.3
Oct	58.4	26.0	64.1	25.9	66.3	24.9
Nov	29.3	12.0	34.3	12.5	37.2	12.4
Dec	15.1	6.2	18.3	6.6	20.4	6.7
Year	1191.4	500.8	1205.2	487.3	1157.1	459.0

*Units in kWh/m^2.

2.2.3. PVGIS

Photo Voltaic Global Information System or PVGIS isa set of models of which main part is “r.sun” implemented in “GRASS GIS”, (PVGIS, 2011). It is similar to the model described by Satel-Light and also known as Helioclim model.

Typically global horizontal radiation is measured, separated into direct/diffuse with an appropriate radiation model. If plane is tilted transposition model of Muneer (1990) is used.

European Solar Radiation Atlas or ESRA is specified as data source. Data for global solar irradiation is in daily sums in Wh/m^2 with 80% data reliability. Interpolation algorithms are implemented for calculation of irradiation, for places of chosen latitude and longitude.

For Stockholm 59.35°N and 18.07°E and for Athens 38.97°N and 23.72°E, data locations were chosen. For Stockholm global horizontal solar irradiation is shown in Table 11. Table 12 shows global solar irradiation on tilted surfaces.

Table 11: PVGIS – global horizontal solar irradiation for Stockholm.

	global	*diffuse*
Jan	9.2	7.0
Feb	25.3	15.9
Mar	61.3	35.6
Apr	107.7	54.9
May	164.6	72.4
Jun	160.8	82.0
Jul	161.2	80.6
Aug	119.9	64.7
Sep	73.5	40.4
Oct	35.9	22.3
Nov	13.3	9.4
Dec	5.4	4.4
Year	938.5	490.0

*Units in kWh/m^2.

Table 12: PVGIS –global solar irradiation for tilted surfaces for Stockholm.

	30°	*45°*	*60°*
Jan	17,8	20,9	22,8
Feb	44,2	50,4	53,8
Mar	85,6	91,8	93,0
Apr	130,2	132,0	127,2
May	180,1	175,5	162,1
Jun	165,3	157,2	142,2
Jul	169,9	163,1	148,8
Aug	136,4	135,5	127,7
Sep	96,9	101,7	101,1
Oct	56,1	62,0	64,8
Nov	25,5	29,8	32,4
Dec	10,3	12,0	13,1
Year	1118,3	1131,8	1089,0

*Units in kWh/m^2.

2.2.4. Meteonorm

Meteonorm is developed by Meteotest institute. It offers data from ground stations and satellite images. Uncertainty is 9% for global horizontal solar irradiation and inter-annual variation is less than 2%. Transposition models overestimate total irradiation on tilted surface by 6% for yearly values. Optional input is offered for albedo, transposition model and radiation models.

For location of Stockholm two locations are suitable, i.e. Stockholm SW referring to city Stockholm and Stockholm Bromma referring to ground station at Bromma airport, near Stockholm.

For Athens also two locations are chosen Athens also has two inputs, Athinai GR referring to city of Athens and Athinai station. Meteonorm also offers four transposition models and two radiation models:

- Default (hour).
- Minute.
- Clear sky radiation.

Transposition model are:

- Hay's model (1979);
- Skartveit and Olset model (1986);
- Gueymard's model (1987);
- Minute time resolution model (Skartveit and Olseth, 1986);

Aguiar et al. (1988) translates average monthly into daily irradiation. Aguiar at al. and Collares-Pereira (1992) TAG model calculate hourly irradiation from daily irradiation.

For Stockholm the horizontal solar irradiation for the two sources SW and Bromma are shown in Table 13. Also it contains values for the diffuse solar irradiation. Both stations have same solar energy input values.

Table 13: Meteonorm – horizontal solar irradiation for Stockholm.

	Stockholm SW		*Stockholm/Bromma*	
	global	Diffuse	Global	diffuse
Jan	10	7	10	7
Feb	26	17	26	16
Mar	68	32	68	31
Apr	110	53	110	50
May	164	74	164	76
Jun	174	72	174	84
Jul	165	75	165	78
Aug	130	58	130	66
Sep	78	41	78	44
Oct	36	24	36	23
Nov	12	9	12	8
Dec	6	5	6	4
Year	979	467	979	487

*Units in kWh/m^2.

Tables 14 and 15 show solar irradiation on tilted surfaces for Stockholm, using Meteonorm as a data source. Table 14 shows for Stockholm SW and Table 15

Stockholm Bromma. Notable is that they show different values for irradiation on tilted surfaces, despite same global horizontal solar irradiation (Table 13).

Table 14: Meteonorm – global solar irradiation for tilted surfaces for Stockholm-using Stockholm SW.

	Perez			*Hay*			*Gueymard*			*Skartveit/Olseth*		
	30°	*45°*	*60°*	*30°*	*45°*	*60°*	*30°*	*45°*	*60°*	*30°*	*45°*	*60°*
Jan	20	24	27	18	21	22	19	22	24	18	20	22
Feb	46	53	57	42	47	49	44	49	52	42	46	48
Mar	98	106	108	94	100	100	95	102	103	93	99	99
Apr	136	138	133	131	132	126	132	134	129	130	131	124
May	179	174	160	174	168	154	175	169	156	174	167	152
Jun	182	174	158	179	169	153	179	170	154	178	168	150
Jul	174	167	152	171	162	148	171	163	148	170	161	145
Aug	151	150	142	147	145	136	148	146	138	146	144	134
Sep	105	111	110	100	104	103	102	106	105	100	103	101
Oct	55	60	62	51	55	56	52	56	58	50	54	54
Nov	21	24	25	19	21	22	20	22	23	19	21	21
Dec	12	15	16	10	12	13	11	13	14	10	12	13
Year	1179	1196	1150	1136	1136	1082	1148	1152	1104	1130	1126	1063

*Units in kWh/m^2.

Table 15: Meteonorm – global solar irradiation for tilted surfaces for Stockholm-Bromma.

	Perez			*Hay*			*Gue*			*S/O*		
	30°	45°	60°	30°	45°	60°	30°	45°	60°	30°	45°	60°
Jan	20	24	26	18	20	22	18	22	23	17	20	22
Feb	47	53	57	42	47	50	44	50	53	42	47	49
Mar	100	109	111	96	102	103	97	105	106	95	101	102
Apr	136	139	135	132	133	128	133	135	130	131	132	126
May	180	175	163	175	169	156	176	171	158	175	168	153
Jun	180	171	155	176	166	150	176	167	150	175	164	147
Jul	174	167	152	170	162	147	171	163	148	170	160	145
Aug	149	147	139	144	141	132	145	143	134	143	140	130
Sep	104	108	108	99	102	100	100	104	102	98	101	98
Oct	54	59	61	51	54	55	52	56	57	50	54	54
Nov	23	27	29	21	24	26	22	25	27	21	24	26
Dec	15	19	21	13	16	18	14	17	19	13	16	18
Year	1182	1198	1157	1137	1136	1087	1148	1158	1107	1130	1127	1070

*Units in kWh/m^2.

2.2.5. SP EOC v3.0

SP EOC v3.0 is a product of SP Technical Research Institute of Sweden and Solar Keymark II project. It is solar simulation software for thermal flat-plate and vacuum tube collectors. Written in excel tool and Visual Basic algorithms, which serve as a solar simulation for thermal collectors.

Planes azimuth and tilt (horizontal, 30°, 45°, 60° and 90°) are optional for locations of Stockholm, Athens and others. Inputs are embedded, thus they cannot be changed. Irradiation input is taken from Meteonorm. Albedo is 0.20, but is not shown. Table 16 sums global horizontal solar irradiation and solar irradiation on tilted surfaces for Stockholm.

Table 16: SP EOC v3.0 – global solar irradiation for horizontal and tilted surfaces for Stockholm.

	Horiz.	*30°*	*45°*	*60°*
Jan	10,0	20,0	23,0	26,0
Feb	26,0	45,0	51,0	54,0
Mar	68,0	97,0	104,0	106,0
Apr	110,0	133,0	134,0	129,0
May	164,0	175,0	168,0	155,0
Jun	174,0	178,0	169,0	152,0
Jul	165,0	171,0	163,0	148,0
Aug	130,0	149,0	147,0	139,0
Sep	78,0	104,0	109,0	109,0
Oct	36,0	54,0	59,0	61,0
Nov	12,0	21,0	24,0	25,0
Dec	6,0	12,0	14,0	15,0
Year	979,0	1.159,0	1.165,0	1.119,0

*Units in kWh/m^2.

2.2.6. RETScreen

RETScreen Clean Energy Project Analysis Software is comprehensive simulation software. It offers a variety of system technologies that can be simulated such as: Power, containing Photovoltaic, Thermal etc. Also it offers other methodologies such as energy efficiency measures, heating, cooling etc. It is a product of National Resources Canada and CanmetENERGY research center. RETScreen uses data from ground stations and NASA's SSE database. Satellite data is from NASA's SSE, while ambiguity exists in that which data source is being used for ground stations.

This software does not provide option to alter or input another climate data. Only azimuth and tilt are optional. It offers data for multiple locations for Stockholm and Athens. For Stockholm offered stations are Stockholm (ground), Stockholm KTH (ground), Stockholm/Arlanda (NASA) and Stockholm/Bromma (NASA) (Table 17). Athens is Athinai (Athens) Observatory, Athinai Filadelfia and Athens/Hellenkion. First two are ground stations and third is NASA's SSE derived station.

Table 17: RETScreen - horizontal solar irradiation for Stockholm.

	1	2	3
Jan	10,2	9,9	12,4
Feb	26,3	26,6	31,4
Mar	65,4	69,4	75,3
Apr	108,9	110,4	117,0
May	162,8	164,0	166,2
Jun	172,5	197,4	165,3
Jul	164,0	173,3	163,1
Aug	129,6	140,1	129,6
Sep	77,4	81,0	82,5
Oct	36,6	38,4	40,0
Nov	13,2	13,8	17,1
Dec	6,5	7,1	7,8
Year	973,4	1031,5	1007,5

*Units in kWh/m^2.

Legend: 1 - Stockholm KTH station, 2 – Stockholm, 3 – Stockholm Arlanda/Bromma ground stations.

Table 18: RETScreen – global solar irradiation for tilted surfaces for Stockholm.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Stock. KTH													
30°	23,5	46,7	92,0	128,5	172,8	174,4	169,0	145,6	100,3	58,7	28,1	17,9	1157,7
45°	28,5	53,6	98,6	129,5	166,8	164,9	161,1	144,1	104,6	65,4	33,5	22,2	1172,9
60°	31,8	57,8	100,0	124,1	153,6	149,3	147,0	135,7	103,5	68,6	37,0	25,3	1133,7
Stockolm													
30°	23,2	48,3	100,0	130,9	174,4	200,6	179,3	159,2	106,6	63,8	31,5	21,5	1239,4
45°	28,3	55,9	107,9	132,1	168,4	189,9	171,1	158,1	111,6	71,7	37,9	27,1	1260,0
60°	31,8	60,7	110,0	126,7	155,3	172,0	156,2	149,3	110,8	75,6	42,1	31,0	1221,4
Stock.Arl.													
30°	34,7	61,9	111,5	140,1	177,0	167,0	168,2	145,9	109,2	67,8	45,9	25,8	1254,9
45°	43,2	72,7	121,1	141,8	171,0	158,0	160,4	144,6	114,5	76,6	56,6	32,8	1293,3
60°	49,2	79,6	124,0	136,4	157,7	143,2	146,5	136,2	113,9	81,1	63,9	37,8	1269,4
Stock. Bro.													
30°	32,9	60,6	110,7	139,7	176,7	166,9	168,1	145,7	108,7	66,8	44,0	23,8	1244,5
45°	40,7	70,9	119,9	141,3	170,6	157,7	160,2	144,2	113,8	75,2	54,0	29,9	1278,5
60°	46,1	77,3	122,6	135,7	157,2	142,9	146,1	135,7	113,0	79,5	60,7	34,3	1251,1

*Units in kWh/m^2.

