A METHOD FOR GENERATING HOURLY SOLAR RADIATION ON BUILDING ROOFTOPS ACCOUNTING FOR CLOUD COVER VARIABILITY

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ABSTRACT

Building Integrated Photovoltaic systems (BIPV) are gaining popularity as urban energy systems move towards decentralization. The calculation of the incoming solar radiation for building rooftops at a high temporal resolution is a key input to perform an energy balance of buildings within the larger context of an urban energy planning exercise and to control the supply and demand of energy. Solar radiation on building rooftop surfaces is highly stochastic due to highly variable cloud cover. Hence, for improving the accuracy in calculating the energy potential of BIPV, it is important to incorporate varying cloud cover in the simulation approach. This study presents a GIS based methodology for calculating hourly solar radiation on building rooftop surfaces taking into account the variability in cloud cover. The location of the study is the Fluntern weather station in Zürich, Switzerland. The r.sun module of the open source GIS software suit GRASS is used to calculate the clear sky irradiation (CSR). To account for the cloud cover, a reduction factor called the clear sky index (KC) which is dependent on the cloud cover is applied to the calculated CSR to obtain the real sky radiation. KC is calibrated for different values of cloud cover and time of day using measured meteorological data spanning a time period from 1981 to 2014 from the weather station. The hourly cloud cover is predicted through a discrete state Markov process. KC, the measured cloud cover, the simulated clear sky radiation are then used to obtain the real sky radiation and is validated against the measured values of solar radiation. Results show that the taking into account the cloud cover for calculating radiation reduces the root mean square error and the mean bias deviation by 37% and 86% respectively.

Keywords: Building Integrated Photovoltaics, GIS, Cloud cover, Rooftop solar

INTRODUCTION

As solar technology matures, Building Integrated Photovoltaic (BIPV) systems are becoming more frequently installed. These systems can be installed on building rooftops due to large area availability and be used for the production of a part of a building's electricity and/or heating needs. A detailed energy production profile from the BIPV system is an important input to the design and operation of a building's energy system which consists of multiple energy consuming and producing devices. Hence, it is important to have the knowledge of the amount of solar radiation received by the rooftops at a high temporal resolution. Although the extraterrestrial solar radiation remains constant, the terrestrial radiation exhibits spatial and temporal variability. This variability in solar radiation can be attributed to three factors as listed by Hofierka and Šúri [1]. Firstly, the sun's location in the sky which has a daily as well as a seasonal cycle given a particular geographical location. Secondly, it is affected by the local topography, the orientation of the surface and shadowing effects from neighboring structures. Thirdly, the atmospheric attenuation caused by scattering and absorption by particles and clouds in the local sky cause the radiation to become highly variable. The high intermittency of the solar radiation can be attributed to the stochastic nature of the local atmospheric conditions especially cloud cover. This emphasizes the need for incorporating the cloud cover variability in the calculation of the net solar radiation received by rooftops.

There are several studies conducted in the past that utilize a Geographical Information System (GIS) based approach to calculate solar radiation for building rooftops [2-6]. Chow and Fung [2] use a 2.5D Digital Elevation Model (DEM) to represent the local topography and the building topologies. They use a hemispherical viewshed algorithm implemented in Esri's Solar Analyst plugin, to calculate hourly solar radiation taking into account local terrain effects. Atmospheric conditions are modeled using constant values of transmissivity and diffuse proportions. Kodysh et.al. [3] use the same algorithm using a LiDAR based DEM for daily/monthly averages of solar radiation. Agugiaro et. al. [4] use the *r.sun* algorithm [1] implemented in the GRASS GIS open source software suit for spatial analysis. It is also a DEM based algorithm which takes into account the local terrain and shadowing effects. Local atmospheric conditions are modeled using a parameter named Linke Turbidity. Jakubiec and Rheinhart take in their study [6] a different approach towards computing hourly solar radiation on building rooftops. They use a 3D model of the buildings and a Typical Meteorological Year (TMY) instead of a DEM and a ray tracing algorithm called DaySim. The hourly cloud cover is not modeled in any of the listed studies to calculate the solar radiation.

