Evaluation of Two Solar Radiation Algorithms on 3D City Models for Calculating Photovoltaic Potential

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Keywords: Solar Irradiance, Algorithms, 3D City Models, Python.

Abstract: Different algorithms are used to calculate solar irradiance on horizontal and vertical surfaces of the 3D city models. The goal of this paper is to evaluate the hourly solar irradiance calculated by two widely used algorithms in order to assess photovoltaic (PV) potential of the 3D city models. Both algorithms are implemented in an open source software infrastructure consisting of PostgreSQL database connected with PostGIS, Python, etc. The results show a significant variation of solar irradiances on horizontal, vertical and tilted surfaces. Finally, the justification of a particular algorithm to assess citywide PV potentials is made.

1 INTRODUCTION

Calculation of solar irradiance on horizontal, vertical and tilted building surfaces helps to correctly estimate techno-economic photovoltaic (PV) potential, assess building heating and cooling energy needs (Murshed et al., 2017; Bahu et al., 2014), identify the Urban Heat Island (UHI) effects (Vitucci et al., 2014).

Solar energy is one of the environmentally sustainable resources for producing electricity using photovoltaic systems (Šúri and Hofierka, 2004). Different building surfaces are exposed to the sun, which can be utilized to generate energy by efficient installation and design of the PV panels. In this regard, it is important to know the exact irradiance received by the horizontal, vertical and tilted surfaces. Moreover, based on the different tilt angles and orientation of the panels, the same surface may receive more or less radiation. Several other factors such as shading, sky condition also influence the amount of solar irradiance received by a surface.

Numerous algorithms (methods) and tools have been developed across different climatic conditions to analyze solar irradiance (Šúri and Hofierka, 2004). A comprehensive and comparative overview has been given by Freitas et al. (2015), Catita et al. (2014), Redweik et al. (2013), Gueymard (2012) The GIS-based analysis of solar irradiance was also performed in different spatial-temporal scales and resolution: from building surfaces to districts, hourly or monthly basis, using vector or raster data (Huld, 2017; Li and Liu, 2017; Hachem et al., 2013; Nguyen and Pearce, 2010; Lee and Zlatanova, 2009). However, the use of 3D city models is rather recent and innovative (Freitas et al., 2015; Wieland et al., 2015). With the availability of comprehensive 3D building data across many cities, it is possible to carry out sophisticated analysis of solar irradiance at a greater detail. It allows assessing the shadow effect from the neighbouring buildings, terrain or other urban objects, calculating slope and orientation of the surface, etc. Several commercial tools such as Archiwizard, Rhinosolar, Autodesk Ecotect, ArcGIS are also available but they are not able to perform analyses on vertical surfaces or are not suitable to be used in large 3D city models.

The aim of this paper is to perform a comparative evaluation of two widely used solar irradiance algorithms i.e., Šúri and Hofierka (2004) and Duffie and Beckman (2006) to identify the more suitable algorithm for assessing PV potential at an urban scale. The hourly solar irradiance on horizontal, vertical and tilted surfaces is calculated using an open source software infrastructure. In this regard, the input weather data, 3D city models and other assumptions are considered identical in the implementation of both algorithms.

Murshed, S., Simons, A., Lindsay, A., Picard, S. and De Pin, C.
Evaluation of Two Solar Radiation Algorithms on 3D City Models for Calculating Photovoltaic Potential.
DOI: 10.5220/0006789702960303
In *Proceedings of the 4th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2018)*, pages 296-303
ISBN: 978-989-758-294-3

2 METHODOLOGY

2.1 Main Approach

The broad methodological steps of this study can be divided into 3 main parts (Figure 1). First, the analyses of the 3D city models (e.g., CityGML format) include preparation of the data, configuration of the software and tools, generation of the point grids on the building surface, calculation of the shading and sky view factor of the points, solar position, etc. (Section 3.1). Then the outcomes of these analyses are considered as inputs to both solar irradiance algorithms. The algorithm proposed by Šúri and Hofierka (2004) was adapted earlier to calculate monthly irradiation on CityGML data (Wieland et al., 2015). This study improves the previous modelling approach to incorporate the calculation of hourly irradiance and advance the 3D analyses part. In this regard, hourly measured weather data of a ground station is considered (Section 3.2). Afterwards, the algorithm proposed by Duffie and Beckman (2006) is implemented, which also requires the same weather data (Section 3.3). Both algorithms estimate solar irradiance (direct and diffuse) on horizontal, vertical and tilted surfaces on an hourly basis. In order to perform a comparative evaluation of both algorithms, the spatial and temporal irradiation results are aggregated to buildings and annual level, respectively. Finally, the results are visualized and evaluated (Section 4).