2.2.7. SAM

SAM or System Advisor Model is simulation software developed by National Renewable Energy Laboratory (NREL) which includes multiple solar technologies such as PV, Thermal etc. As input it uses meteo files TMY2, TMY3 and EPW files. They contain information for solar irradiation (global, direct and diffuse) on hourly basis and monthly averages.

It offers choice on how the solar data will be processed i.e. which part of the solar energy will be measured and which calculated. It offers: Total+Beam, Total+Diffuse and Beam+Diffuse. Where total+diffuse was chosen as input parameters, since Meteonorm, PVSYST use total and diffuse as inputs.

Difference between Total+Diffuse and other two models around 0.1%, for horizontal solar irradiation. For tilted surface Perez 1988 showed highest differences of 2%, 2%, and 3% for 30°, 45° and 60° vs. T+B and B+D. Other models showed 1% difference or less. No explanation for radiation modeling was given whatsoever.

Several transposition models are offered, such as: Isotropic sky, Hay and Davies, Reindl and Perez 1988 and 1990. For ground reflected radiation, two inputs are offered of “ground reflectance with snow” and “ground reflectance”. It is not shown what their impact on the albedo is. The table below shows solar irradiation for Stockholm, (Table 19).

Table 19: SAM –horizontal solar irradiation for Stockholm.

	global	*diffuse*
Jan	8.06	6.51
Feb	21.39	15.37
Mar	54.78	33.57
Apr	112.29	54.09
May	163.62	76.57
Jun	160.80	89.13
Jul	156.95	89.62
Aug	118.11	74.52
Sep	69.72	45.51
Oct	36.52	22.85
Nov	13.41	9.60
Dec	6.20	4.50
Year	921.85	521.84

*Units in kWh/m^2.

Using SAM's build in transposition models and albedo of 0.20, solar irradiation on tilted surfaces is calculated and shown (Table 20). Notable is that Perez 1990 model shows higher energy yield and the isotropic model shows the lowest.

Table 20: SAM –global solar irradiation on tilted surfaces for Stockholm.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Isotropic													
30°	12,9	31,4	70,5	133,5	178,0	166,1	162,7	127,9	82,6	51,9	24,0	13,1	1054,6
45°	14,5	34,3	73,7	134,6	172,9	158,1	155,4	124,8	83,7	56,1	27,7	15,7	1051,4
60°	15,3	35,6	73,3	129,2	160,0	143,8	141,8	116,6	81,2	57,5	29,9	17,3	1001,6
Hay													
30°	14,3	34,3	74,2	138,5	182,4	169,1	166,3	132,1	86,9	55,9	26,9	15,0	1096,0
45°	16,5	38,4	78,7	141,2	178,2	161,5	159,5	130,2	89,6	61,6	31,7	18,3	1105,4
60°	17,8	40,5	79,2	136,5	165,3	146,9	145,8	122,4	88,0	64,0	34,7	20,6	1061,5
Reindl													
30°	14,3	34,4	74,3	138,8	182,9	169,6	166,8	132,5	87,2	56,0	26,9	15,0	1098,9
45°	16,5	38,6	79,1	142,1	179,6	163,0	161,1	131,5	90,3	61,9	31,8	18,4	1114,0
60°	17,9	40,9	80,0	138,3	168,0	149,9	149,0	124,9	89,4	64,6	34,9	20,7	1078,4
Perez 88													
30°	15,6	36,0	75,7	140,1	184,3	171,0	168,9	135,4	89,6	57,0	27,8	15,5	1116,9
45°	18,2	40,7	80,8	143,3	180,7	163,7	162,7	134,4	93,1	63,0	33,0	19,0	1132,7
60°	19,9	43,2	81,6	138,9	168,0	149,0	149,1	126,9	92,0	65,7	36,3	21,4	1091,9
Perez 90													
30°	15,6	36,0	76,2	141,3	186,2	172,4	170,1	135,9	89,7	57,3	28,0	15,7	1124,3
45°	18,2	40,8	81,4	144,9	183,3	165,7	164,4	135,1	93,4	63,5	33,2	19,3	1143,2
60°	19,9	43,3	82,4	140,9	171,1	151,5	151,2	127,8	92,4	66,2	36,6	21,7	1105,0

*Units in kWh/m^2.

2.2.8. PVSYST

It is comprehensive and detailed data tool and simulation software. PV technology simulation is its aim, particularly grid connected, stand alone and other system types. It's developed by Dr. Andre Mermoud from the institute for Environmental Sciences - Energy Group, University of Geneva.

Interestingly it provides list for optional data sources, then the build in. As optional data sources listed are Meteonorm, Satel-Light, NASA's SEE, WRDC and etc. Additionally option is left for custom user input, preformatted in ASCII.

Thus, PVSYST compared to rest of softwares/tools, for data obtaining and processing, offers more possibilities. Such are data evaluation, hourly data generation, albedo input and optional solar irradiation data input.

PVSYST offers Hay and Perez-Inichein transposition models. Solar irradiation data for horizontal surface and tilted for tilts of 30º, 45º and 60º with albedo 0.20 is obtained. Table 21 gives data output, from PVSYST, for horizontal surface and Table 22 for tilted surface.

Table 21: PVSYST – horizontal solar irradiation for Stockholm, WRDC.

	PVSYST, WRDC	
	diffuse	*Global*
Jan	7.4	10.2
Feb	16.4	26.2
Mar	38.1	65.4
Apr	57.3	109.8
May	80.2	163.1
Jun	80.8	172.8
Jul	82.4	164.4
Aug	62.9	129.4
Sep	42.9	77.5
Oct	24.3	36.8
Nov	9.2	13.2
Dec	4.4	6.5
Year	506.9	975.9

*Units in kWh/m^2.

Table 22: PVSYST - global solar irradiation on tilted surfaces for Stockholm.

		30°		*45°*		*60°*
	Hay	*Perez*	*Hay*	*Perez*	*Hay*	*Perez*
Jan	22.3	22.8	26.7	27.4	29.6	30.4
Feb	46.2	47.1	52.7	54.0	56.3	57.9
Mar	90.4	92.6	96.3	99.5	97.2	100.8
Apr	130.4	133.4	131.4	135.5	125.9	130.5
May	174.3	178.2	168.2	173.4	155.0	160.5
Jun	177.4	181.6	168.2	173.7	151.9	158.1
Jul	166.7	170.4	158.9	163.7	144.7	149.9
Aug	146.7	150.0	145.0	149.6	136.2	141.3
Sep	102.5	104.6	107.4	110.3	106.6	110.0
Oct	54.5	55.9	59.5	61.5	61.5	63.8
Nov	24.8	25.4	28.8	29.1	31.3	32.3
Dec	13.8	17.0	20.6	21.0	23.3	23.8
Year	1150.7	1179.7	1164.4	1199.8	1120.2	1159.9

*Units in kWh/m^2.

2.3 Calculations models

Provided solar irradiation data, for global irradiation in horizontal plane, is real-time/measured data. Data for tilted surfaces is calculated using known transposition and radiation models.

Solar simulators work with hourly irradiation and so solar irradiation data firstly has to be processed and convert into hourly values. Even more, it has to be divided into beam and diffuse parts, because of the various impacts on systems these two types of solar energy deliver.

Each software has in-built models that work with the data to convert it to the needed hourly values for needed tilt, in global and diffuse parts. First step in the processing is splitting the global radiation into diffuse and beam parts. Gueymard (2009) treats this process. It is concluded that this splitting can create biggest source for discrepancy in the data output.

When obtaining measured solar irradiation data, some stations offer it in hourly values already divided in beam and diffuse parts. But it is very common to find only data for daily/monthly averages for global solar irradiation.

The tilt and azimuth for desired plane receiving solar radiation, is subject to variation due to terrain constrains and shading. And it is difficult to have measured data for every tilt and azimuth occurrence that can happen. If data is not provided, it has to be assumed or calculated. Bottom line is that the process of obtaining solar irradiation for desired place and plane is difficult.

Duffie and Beckman (1991) give good explanation on how solar energy is being converted from the Sun as a source to the Earth as a receiver. Treated are extraterrestrial radiation, terrestrial radiation and radiation on desired plane on Earth's surface. It is assumed that either average monthly or average hourly/daily irradiation data are available.

For proper assessment of solar resource, simulation software need to account for and calculate sun-earth correlations such as terrestrial radiation and its variation, effects of Earth's rotation and etc. in regards to actual location of the desired surface. Also, plane's tilt and azimuth, potential shading and atmospheric variation due to clouds, need to be considered. Generally softwares works with average monthly solar irradiation, convert to daily and daily to hourly irradiation, lastly hourly is divided into beam and diffuse parts.

Figure 3 show calculation steps to derive average monthly/daily data in desired hourly time steps and division of solar irradiation to beam and diffuse parts. It is done according to Duffie and Beckman (1991).

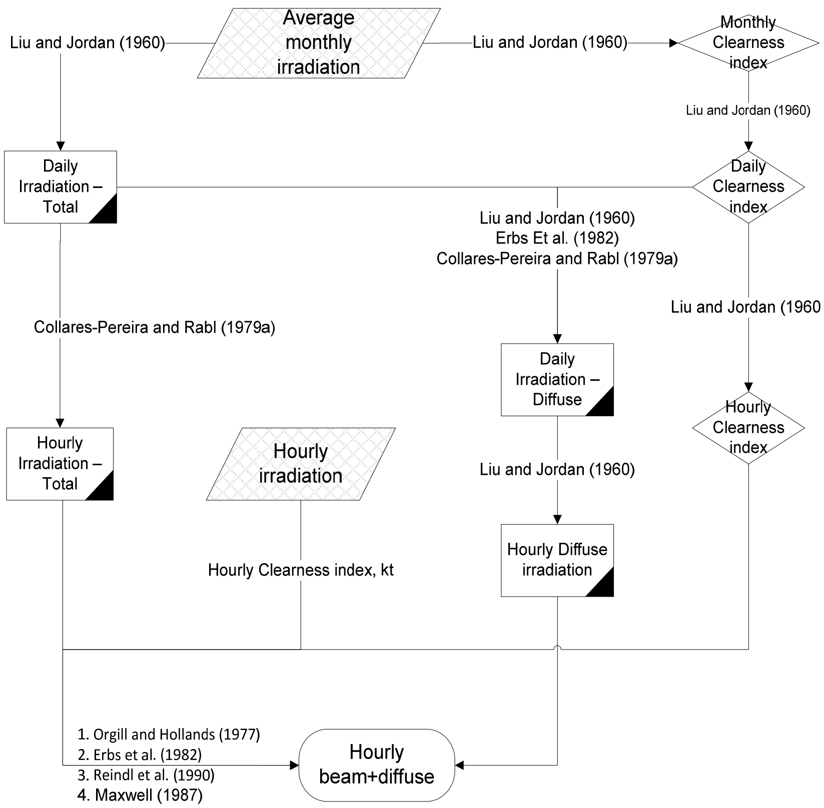

Figure 3: Radiation models, used for calculation/conversion from average monthly into average hourly, total and diffuse solar irradiation.