METHOD

Against this background, a method is developed to compute hourly solar radiation on rooftop surfaces taking a DEM based approach. The *r.sun* algorithm is applied to calculate the clear sky radiation on building's rooftop surfaces. To further compute real sky radiation data taking variations of cloud cover over the year into account, an attenuation factor called the clear sky index (K_C) is used which is calibrated with available measurement data from a nearby weather station. Available past data on cloud cover for the specific weather station location are additionally analyzed and hourly cloud cover values are predicted using a Markov process. The predicted cloud cover values and the calibrated K_C are used in the second step to calculate the real sky radiation on the roof surfaces. The method is deployed at the location Zurich Fluntern and validated using measured data.

Meteorological data from the IDAWEB service hosted by the Swiss Federal Office of Meteorology and Climatology, MeteoSwiss [7] are used. Hourly time series for sunshine duration and Global Horizontal Radiation (GHR) at the Fluntern weather station are extracted from this database spanning a time period from 1981 to 2014, to be used as inputs to this study.

Cloud Cover Prediction

A first order discrete state Markov process is modeled to predict the hourly values of local cloud cover using historical meteorological data from the Fluntern weather station. There have been previous studies conducted using a similar approach [8, 9]. This model assumes that the future state of the cloud cover is dependent only on the current state (memoryless property) and the preceding states have no influence on it. This method of modeling of cloud cover enables capturing historic information of the general cloud cover patterns and using it for prediction rather than using point data from a specific year.

Cloudiness, is a meteorological variable that is most commonly used to represent cloud cover and is measured at most weather stations. Since the cloudiness data was only available at a three hourly resolution it could not be used in this study. Instead, sunshine duration (SD) is used to represent cloud cover (CC). Neske [10] validates the linear relationship between cloudiness and sunshine duration for Hamburg. This linear relationship is as well concluded by Badescu in [11] analytically and validated for Romania. Based on the above studies SD is assumed to be representative of the local cloud cover as described by equation (1). SD is usually measured using a pyranometer which gives an advantage of lower levels of uncertainty as opposed to manually observed cloudiness.

$$CC(t) = 1 - \frac{SD(t)}{60} \quad (1)$$

To generate hourly patterns the state space of the Markov process which consists of ten discrete cloud cover levels ranging from 1 to 10 is used. The cloud cover fraction is classified into ten equal intervals of size 0.1 and allotted the corresponding next higher state (for instance, 0.24 is allotted state 3). The SD time series data is converted to cloud cover states and is used to construct a first order, monthly state transition probability matrices. These matrices are then used to predict the hourly cloud cover time series.

Solar Radiation Modeling

In the second step the clear sky index (K_C) is calculated. K_C is defined as the ratio between the GHR for a given cloud cover to the CSR.

$$Kc(cc,t) = \frac{GHR(cc,t)}{CSR(t)} \tag{2}$$

Whereby clear sky radiation (CSR) is defined as the radiation received by the surface after scattering from the atmosphere without the presence of any clouds and real sky radiation is defined as the net GHR received by a surface after taking into account the attenuation from clouds.

A GIS based workflow is implemented to calculate the hourly radiation values for the rooftop of the Fluntern weather station building. The workflow is implemented in the open source GIS software suite called GRASS GIS which implements the *r.sun* algorithm. This algorithm takes into account the solar position for each time step, shadowing effects from local terrain features and surrounding topography and atmospheric scattering. The key input parameters for this model are; timestamp (hour, day of the year), DEM (constructed from a 3D model of the building), Linke turbidity and albedo. The monthly Linke turbidity values are obtained for Zürich from the global solar radiation database SoDa [12]. A constant value of 0.2 is used for albedo. To decrease computational time, the DEM consists only of the rooftop area of the weather station and not the surrounding terrain as shown in figure 1. This eliminates the shadow effect from the surrounding terrain. This is justified after the visual observation of the topography on the region reveals a flat horizon and no obstructing topographic features especially in the south direction. The result of this calculation is the CSR value averaged over the whole rooftop for each hour in kWh/m^2.