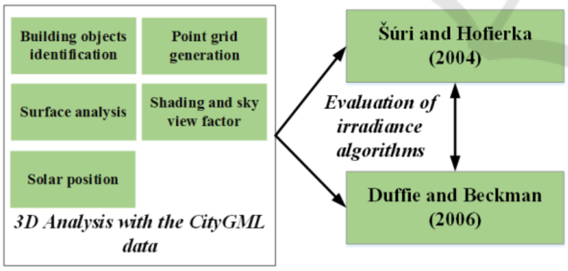

Figure 1: Broad methodological approach.

2.2 Data

The hourly weather data on wind speed, temperature and horizontal radiation are collected from the Meteonorm software in TMY3 format (Wilcox and Marion, 2008). The 3D city model of the CityGML format having Level of Detail 2 (LoD2 includes appropriate roof structure) of the city of Karlsruhe is also gathered. A detailed description of the CityGML data format and different LoDs is given in (OGC, 2012).

2.3 Software Architecture

Several software such as FME, 3DCityDB, pgAdminIII and Eclipse are deployed to perform the 3D and solar irradiance analysis (Murshed et al., 2017). The algorithms are written in Python scripts, considering the object oriented approach (Figure 2).

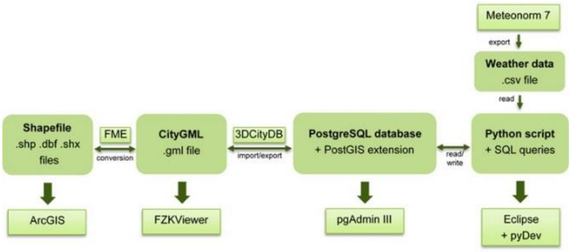

Figure 2: Software architecture and data flow (Murshed et al., 2017).

The LoD2 data of the CityGML format are imported in a PostgreSQL database provided with PostGIS extension, which allows treating spatial objects by creating a special structure in the database. The original CityGML file is adapted to the relational schema by transforming through 3DCityDB, which reorganizes files into specific tables. Finally, the data can be retrieved using the Python code for further calculations, analysis, and saving of results.

3 IMPLEMENTATION

3.1 3D Analysis Part

The 3D analysis part involves treating of CityGML data and performing necessary geometric calculations. The main steps are:

a. Surface analysis,
b. Definition of the objects: building, surface and surface points,
c. Creation of the grid of surface points,
d. Shading characterization and sky view factor calculation,
e. Solar position and characterization.

Figure 3 explains the different processing steps, inputs and calculated results.

a. Surface analysis is the main module from which all other 3D analysis parts are called. It determines which points are "shared" i.e., in-between two surfaces. This is done by spatial analysis and by checking for an intersection of a buffer (0.1 m) around the point, if any other wall surface is nearby. Such an assumption helps to avoid unnecessary