The next step is calculation of irradiation on sloped surface. It is done with transposition models. They work with hourly irradiation values, which emphasizes the need have hourly irradiation data, as described before.

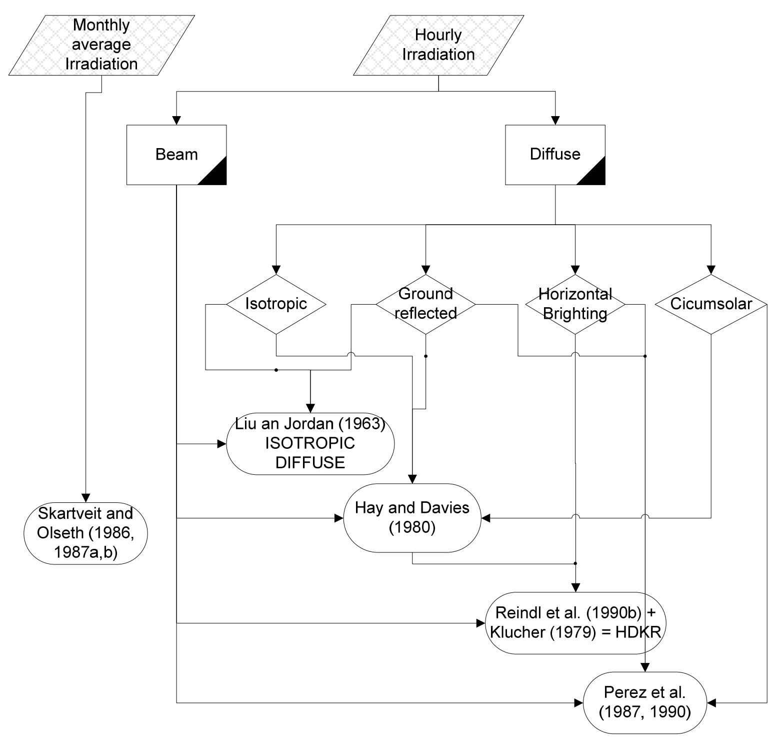

Figure 4: Overlay of transposition algorithms, Duffie and Beckman (1991).

Generally transposition models can be divided into isotropic diffuse model and anisotropic models. In isotropic sky models, such as Liu and Jordan’s (1963), horizontal brightening and circumsolar diffuse are not considered. Anisotropic sky models such as: Hay and Davies (1980), Reindl et al. (1990b), Hay and Davies model as proposed by Kucher (1979) – HDKR model; Skartveit and Olseth (1986, 1987a,b) treat each part of the irradiation as separate. This is shown by Duffie& Beckman (1991) and depicted in Figure 4.

Notably, only Perez (1990) takes into accounts four parts of the irradiation that falls on a surface. Also it’s commonly used and proven to have fewer errors than compared with other models. Not shown are newer transposition algorithms such as DirInd,DirIndex and Muneer.

WRDC, NASA’s SSE and Satel-Light have only horizontal monthly irradiation.

Table 23: List of sources and models they use.

Item	*Radiation model*	*Transposition model*
WRDC	/	/
NASA SSE	/	/
RETScreen	Erbs, Collares-Pereira and Rabl and Liu and Jordan	Liu and Jordan (1963)
PVGIS	Muneer(1997)	Muneer(1997)
Satel-Light		Skartveit and Olset
Meteonorm		

Notable is that Satel-Light, Meteonorm, RETScreen and PVGIS provided information of processing phases as shown on the figure; starting from data that is measured or obtained information of average monthly radiation or average hourly radiation.

Radiation models bring data from average monthly/daily irradiation into hourly time steps as used in simulations. Then hourly values are split into beam and diffuse components, providing inputs for the transposition algorithms.

Clearness index is calculated from average total values and play role in calculation of daily from monthly irradiation as well as for hourly from daily irradiation and in splitting phase of global solar radiation/irradiation.

Generally one can observe fixed and functional albedo. Commonly biggest fluctuations of the albedo are due to snow and usually softwares have way to deal with seasonal fluctuations with introducing snowy and not snowy days.

Figure 5, shown below, gives summation for albedo values that softwares/tools use. As seen WRDC, Satel-Light and NASA’s SSE do not provide albedo values, only solar irradiation on horizontal plane. PVGIS and SP EOC v3.0 use average value for albedo throughout the year. PVSYST use average monthly input, while RETScreen and Meteonorm developed relation between ambient temperature and the albedo. Interestingly they increase albedo for negative temperature in matter shown and decrease it for positive, and small zone is left as “not sure” zone.

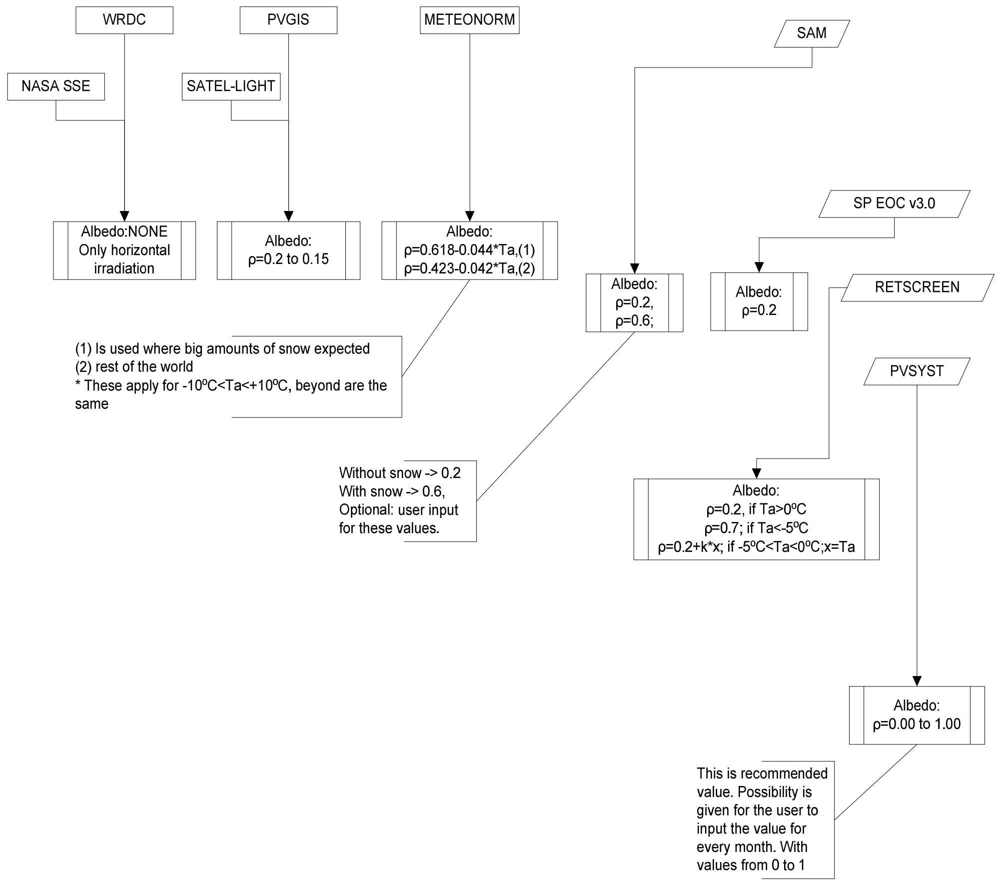

Figure 5: Albedo as used by different data tools/softwares.

Investigating the individual software data and information on how it calculates its energy yield from the appropriate guidelines associated gives the following: Formulas for MBE, RMSE, S, rMBE, rRMSE and rS are:

$$MBE = \frac{\sum_{i=1}^{i=N}(yi - xi)}{N} \qquad \textit{Equ. 2.1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=N}(yi - xi)^2}{N}} \qquad \textit{Equ. 2.2}$$

$$S = \sqrt{\frac{\sum_{i=1}^{i=N}(xi - \bar{x})^2}{N-1}} \qquad \textit{Equ. 2.3}$$

$$rMBE = \frac{MBE}{y} * 100\% \qquad \textit{Equ. 2.4}$$

$$rRMSE = \frac{RMSE}{\bar{x}} * 100\% \qquad \textit{Equ. 2.5}$$

$$rS = \frac{S}{Gannual} * 100\% \qquad \textit{Equ. 2.6}$$

S_a and S_n use Equation 3.3, with difference in data they represent i.e. S_a uses monthly values of particular data set for one year, where S_n uses monthly or yearly values. In similar fashion, rS_a and rS_n use equation 3.6.

2.4 Assumptions

Data sources such as RETScreen and Meteonorm offer multiple sources for the same site. In this study four data sources (respectively three) were taken into account for Stockholm (respectively Athens).Ambiguity in term “site” or “city” is obvious, since it can refer to larger area where solar irradiation, if measured in different areas can differ, especially if obstructed by nearby terrain or structure. In future, as cities grow bigger, more stations can be installed for same city, site, and can give different values.

Ground reflected radiation is a parameter that can play important role in solar irradiation discrepancies for tilted surface. Some softwares/tools such as RETScreen and Meteonorm use functional dependence of albedo with ambient temperature, as implicit dependence exists between snow cover and ambient temperature.

Solar simulation softwares besides the solar irradiation data, global and/or diffuse, work with ambient temperature. It is well known that almost all solar technologies for production of energy exhibit temperature dependence. In this case multiple different data for ambient temperatures were obtained also with solar irradiation data. Example, Stockholm/Arlanda and Stockholm/Bromma have same global solar irradiation while average ambient temperature are 6.5°C and 6.9°C. The impact that the temperature has in solar simulation softwares needs to be described in more detail (and it’s modeling), and as such is a good topic for further examination.

2.5 Horizontal solar irradiation, summation

From all the data sources presented earlier for horizontal global solar irradiation data is summed in Table 23 for Stockholm and Table 24 for Athens.

Table 23: Horizontal global solar irradiation for Stockholm.

	Jan	*Feb*	*mar*	*apr*	*may*	*jun*	*Jul*	*aug*	*sep*	*oct*	*nov*	*dec*	*year*
WRDC	10,2	26,3	65,5	109,9	163,1	172,8	164,5	129,4	77,5	36,8	13,3	6,6	975,9
SSE	12,5	30,0	75,5	122,4	173,6	175,7	173,4	135,7	85,4	41,5	16,5	7,7	1049,9
S-L	10,1	29,0	72,1	112,3	160,9	164,4	161,5	136,1	83,1	38,1	14,9	6,5	988,9
PVGIS	9,3	25,4	61,4	107,7	164,6	160,8	161,2	120,0	73,5	36,0	13,3	5,4	938,5
MET. SW	10,0	26,0	68,0	110,0	164,0	174,0	165,0	130,0	78,0	36,0	12,0	6,0	979,0
MET. BR	10,0	26,0	68,0	110,0	164,0	174,0	165,0	130,0	78,0	36,0	12,0	6,0	979,0
RS-KTH	10,2	26,3	65,4	108,9	162,8	172,5	164,0	129,6	77,4	36,6	13,2	6,5	973,4
RS-STO.	9,9	26,6	69,4	110,4	164,0	197,4	173,3	140,1	81,0	38,4	13,8	7,1	1031,5
RS-A/B	12,4	31,4	75,3	117,0	166,2	165,3	163,1	129,6	82,5	40,0	17,1	7,8	1007,5
SAM	8,1	21,4	54,8	112,3	163,6	160,8	156,9	118,1	69,7	36,5	13,4	6,2	921,8
SP EOC	10,0	26,0	68,0	110,0	164,0	174,0	165,0	130,0	78,0	36,0	12,0	6,0	979,0

*Units in kWh/m^2.