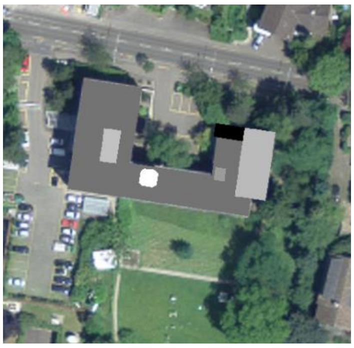


Figure 1: The Fluntern weather station building represented as a Digital Elevation Model (DEM) overlaid on an aerial image

Clear Sky index (Kc) calibration

The hourly time series of the measured GHR, the calculated CSR and the measured cloud cover are used to calibrate the Kc values. The entire dataset is split into two parts; for calibration (1981-2013) and for validation (2014). Kc is calculated for each hour of the calibration dataset. There are some data entries for which the value of the clear sky index exceeds 1, infinite or is negative. These values are eliminated from the calibration process. The rest of the dataset is then used to calculate monthly means of K_C for each cloud cover state and hour of the day. The seasonal variation of KC is taken into account by defining seasons as winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

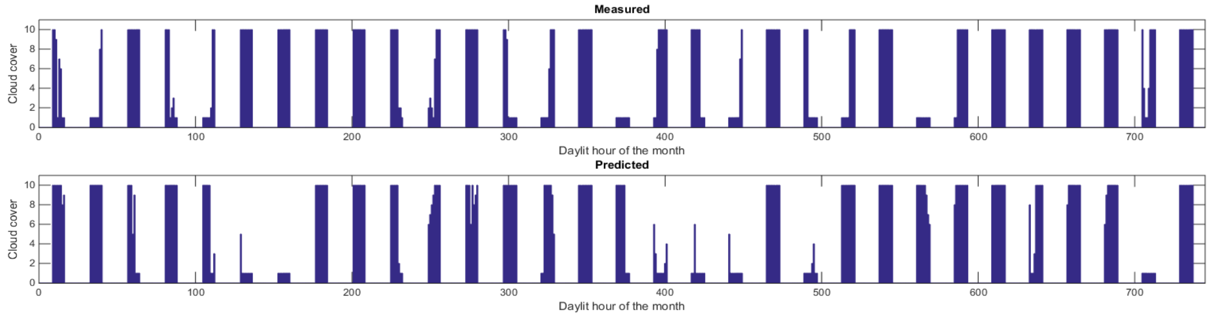
Real sky radiation

The real sky radiation is obtained using equation (2) for a given cloud cover and hour of day using calibrated K_C. Two hourly datasets for the real sky radiation are created. One each from measured cloud cover and predicted cloud cover. The real sky radiation dataset calculated from measured cloud cover is used for validation of GHR and eventually K_C. Since the predicted cloud cover is stochastic direct validation of real sky radiation values produced from it is not performed.

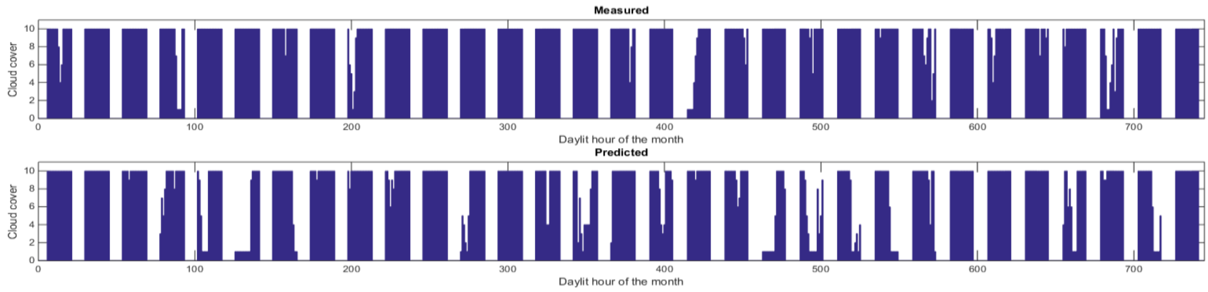
RESULTS & DISCUSSION

Cloud cover prediction

The hourly cloud cover as predicted by the Markov process is compared with the hourly cloud cover measured at the weather station in figure 1. A perfect match of the cloud cover is not expected since it is predicted through a stochastic process. However, visual observation suggests a general agreement of the measured and predicted values.