Stockholm data has 11 data sources with units of monthly[2] global solar irradiation in kWh/m^2

For Stockholm Meteonorm reported two stations, Stockholm SW and Meteonorm Bromma. RETScreen reported four stations, KTH, Stockholm, Stockholm Arlanda and Stockholm Bromma. Where: S-L refers to data from Satel-Light, SSE to NASA’s SSE etc.

[2] Where average daily solar irradiation exists, translation into monthly radiation is done, multiplication factor of the number of days for desired month with the energy value examined.

Table 24: Horizontal global solar irradiation for Athens.

	jan	feb	mar	apr	may	Jun	jul	aug	sep	oct	nov	dec	year
WRDC	58,8	73,9	116,9	153,4	193,9	209,5	216,2	194,5	150,6	107,3	68,6	54,0	1597,7
SSE	66,5	80,6	124,0	161,0	199,3	224,0	228,0	205,7	155,8	106,3	65,3	53,9	1670,3
S-L	68,9	91,1	123,7	175,1	221,9	248,0	255,5	226,0	169,7	121,2	78,6	60,6	1840,3
PVGIS	63,9	73,9	120,0	157,2	193,4	211,8	216,1	193,4	153,9	106,3	65,1	54,6	1609,6
MET. GR	64,0	75,0	113,0	152,0	191,0	207,0	218,0	201,0	155,0	108,0	69,0	54,0	1607,0
MET. AT	62,0	77,0	122,0	158,0	200,0	215,0	223,0	202,0	156,0	111,0	72,0	56,0	1654,0
RS-HEL	66,3	80,6	124,0	161,1	199,3	223,8	228,2	205,2	156,3	106,6	65,4	53,6	1670,6
RS-OBS.	58,9	73,4	116,9	153,3	194,1	209,4	216,1	194,4	150,6	107,3	68,7	53,9	1596,8
SAM	64,1	78,8	124,4	154,3	192,7	224,4	233,4	205,4	162,6	109,2	64,2	56,1	1669,6
SP EOC	64,0	75,0	113,0	152,0	190,0	207,0	218,0	201,0	155,0	108,0	69,0	54,0	1606,0
RS-FIL	43,1	53,5	86,2	115,5	155,3	158,1	152,8	143,2	117,9	77,2	46,2	37,8	1186,8

*Units in kWh/m^2.

Athens data consists of 11datasets.Where 10 are used since 1 i.e. RS-FIL or RETScreen-Filadelfia was not used due to low irradiation value, pointing to a possible problem.

For Athens Meteonorm offers two data sources, Meteonorm GR and Athinai. RETScreen offers three i.e. Athens/Hellenkion, Athinai (Athens) Observatory and Athinai (Filadelfia). Same as data for Stockholm all data is in kWh/m^2/day and translated in kWh/m^2, besides Meteonorm data, this already is in kWh/m^2.

2.6 Solar irradiation on tilted surfaces, summation

The next step is the calculation of global solar irradiation on tilted surface facing south. It is done in RETScreen, Satel-Light, Meteonorm, SAM, PVGIS and SP EOC v3.0 for tilts of 30°, 45° and 60°, and azimuth 0°.

The data for tilted surface is calculated, since measured solar irradiation data on tilted surface for the examined sites was not found. Moreover, typically in real cases solar systems are tilted.

Calculations are done using each tool/software's inbuilt options. Aiming to provide proper comparison WRDC data (global horizontal solar irradiation)is used as a reference. It is entered in every tool/software and using its calculation model data for tilted surface is obtained and used. Unfortunately some software/tools such as Satel-Light, PVGIS, RETScreen, SAM and SP EOC v3.0 do not provide option to change the solar source data.

Solar irradiation on tilted surfaces is calculated by using software's own sources. Table 24 sums the results for tilted irradiation for Stockholm.

Where with capital letters marked are irradiation sources such as: S-L (Satel-Light), MET. (Meteonorm) SW – Meteonorm SW, MET. Br. – Meteonorm Bromma, RS-KTH – RETScreen KTH, RS-STP. - RETScreen Stockholm etc. With lower letters, marked are the different transposition models, available for appropriate tool/software such as: Gue. – Gueymard, S/O, Skartveit/Olseth etc.

Table 24: Annual solar irradiation for tilted surfaces for Stockholm.

	30°	45°	60°
S-L	1178.2	1205.3	1135.4
PVGIS	1118.3	1131.8	1089.0
MET. SW			
Per.	1179.0	1196.0	1150.0
Hay.	1136.0	1136.0	1082.0
Gue.	1148.0	1152.0	1104.0
S/O	1130.0	1126.0	1063.0
MET. BR			
Per.	1182.0	1198.0	1157.0
Hay.	1137.0	1136.0	1087.0
Gue.	1148.0	1158.0	1107.0
S/O	1130.0	1127.0	1070.0
RS-KTH	1157.7	1172.9	1133.7
RS-STO.	1239.4	1260.0	1221.4
RS-A	1254.9	1293.3	1269.4
RS-B	1244.5	1278.5	1251.1
SAM			
Iso.	1054.6	1051.4	1001.6
Hay.	1096.0	1105.4	1061.5
Rei.	1098.9	1114.0	1078.4
Per. 88	1116.9	1132.7	1091.9
Per. 90	1124.3	1143.2	1105.0
SP EOC	1159.0	1165.0	1119.0

*Units in kWh/m^2.

In similar fashion, solar irradiation data for tilted surface for Athens in obtained and shown in table 25. Red marked is RETScreen's Filadelfia station, which was discarded (showed 28% lower energy than next lowest in series).

Table 25: Annual global solar irradiation for tilted surfaces for Athens.

	30°	45°	60°
S-L	2014,4	1945,8	1778,4
PVGIS	1793,2	1750,1	1613,1
MET. GR			
per.	1873,0	1917,0	1899,0
Hay	1819,0	1846,0	1819,0
gue.	1835,0	1872,0	1853,0
s/o	1816,0	1836,0	1803,0
MET. AT			
per.	1937,0	1986,0	1967,0
Hay	1882,0	1913,0	1883,0
gue.	1901,0	1939,0	1921,0
s/o	1876,0	1903,0	1868,0
RS-HEL	1820,4	1762,3	1617,4
RS-OBS	1737,3	1682,2	1545,4
RS-FIL	1244,1	1191,3	1087.2
SAM			
iso.	1792,4	1723,9	1573,8
hay.	1833,2	1772,0	1619,8
rei.	1837,3	1784,1	1643,5
per. 88	1855,8	1801,6	1653,0
per. 90	1872,4	1824,5	1680,1
SP EOC	1766,0	1716,0	1582,0

*Units in kWh/m^2.

2.7 Data analysis

The variation of data can be divided in variation for horizontal plane and tilted plane. Difference is in the fact that horizontal solar irradiation is measured while tilted irradiation is calculated. Thus tilted irradiation did not have proper reference for comparison, as the horizontal, which used WRDC.

Estimated standard variation is used as a benchmark tool for quantifying degree of variation in both horizontal and tilted solar irradiation. Proper analysis and comparison of data variation is suggested in the following steps:

- ❖ Determine the data source with highest difference from WRDC data in terms of MBE and RMSE;
- ❖ Use PVSYST and Meteonorm in solar simulation for chosen sources.
- ❖ Compare with WRDC data (Simulated in PVSYST and Meteonorm);

Table 26 shows average solar irradiation, S_a and rS_a. The referenced data or WRDC is being used with average, MBE, RMSE and rRMSE.

Table 26: Variation of global solar irradiation for Stockholm.

	Average	*S_a*	*rS_a*
Horz.	984,04	36,57	3,72%
30°	1152,30	51,34	4,46%
45°	1164,11	60,10	5,16%
60°	1119,96	66,29	5,92%
WRDC	975,90	37,55	3,85%
		140,49	14,4%

*Units in kWh/m^2.

MBE is-9 kWh/m^2 or -0.9%, RMSE is 37.6 kWh/m^2 and rRMSE of 3.8%. S_a starts from 36.6till 66.3 with roughly 10 kWh/m^2increases per tilt. rS_a increases steadily from 3.7% to 6.0% with little more than 1% increase per tilt.

The data from WRDC and average are 984 and 976 kWh/m^2 with 8 kWh/m^2 difference (0.8%) and S_a of 36.6 kWh/m^2 and 37.5 kWh/m2 with 1 kWh/m^2 (3%) difference. The natural variation or S_n of WRDC data is 140 kWh/m^2, surpassing variation for any tilt for Stockholm.

In same fashion as in Table 26 for Stockholm, table 27 for Athens is:

Table 27: Variation of solar irradiation for Athens.

	Average	*S_a*	*rS_a*
Horz.	1652,19	73,32	4,44%
30°	1814,07	65,40	3,60%
45°	1757,64	80,50	4,52%
60°	1613,15	116,67	7,02%
WRDC	1597,73	93,12	5,83%
		127,23	7,96%

*Units in kWh/m^2.

MBE is -60,51 kWh/m^2 or -3,8%, while RMSE was 93,12 kWh/m2 or 5.8%. S_a was 73.3 for horizontal and 64.77, 64.76 and 61.2 for 30°, 45° and 60° consequently. rS_a decreased from 4.44% to 3.79% for 60°, being lowest for 45° tilt. WRDC's data and average for horizontal solar irradiation are 1598 and 1652 kWh/m^2 with 54 kWh/m^2 (3%) difference. RMSE and S_a, 93 kWh/m^2 and 70 kWh/m^2 with 23 kWh/m^2 difference.

The natural variation of WRDC data estimated standard deviation was 127 kWh/m^2, which is lower than the one of Stockholm (140 kWh/m^2).

Furthermore form each dataset three values are chosen, that exhibit maximum variation, in terms of MBE and RMSE, from WRDC referent data. For these, equations 3.1 and 3.2 are used. They describe the extent of variation of each dataset from the reference on monthly or yearly basis.

The analysis of MBE and RMSE for Stockholm from WRDC's data is shown in Table 28. Notably the highest variation from WRDC in term of MBE and RMSE was for NASA's SSE, RETScreen Stockholm and SAM data sources.

Table 28: Variation of horizontal global solar irradiation for Stockholm using MBE and RMSE.

	MBE	*RMSE*
SSE	**6.17**	**7.13**
S-L	1.08	4.30
PVGIS	-3.12	4.91
MET. SW	0.26	1.00
MET. BR	0.26	1.00
RS-KTH	-0.21	0.35
RS-STO.	**4.64**	**8.31**
RS-A/B	2.64	4.98
SAM	**-4.51**	**6.71**
SP EOC	0.26	6.46

*Units in kWh/m^2.

For Athens in same fashion as in Table 28, analysis of MBE and RMSE for Athens is done and shown in Table 29. Thus Satel-Light and SAM show highest variation from WRDC data. Only two sources were chosen since, they all exhibited positive difference.

Table 29: Variation of horizontal global solar irradiation for Athens using MBE and RMSE.

	MBE	*RMSE*
SSE	6,05	7,92
S-L	**20,22**	**23,12**
PVGIS	0,99	2,58
MET. GR	0,77	3,25
MET. AT	4,69	4,95
RS-HEL	6,07	7,88
RS-OBS.	-0,08	0,18
SAM	**5,99**	**8,75**
SP EOC	0,69	6,02

*Units in kWh/m^2.

2.7.1. Meteonorm and PVSYST simulations

Meteonorm and PVSYST were used to simulate data that showed maximum deviation from WRDC data. This is done to examine how S_a and rS_a behave with tilt increase. Procedure is:

- Average global horizontal monthly irradiation in kWh/m^2 was entered for both tools;
- Ground reflected irradiation coefficient of 0.20 was set;
- Simulations were done for each tilt using available transposition model:
  - Hay and Perez-Inchen for PVSYST,
  - Perez, Hay, Gueymard, Skartveit/Olseth for Meteonorm.

Since solar irradiation data from WRDC shows only global horizontal irradiation, PVSYST and Meteonorm first divide the data into global and diffuse, then use transposition model to calculate data on given tilt.

To eliminate errors due to different input data, global horizontal irradiation data from every source exhibiting difference from WRDC's data was entered separately.

For Stockholm as seen in Table 28maximum variation from WRDC data was noted for NASA's SSE (-7.6%), RETScreen's Stockholm (-5.7%) and SAM (5.5%). Positive values show that WRDC has higher value for the given fraction, and vice versa for negative values. In same fashion for Athens, following Table 29, maximum variation is noted for Satel-Light (-15,2%) and SAM (-4.5%).

2.7.1.1 PVSYST

It is used as simulation tool/software for testing data variation on tilted surfaces. It offers two transposition models, Hay and Perez-Inchen and optional input for monthly ground reflected radiation in term of fixed number from 0.00 to 1.00.

The procedure for entering data is not complex. Firstly data in form of monthly/daily average horizontal irradiation is entered. Next data location is entered in form of latitude, longitude and elevation. Last, data is simulated for horizontal irradiation and tilted surfaces of 30°, 45° and 60°. Procedure was repeated for both models Hay's and Perez-Inchen's.

Table 30 and 31 show summation of simulated solar irradiation for Stockholm and Athens accordingly, using PVSYST as simulation software. Data sources that show biggest difference from average are NASA's SSE, SAM and RETScreen. For Athens they are: Satel-Light and SAM.

H.-30 means usage of Hay's transposition model for surfaces with tilt of 30°, Ave.-30 means average solar irradiation on surface with tilt 30° etc.

Where data from NASA's SSE, SAM and RETS. STO. (RETScreen Stockholm) is compared to WRDC data. The difference in percentage is shown, where negative values denote that WRDC is smaller and positive larger. Example, SAM's average value for 30° tilt is 7.3% meaning SAM data is 7.3% lower than the WRDC data which has average solar irradiation of 1088.4 kWh/m^2 (30° tilt).

Table 30: Simulation of global solar irradiation on tilted surface in PVSYST for Stockholm.

	WRDC	*NASA SSE*	*SAM*	*RETS. STO*
Horizontal	975.9	-7.6%	5.5%	-5.7%
H. - 30	1160.7	-10.7%	7.3%	-5.0%
P-I - 30	1187.4	-10.6%	7.3%	-4.4%
Ave. -30	1174.1	-10.7%	7.3%	-4.7%
S– 30	13.3	-6.7%	8.6%	21.3%
H. – 45	1171.8	-11.8%	7.7%	-4.6%
P-I - 45	1207.6	-11.8%	7.8%	-5.0%
Ave. -45	1189.7	-11.8%	7.8%	-4.8%
S-45	17.9	-10.1%	11.2%	-16.5%
H. - 60	1126.4	-12.8%	8.1%	-4.3%
P-I - 60	1167.0	-12.7%	8.2%	-4.7%
Ave.-60	1146.7	-12.7%	8.1%	-4.5%
S-60	20.3	-11.3%	12.6%	-16.0%

*Units in kWh/m^2.

Table 31: Simulation for global solar irradiation on tilted surfaces using PVSYST for Athens.

	WRDC	*S-L*	*SAM*
Horizontal	1597,6	-15,2%	-16,3%
H. – 30	1742,0	-16,3%	-4,4%
P-I – 30	1781,7	-16,3%	-4,5%
Ave. -30	1761,9	-16,3%	-4,4%
S- 30	19,9	-17,6%	-7,8%
H. – 45	1681,6	-16,4%	-4,3%
P-I - 45	1734,4	-16,5%	-4,4%
Ave. -45	1708,0	-16,5%	-4,3%
S- 45	26,4	-21,0%	-8,5%
H. - 60	1539,0	-16,2%	-4,1%
P-I - 60	1597,4	-16,5%	-4,3%
Ave. -60	1568,2	-16,4%	-4,2%
S- 60	29,2	-25,3%	-9,8%

*Units in kWh/m^2.

2.7.1.2 Meteonorm

Meteonorm is a data tool that provides access to data that is measured and/or interpolated for custom locations. It offers four transposition models and optional input for monthly ground reflected radiation, in term of fixed number from 0.00 to 1.00. It also has mean for calculation of ground albedo, based on average temperature (not used for proper data comparison to be done).

The procedure for entering data was not complex. First data in form of monthly/daily average horizontal irradiation is entered. Next data location is entered in form of latitude, longitude and elevation. Software splits horizontal solar irradiation into beam and diffuse part and calculates data on tilted planes.

Tilts of 30°, 45° and 60°are used with surface facing south. The procedure is repeated for every transposition model available.

Tables 32 and 33 show summation of results. For every data source RMSE, tilt and transposition model is calculated and shown. Data for WRDC is in kWh/m^2

and for other sources is in fractions (positive or negative) from WRDC data, as explained before.

Table 32: Simulation for global solar irradiation on tilted surfaces using Meteonorm for Stockholm.

	WRDC	*NASA SSE*	*SAM*	*RETS. STO*
Horizontal	979,0	-7,2%	5,7%	-5,2%
P. - 30	1228,0	-11,6%	6,4%	-5,3%
H. - 30	1183,0	-11,5%	6,5%	-5,5%
G. - 30	1197,0	-11,6%	6,8%	-5,5%
S/O - 30	1177,0	-11,6%	6,5%	-5,6%
Ave. -30	1196,3	-11,6%	6,5%	-5,5%
S- 30	19,7	-14,5%	3,1%	1,2%
P. - 45	1301,0	-12,9%	6,8%	-5,4%
H. - 45	1239,0	-12,8%	6,6%	-5,6%
G. - 45	1258,0	-13,0%	7,0%	-5,4%
S/O – 45	1226,0	-13,1%	6,7%	-5,8%
Ave. -45	1256,0	-13,0%	6,8%	-5,5%
S- 45	28,4	-11,7%	8,6%	0,5%
P. – 60	1331,0	-13,8%	6,8%	-5,2%
H.– 60	1260,0	-13,4%	6,7%	-5,3%
G. – 60	1280,0	-14,1%	7,0%	-5,4%
S/O – 60	1237,0	-14,1%	6,6%	-5,7%
Ave. -60	1277,0	-13,9%	6,8%	-5,4%
S- 60	34,7	-13,9%	8,6%	0,9%

*Units in kWh/m^2.

Table 33: Simulation for global solar irradiation on tilted surfaces using Meteonorm for Athens.

	WRDC	*S-L*	*SAM*
Horizontal	1597,0	-15,2%	-4,6%
P. - 30	1861,0	-16,5%	-4,6%
H - 30	1812,0	-16,4%	-4,4%
G. - 30	1829,0	-16,5%	-4,4%
S/O - 30	1807,0	-16,4%	-4,3%
Ave. -30	1827,3	-16,4%	-4,4%
S- 30	21,1	-19,3%	-12,7%
P. - 45	1909,0	-16,4%	-4,2%
H - 45	1842,0	-16,3%	-4,0%
G. - 45	1868,0	-16,5%	-4,0%
S/O - 45	1831,0	-16,6%	-4,0%
Ave. -45	1862,5	-16,5%	-4,1%
S- 45	30,0	-16,0%	-9,1%
P. - 60	1892,0	-16,2%	-4,0%
H - 60	1816,0	-16,0%	-3,5%
G. - 60	1847,0	-16,4%	-3,9%
S/O - 60	1799,0	-16,3%	-3,8%
Ave. -60	1838,5	-16,2%	-3,8%
S- 60	35,4	-16,7%	-9,4%

*Units in kWh/m^2.

For the Station of Athinai, Athens solar irradiation was simulated with fixed albedo of 0.20 and with functional dependence as the software offers. Resulting table is shown in Table 34.

Table 34: Comparison of global solar irradiation for tilted surfaces with albedo of 0.20 and with functional dependence of ambient temperature for Athens, Athinai station.

	0.20	*func.*	*Diff*
P. - 30°	1873	1800	-4.1%
P. - 45°	1917	1753	-9.4%
P. - 60°	1899	1620	-17.2%
H. - 30°	1819	1744	-4.3%
H. - 45°	1846	1684	-9.6%
H. - 60°	1819	1539	-18.2%
G - 30°	1835	1762	-4.1%
G - 45°	1872	1707	-9.7%
G - 60°	1853	1569	-18.1%
S/O - 30°	1816	1738	-4.5%
S/O - 45°	1836	1670	-9.9%
S/O - 60°	1803	1519	-18.7%

*Units in kWh/m^2.

Notably the simulated solar irradiation with functional dependence is 10.6% less than compared with fixed albedo of 0.20.

2.8 Exact Location

Exact choice of location is an ambiguous decision, since some places refer to wider physical area. Airports are often chosen as locations for putting sensors for metering solar irradiation.

Meteonorm and RETScreen offer multiple locations for same place as source of solar irradiation data. For Stockholm are Arlanda and Bromma, which are airports nearby Stockholm. For Athens Filadelfia and Observatory denoting airport and observatory consequently.

Typical information available from every data sources is location in latitude and longitude and terrain elevation. Distance from each of the locations from WRDC location is noted and used to compare with the appropriate annual solar irradiation. This is summed and shown in Table 35 and 36.

Table 35: Latitude, longitude, altitude, horizontal global solar irradiation and difference from WRDC data for Stockholm.

	latitude(°)	*longitude(°)*	*elevation(m)*	*km*	*kWh/m2*	*dG*[3]
WRDC	59,35	18,07	30	0,0	975,9	-
SSE	59,35	18,07	14	0,0	1049,9	74,0
S-L	59,32	18,05	16	3,5	988,9	13,0
PVGIS	59,35	18,07	44	0,0	938,5	-37,4
MET. SW	59,35	18,08	15	0,6	979,0	3,1
MET. BROM.	59,35	17,95	11	6,8	979,0	3,1
RET.KTH.	59,40	18,10	30	5,8	973,4	-2,5
RET. STO.	59,10	18,10	44	28,0	1031,5	55,6
RET. ARL.	59,70	18,00	61	39,0	1007,5	31,6
RET.BRO.	59,40	17,90	14	11,1	1007,5	31,6
SAM	59,65	17,95	61	34,0	921,8	-54,1

[3]dG denotes the difference in solar irradiation between WRDC and required source, ex. dG(SAM)=Gsam-Gwrdc

Table 36: Latitude, longitude,altitude, horizontal global solar irradiation and difference from WRDCdata forAthens.

	latitude(°)	*longitude(°)*	*elevation(m)*	*km*	*kWh/m2*	*dG*
WRDC	37,97	23,72	107	0,0	1597,7	-
SSE	37,50	23,50	65	55,0	1670,3	72,6
S-L	37,97	23,72	110	0,0	1840,3	242,6
PVGIS	37,97	23,72	101	0,0	1609,6	11,9
MET. GR	38,00	23,73	0	115,0	1607,0	9,3
MET. ATI.	37,97	23,72	107	0,0	1654,0	56,3
RETS.HEL.	37,90	23,70	15	8,0	1670,6	72,8
RETS. OBS	38,00	23,70	107	28,0	1596,8	-0,9
RETS. FIL.	38,10	23,70	138	14,0	1186,8	-410,9
SAM	37,95	23,73	15	2,4	1669,6	71,8

3 Discussion and conclusion

Firstly list of data sources is made and used as inputs for initial assessment. However, it is apparent that for proper and correct comparison more specific boundaries have to be brought. This is due to sole reason of genuine discrepancies existing in solar irradiation data. And those boundaries have to be set in a way that result will not be ambiguous. For example solar irradiation can have simulated or measured values, can originate from satellite or ground station or hybrid datasets. They can have fixed or calculated albedo, use different radiation and transposition models.