(a)



(b)

Figure 2: Measured vs predicted cloud cover (discrete states 1-10) for (a) January 2014 and (b) July 2014

Clear Sky Index (K_C)

The comparison of the mean K_C values obtained from the calibration procedure is shown in figure 3. The clear sky index exhibits variations with cloud cover, time of day as well as seasonal variations.

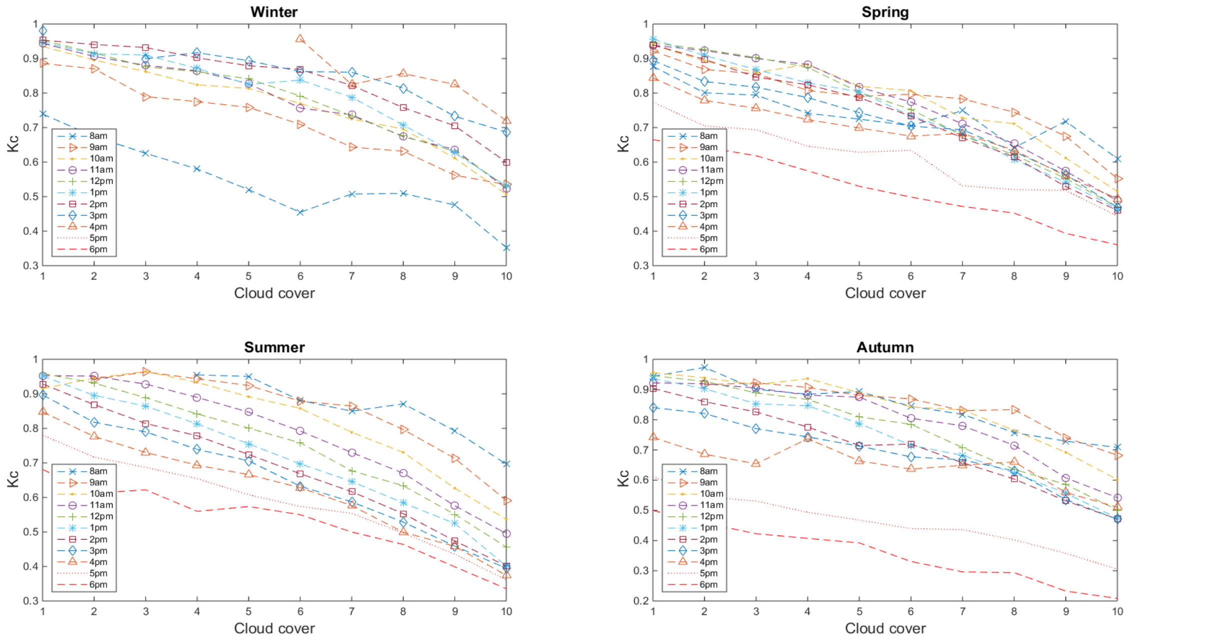


Figure 3: Comparison of clear sky index mean values as a function of cloud cover state and time of day for different seasons.

Validation

The real sky radiation calculated using the measured cloud cover and calibrated K_C is validated against the measured GHR obtained from the weather station database. A comparison of the measured vs predicted GHR is shown in figure 4. The root mean square error (RMSE) and the mean bias deviation (MBD) of the predicted values are 42.62% and 18.54%.