Goal of variation assessment in solar irradiation data sources is achieved through comparison with data with least inter-annual variation. Therefore WRDC data is chosen as a reference and used for comparison. Also for Stockholm and Athens, MBE and RMSE are calculated. Their purpose is to effectively show which data sources exhibit maximum variation (positive and negative) from the referenced data.

Tilted solar irradiation, on the other hand, is simulated and cannot be compared with measured, existing data. For that purpose, simulation softwares which allow different solar irradiation data to be entered, simulated and used. That is PVSYST and Metonorm.

Variation is being assessed with the usage of estimated standard variation of S_a and S_n and their relative values with their averages.

WRDC data itself has two types of estimated standard variations, S_a and S_n. S_n represents estimated standard variation due to inter-annual variability of data or natural variation, while S_a represents annualized estimated standard deviation. For example S_a for tilted solar irradiation for 45° for Athens represents estimated standard variation from all data sources being compared using annual solar irradiation. Relative S_a or rS_a and rS_n are also used as comparison between estimated standard deviation and average value of data compared i.e. rS_n for S_n of 100 kWh/m^2 and average yearly value of 1000 kWh/m^2 is 10%.

For horizontal solar irradiation, data was gathered as available/presented from the sources. While for tilted surfaces, it is calculated using each data tool/software source and models and albedo of 0.20.

Next for horizontal solar irradiation MBE and RMSE are calculated. The data with largest variation, from WRDC data, is entered into data tools/softwares, where is simulated with available models. This helps avoid variation due to different models and softwares/tools. Finally data is compared using S_a and rS_a.

Horizontal solar irradiation is important parameter, since as mentioned its basis for further calculations and it's shown in Figure 6. Stockholm has one more data source i.e. RETScreen's Broma. Where MET. SW is data from Meteonorm for Stockholm. MET. GR is referring to Meteonorm data for Athens. MET 1 is Broma and Athinai (Athens).

RS-1 is RS-KTH and RS-HEL., RS-2 is RS-STO., RS-OBS. and RS-3 is RS-Arlanda/Bromma and RS-FIL. Notable is data for RETScreen's Filadelfia (RS-FIL.) for Athens, which is substantially lower that other data sources for Athens.

Generally variation of horizontal solar irradiation for Athens is higher.

The step of calculation of solar irradiation on tilted surfaces with all available transposition models for every software/tool is given in Figure 7.

Notably for Stockholm global solar irradiation of 45° tilt is highest, while Athens exibits highest irradiation for 30° tilt, except Meteonorm data which shows highes values for 45° tilt.

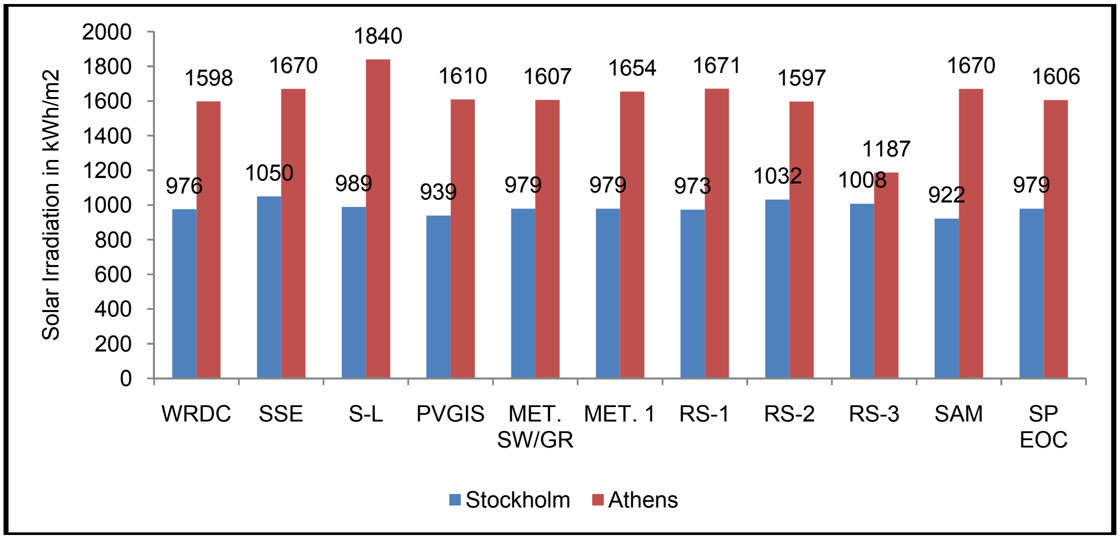

Figure 6: Horizontal global solar irradiation for Stockholm and Athens.

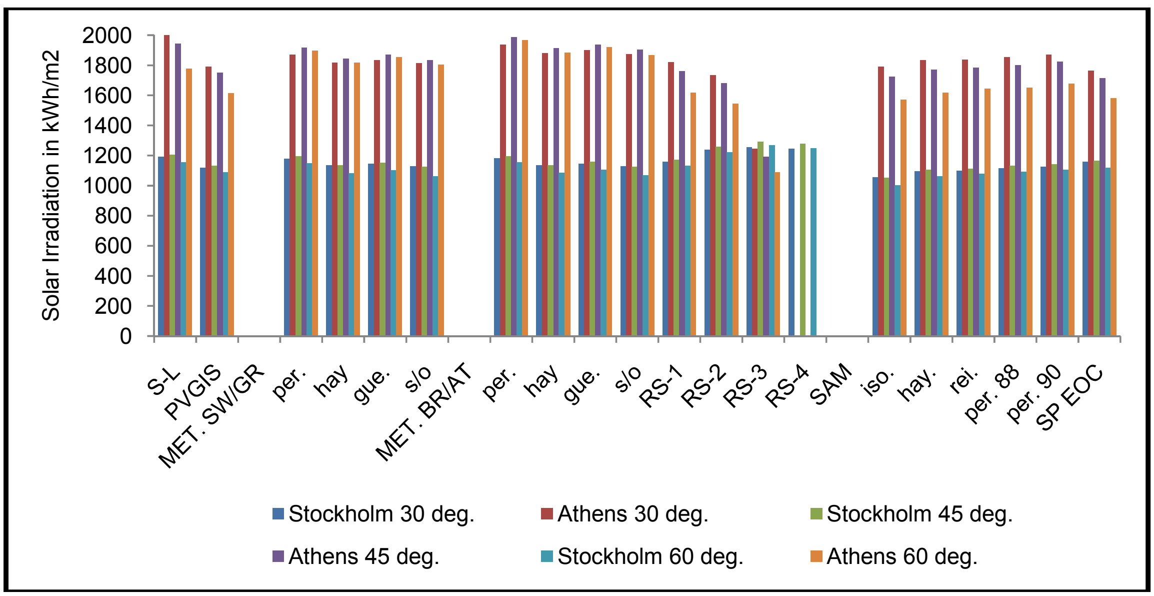

Figure 7: Solar irradiation on tilted surfaces for Stockholm and Athens.

Subsequently, for both sitesaverage global solar irradiation data for horizontal and tilted planes with tilts of 30°, 45° and 60°, S_a and rS_a is given in Figure 8, shown below.Dashed line divides WRDC's data from rest of the figure. Also, WRDC data has two sub-columns, left showing annual solar irradiaiton for Stockholm and Athens, RMSE in and rRMSE and right S_n and rS_n.

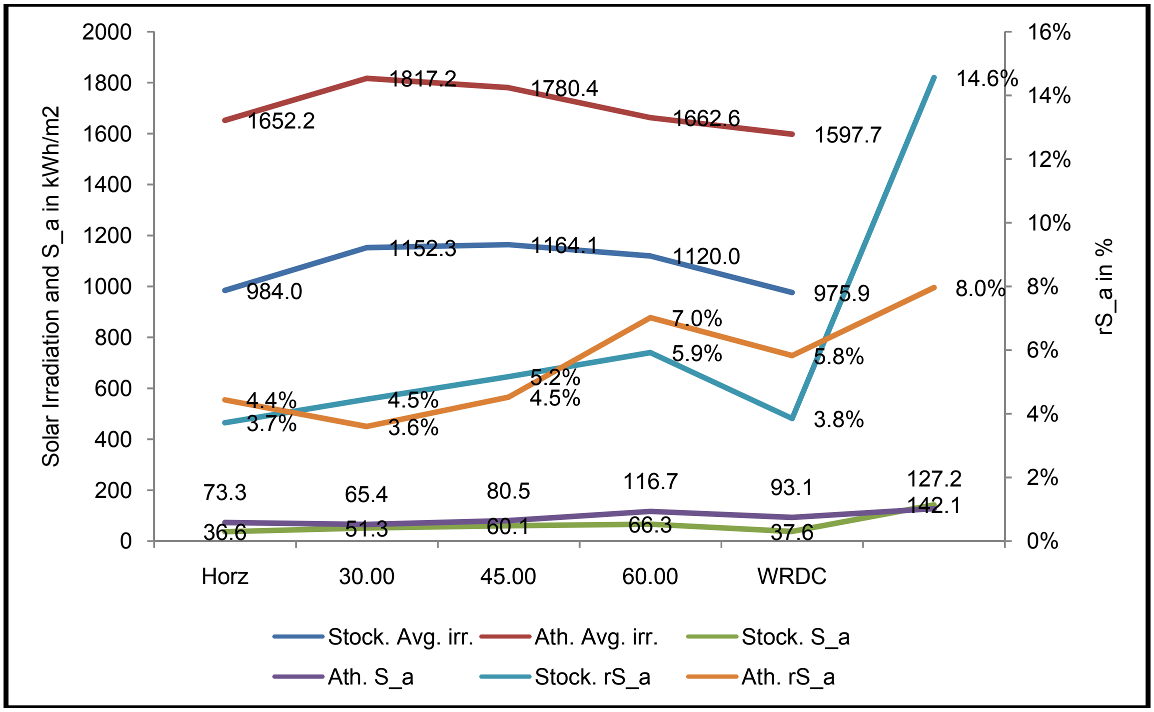

Figure 8: Average, S_n, S_a, rS_n and rS_afor global solar irradiation for Stockholm and Athens.

As can be seen, for Stockholm, estimated standard deviation and its relative value rS_a are highest for 60° tilt or 5.9% and varies from 3.7% to 5.9% as tilt increases. Relative value of estimated standard deviation of inter-annual variation of WRDC data or rS_n is 14.6% and is substantialy higher than other variations, due to different tilt or model.

Athens on the otherhand, exibits highest energy for 30° tilt, with highest rS_a for 60° tilt or7.0% and varies from 3.6% to 7.0%. Unlike Stockholm, which shows continuous increase in variation, Athens's data has changing behaviour, i.e. it's 4.4% rS_a for horizontal irradiation, than lowers to 3.6% for 30° tilt, for 45° increases to 4.5% andfor 60°to 7.0%. For Athens rS_nis 8.0%. It is notable that variation of solar irradiation data for both location generally increases with tilt and is lower than inter-annual variation.

Calculating MBE and RMSEusing equation 3.1 and 3.2 for data from various sources is shown on figure9. As notable solar irradiation data from SSE, SAM and RETScreen for Stockholmexibit highest difference from WRDC data. For Athens it's Satel-Light and SAM.

Thus sources exibiting highest difference from WRDC,are used as basis for calculation of irradiation on tilted surfaces using different models in PVSYST and Meteonorm.

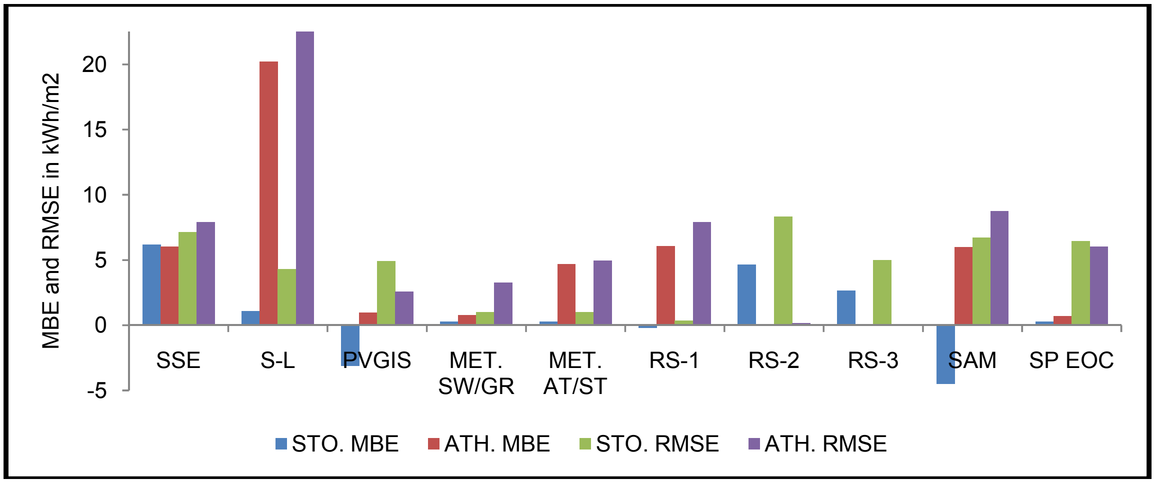

Figure 9: MBE and RMSE for Stockolm and Athens in kWh/m^2.

Using PVSYST and Meteonorm with radiation models they offer, irradiation on tilted surfaces is being calculated for WRDC's data as basis for comparison.

As seen from Figure 9, NASA's SSE, RS-2 and SAM for Stockholm and Satel-Light and SAM for Athens exibit highest variation. Notable is that WRDC's data is lowest for Athens, while for Stockholm PVGIS, RS-1 and SAM are lowest.

PVSYST offered transposition models of Hay and Perez-Ineichen, while Meteonorm uses Perez, Hay, Guyemard and Skartveit/Olseth.Figures 10 and 11 show calculation of tilted irradiation using PVSYST and Meteonorm with WRDC as basis,with all available transposition models, for Athens and Stockholm.

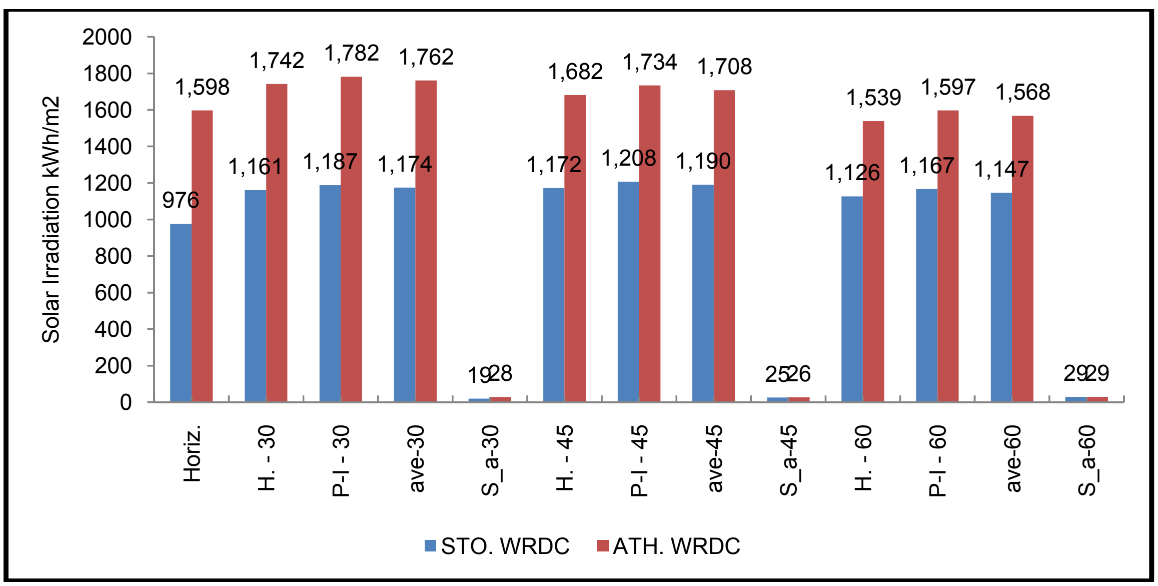

Figure 10: PVSYST simulation of global solar irradiation using WRDC data as basis for calculations, for Stockholm and Athens.

Where H.-30 denotes Hay's model for 30° tilt, P-I-60 denotes Pierre-Inichen model for 60° tilt etc.

In same fasion solar irradiation is simulated in Meteonorm with WRDC as basis. And P.-30 means simulation done using Perez model for 30° tilt, G.-45 means simulation using Guyemard model for 45° tilt etc.

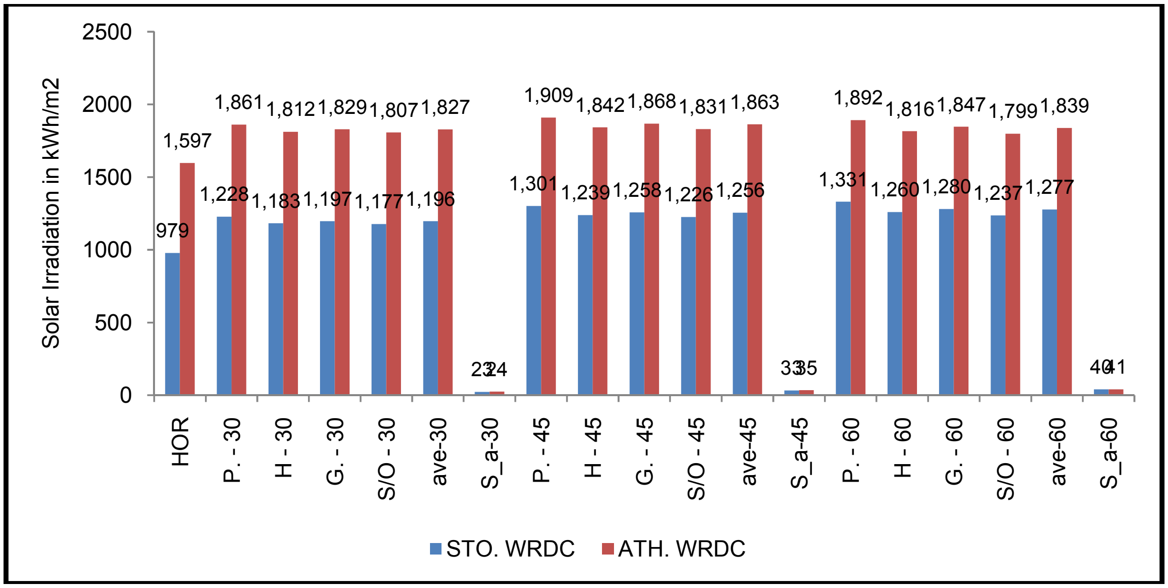

Figure 11: Meteonorm simulation of global solar irradiation using WRDC data as basis for calculation, for Stockholm and Athens.

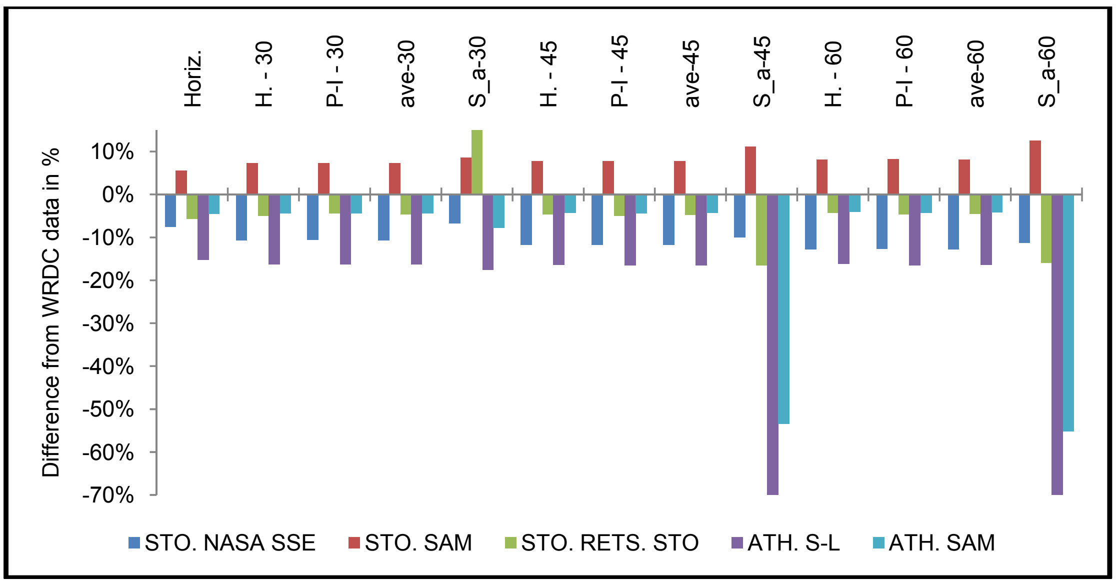

Figure 12: PVSYST simulation-comparison with WRDC data, for Stockholm and Athens, for global horizontal and on tilted surfaces, solar irraidation.

Figures 12 and 13 show the simulated solar irradiation, using PVSYST and Meteonorm, subsequently for data sources that show highest variation in MBE and RMSE from WRDC data.

They are graphical depiction of Tables 28 and 29 for PVSYST and 30 and 31 for Meteonorm. They exibit variation in fractions from data for horizontal surface or WRDC's data, as shown in figures 10 and11. Example Ave.-30 for Stockholm SAM is 7% meaning average solar irradiation for Stockholm with 30° tilt (Figure 11) is 7% higher than the one from PVSYST.