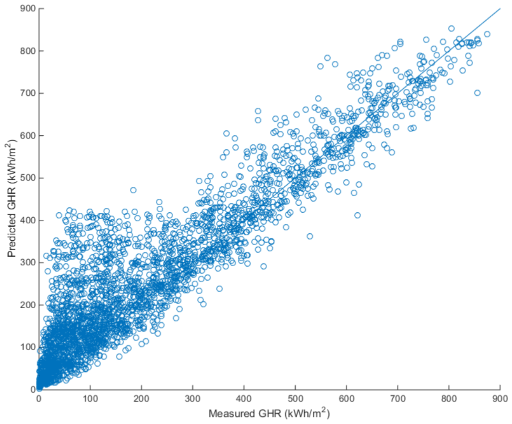
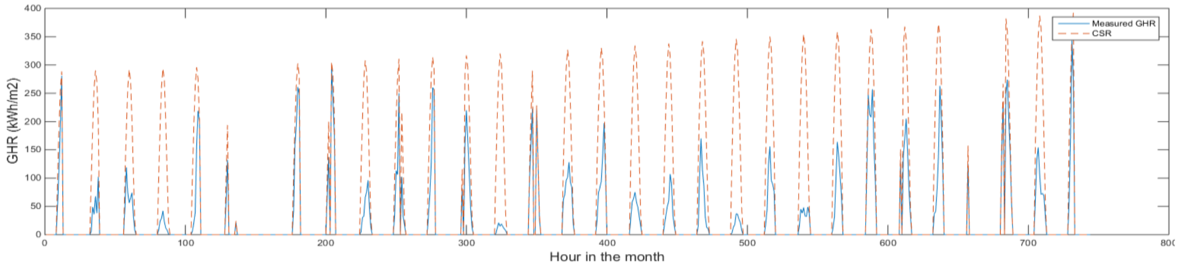


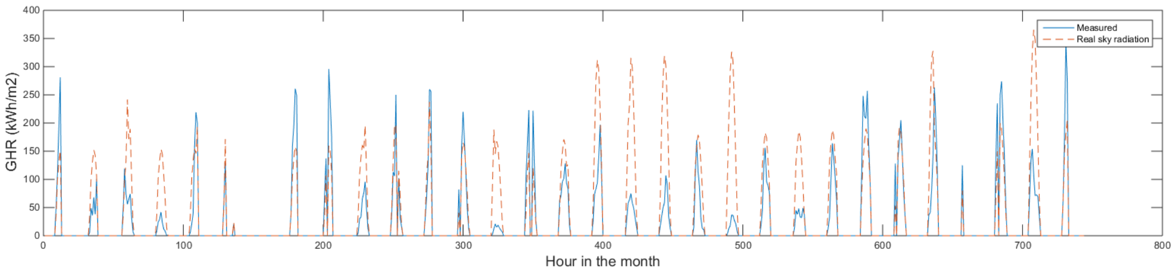
Figure 4: Measured vs predicted GHR in kWh/m²

Real sky radiation

Figure 5 (a) shows a comparison of the measured GHR and the clear sky radiation calculated using the GIS workflow without taking cloud cover adjustment into account for January 2014. . The percent RMSE and the MBD of the CSR and the real sky radiation is 119.75% and +47.68% respectively It is observed that the CSR over predicts the real sky radiation. Hence, cloud cover attenuation must be applied. Figure 5(b) shows the real sky radiation using the predicted cloud cover from the Markov process for the same month. The RMSE and MBD for this case are 74.64% and +6.73%. The values of RMSE and MBD are not expected to be low because the predicted cloud cover is stochastically generated. However, the reduction in RMSE and the MBD shows that the incorporation of cloud cover reduces the error. The MBD is still positive indicating an overprediction but it is considerably reduced.



(a)



(b)

Figure 5 Comparison of the measured GHR with (a) Clear sky radiation (No cloud cover) (b) Real sky radiation (cloud cover from Markov process)

CONCLUSION

A GIS based method for solar radiation calculation combined with a cloud cover prediction model is used in this study to calculate the incoming solar radiation on a building rooftop on an hourly basis. The data generated is useful for applications such building control system in order to manage the mismatch of energy supply and demand in a building if decentralized energy technologies are integrated. The results show that the solar radiation calculated without the consideration of clouds over predicts the actual radiation received by the rooftop. However, taking into account the cloud cover the error in prediction reduces.

ACKNOWLEDGEMENT

This research in the present contribution was funded in part by SCCER “Future Energy Efficient Buildings and Districts”.

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