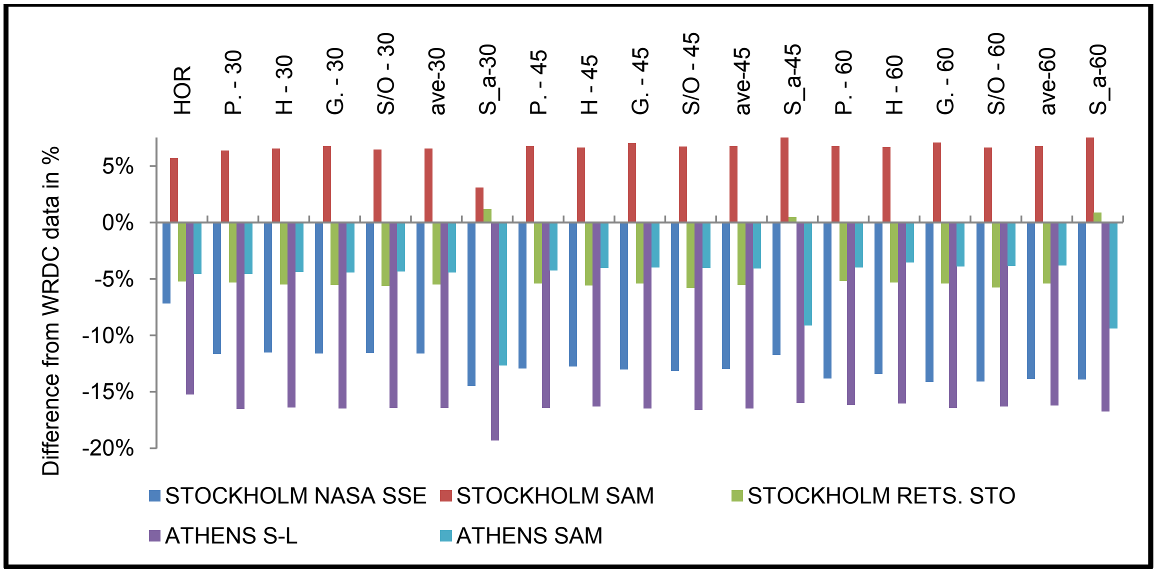

Figure 13: Meteonorm simulation for Stockholm and Athens, for horizontal and tilted surfaces for 30°, 45° and 60°, units in kWh/m^2.

Significant is that variationin solar irradiation, in terms of difference from referent values, for both sites increases constantly withlow increase per tilt of around 1-2%.

Thus main source of difference is different source data used for calculations. Notable S_a for Athens for 45º and 60º is significantly higher, suggesing larger variations with tilt increase.

Also, highest variation in solar irradiation data does not occur due to different radiation models. Its due to difference in solar irradiation sources itself, i.e. the data for solar irradiation for horizontal plane (typ. global solar irradiation in daily or mothly averages).

Inter-annual variation for both location, from WRDC's data source is higher than variation of data as used from different sources, for horizontal plane and plane with tilt of 30°, 45° and 60°. It is important to further examine the variation in smaller time steps, than hourly. The albedo dependance with real-time values for both locations and also the albedo dependance on ambient temperature.

Concluding, variation in solar irradiation (global) shows highest difference due to inter-annual variation. Thus regardless what simulation software, data tool or source is used for data obtaining, the variation will be less than the natural variation of the data itself

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5 Appendix, solar irradiation data for Athens

Table 37: NASA SSE - horizontal global solar irradiation and S_n for Athens.

	global	*S_n*
Jan	66.5	17.4
Feb	80.6	21.3
Mar	124.0	33.3
Apr	161.0	38.7
May	199.3	46.3
Jun	224.0	50.5
Jul	228.0	11.2
Aug	205.7	10.7
Sep	155.8	10.8
Oct	106.3	11.5
Nov	65.3	8.7
Dec	53.9	6.8
Year	1670.3	267.3

*Units in kWh/m^2.

Table 38: Satel-Light - horizontal global solar irradiation for Stockholm.

	global	*diffuse*
Jan	68.85	37.73
Feb	91.14	45.61
Mar	123.72	63.86
Apr	175.11	78.66
May	221.93	92.19
Jun	247.95	87.36
Jul	255.53	84.91
Aug	225.96	82.03
Sep	169.71	70.20
Oct	121.21	57.38
Nov	78.57	40.95
Dec	60.64	34.75
Year	1840.32	775.63

*Units in kWh/m^2.

Table 39: Satel-Light –solar irradiation for tilted surfaces for Athens (albedo 0.20).

	30°		*45°*		*60°*	
	Global	*Diffuse*	*Global*	*Diffuse*	*Global*	*Diffuse*
Jan	99.2	43.2	106.8	43.7	108.5	42.6
Feb	120.5	50.6	125.9	50.6	124.4	48.9
Mar	144.1	66.3	143.3	64.4	135.2	60.4
Apr	184.0	78.9	174.3	75.5	155.9	70.1
May	214.8	89.4	195.0	84.4	166.0	77.4
Jun	229.8	83.5	203.4	78.8	167.9	72.5
Jul	242.0	82.2	216.3	78.1	180.6	72.4
Aug	232.0	82.7	216.5	79.7	189.9	74.6
Sep	193.8	74.1	190.5	72.7	177.0	69.1
Oct	154.3	63.1	158.9	62.9	154.8	60.6
Nov	110.8	46.9	118.4	47.4	119.4	46.3
Dec	89.1	40.0	96.6	40.5	98.7	39.6
Year	2014.4	801.1	1945.8	778.8	1778.4	734.8

*Units in kWh/m^2.

Table 40: PVGIS – horizontal solar irradiation for Athens.

	global	*diffuse*
Jan	63.9	32.6
Feb	73.9	37.7
Mar	120.0	56.4
Apr	157.2	66.0
May	193.4	77.4
Jun	211.8	74.1
Jul	216.1	75.6
Aug	193.4	67.7
Sep	153.9	52.3
Oct	106.3	45.7
Nov	65.1	33.2
Dec	54.6	29.5
Year	1609.6	648.2

*Units in kWh/m^2.

Table 41: PVGIS –global solar irradiation for tilted surfaces for Athens.

	30º global	*45º* global	*60º* global
Jan	95.2	103.5	106.3
Feb	97.4	101.9	101.1
Mar	142.0	142.9	135.8
Apr	167.7	160.5	144.9
May	189.7	173.9	149.4
Jun	199.2	178.2	148.2
Jul	207.1	186.9	157.5
Aug	200.9	188.8	166.5
Sep	180.3	179.1	167.7
Oct	138.9	144.5	142.0
Nov	92.4	99.6	100.8
Dec	82.5	90.2	93.0
Year	1793.2	1750.1	1613.1

*Units in kWh/m^2.

Table 42: Meteonorm – horizontal solar irradiation for Athens.

	Athens GR		*Athiani*	
	global	diffuse	global	diffuse
Jan	64	32	62	33
Feb	75	40	77	38
Mar	113	65	122	60
Apr	152	73	158	76
May	191	80	200	80
Jun	207	78	215	75
Jul	218	74	223	74
Aug	201	70	202	69
Sep	155	60	156	54
Oct	108	51	111	44
Nov	69	34	72	30
Dec	54	30	56	27
Year	1.607	687	1.654	660

*Units in kWh/m^2.

Table 43: Meteonorm – global solar irradiation for tilted surfaces for Athens (Athens GR).

	Perez			*Hay and Davies*			*Gueymard*			*Skartveit/Olseth*		
	30°	45°	60°	30°	45°	60°	30°	45°	60°	30°	45°	60°
Jan	20	24	27	18	21	22	19	22	24	18	20	22
Feb	46	53	57	42	47	49	44	49	52	42	46	48
Mar	98	106	108	94	100	100	95	102	103	93	99	99
Apr	136	138	133	131	132	126	132	134	129	130	131	124
May	179	174	160	174	168	154	175	169	156	174	167	152
Jun	182	174	158	179	169	153	179	170	154	178	168	150
Jul	174	167	152	171	162	148	171	163	148	170	161	145
Aug	151	150	142	147	145	136	148	146	138	146	144	134
Sep	105	111	110	100	104	103	102	106	105	100	103	101
Oct	55	60	62	51	55	56	52	56	58	50	54	54
Nov	21	24	25	19	21	22	20	22	23	19	21	21
Dec	12	15	16	10	12	13	11	13	14	10	12	13
Year	1179	1196	1150	1136	1136	1082	1148	1152	1104	1130	1126	1063

*Units in kWh/m^2.

Table 44: SP EOC v3.0 – global solar irradiation for horizontal and tilted surfaces for Athens.

	Horiz. global	*30°* global	*45°* global	*60°* global
Jan	64.0	98.0	107.0	111.0
Feb	75.0	101.0	106.0	105.0
Mar	113.0	128.0	127.0	119.0
Apr	152.0	158.0	150.0	135.0
May	190.0	183.0	166.0	142.0
Jun	207.0	191.0	170.0	141.0
Jul	218.0	203.0	181.0	151.0
Aug	201.0	204.0	190.0	167.0
Sep	155.0	178.0	176.0	164.0
Oct	108.0	141.0	147.0	145.0
Nov	69.0	99.0	106.0	108.0
Dec	54.0	82.0	90.0	94.0
Year	1606.0	1766.0	1716.0	1582.0

*Units in kWh/m^2.

In table 45 shown are 1 – Athens/Hellenkion, 2 – Athiani Observatory and 3 – Athinai Filadelfia. Notable is the lowered value of Athinai Filadelfia station.

Table 45: RETScreen –Global horizontal irradiation for Athens.

	1	2	3
Jan	66.3	58.9	43.0
Feb	80.6	73.3	53.4
Mar	124.0	116.8	86.1
Apr	161.1	153.3	115.5
May	199.3	194.0	155.3
Jun	223.8	209.4	158.1
Jul	228.1	216.0	152.8
Aug	205.2	194.3	143.2
Sep	156.3	150.6	117.9
Oct	106.6	107.2	77.1
Nov	65.4	68.7	46.2
Dec	53.6	53.9	37.8
Year	1670.5	1596.8	1186.8

*Units in kWh/m^2.

Table 46: RETScreen–global solar irradiation for tilted surfaces for Athens.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
Athn., Hell.													
30°	98.7	105.9	144.0	168.5	191.4	206.2	214.0	208.0	177.2	134.5	92.3	79.7	1820.4
45°	107.4	110.6	143.4	159.8	174.2	183.2	191.9	193.7	174.0	138.4	98.8	86.9	1762.3
60°	110.2	109.5	135.7	143.4	149.0	152.6	161.2	169.7	161.7	135.0	100.1	89.4	1617.4
Athi., Obs.													
30°	84.3	94.3	134.6	159.9	186.4	193.4	203.0	196.7	170.0	135.6	98.6	80.5	1737.3
45°	90.8	97.9	133.7	151.5	169.8	172.5	182.4	183.2	166.8	139.6	106.1	87.9	1682.2
60°	92.5	96.4	126.4	136.1	145.5	144.4	153.8	160.8	155.0	136.3	107.8	90.5	1545.4
Athi.,Fil.													
30°	55.0	63.4	94.7	118.2	149.3	147.4	144.5	143.3	129.3	91.1	58.2	49.7	1244.1
45°	57.4	64.2	92.8	111.8	136.7	132.9	131.3	133.7	125.9	92.0	60.4	52.4	1191.3
60°	57.0	62.1	86.9	100.7	118.4	113.4	113.1	118.3	116.6	88.5	59.7	52.5	1087.2

*Units in kWh/m^2.