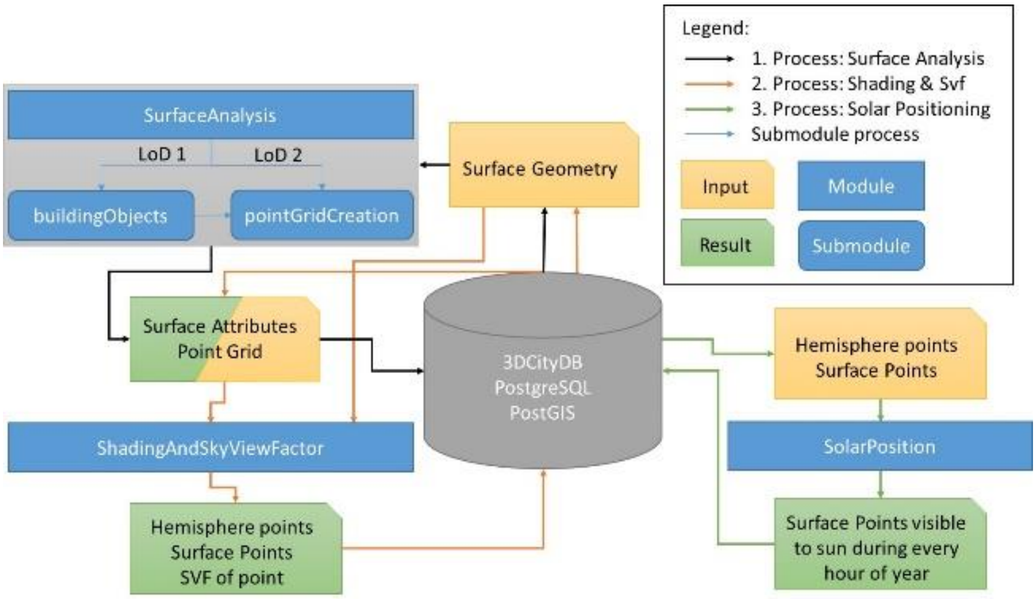

Figure 3: Detailed description of the inputs, different steps and associated results of the 3D analysis part. The outcome of the analyses are saved in the PostgreSQL database.

spatial calculations, in case surface objects of neighboring buildings may have geometric problems (due to the bad quality of 3D city model).

b. The building object module identifies the wall, roof or ground surfaces of the LoD2 (or LoD1) city models. Then it performs different geometric calculations such as normal vector, slope and aspect of surface, using linear algebra.

c. The point grid module creates an homogenous point grid on geometrical objects in 3D space (Figure 4). At first, considering the envelope of the geometry (i.e., building surface), a starting point (3D point with X,Y,Z) is defined. From this point, a distance is added to the right (horizontal) as long as the sum of interspaces (distance among points) is below the expansion value X. Afterwards, the same procedure is performed for all points as a step up (vertical) as long as the interspace distance is below the expansion value Y. Then the newly created points are checked, if they are inside the polygon. This check is done once per surface after the point distribution. Points outside of the polygon are deleted. This approach is applied for the horizontal polygons/surfaces. For non-horizontal surfaces, points are rotated around the axes, according to the orientation of the corresponding polygon.

Therefore, technically speaking, the point grid distribution is performed in 4 ways, depending on the LoDs of the surface and the type of surface (e.g., ground, wall or roof surface). For LoD1, two methods, one for horizontally orientated surfaces and the other for vertically orientated surfaces are observed. For LoD2, the points for horizontal surfaces are distributed with the same method as LoD1. For vertical surfaces, each point is rotated with a matrix calculation into the plane of the surface orientation. For tilted surfaces, different height values of the geometry are taken into account to perform point distribution.

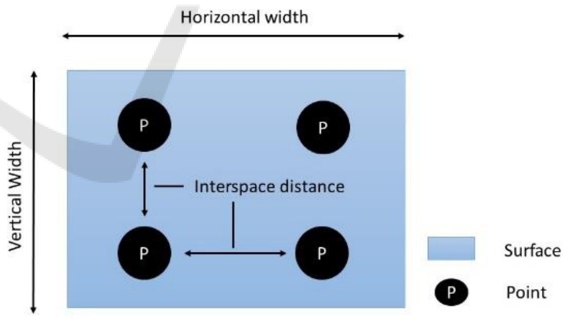

Figure 4: Point grid creation on the surface.

d. Shading is performed through spatial analysis. From each surface point, a line is created towards a point of the hemisphere (a hemisphere of points is created according to the horizontal and vertical intervals chosen earlier, see Figure 5). If the line intersects with another object (e.g., surface of the same building, or another building) the surface point is considered as shaded. If the line is not intersected with another object, the corresponding surface point is considered as not shaded. This process is done for each surface point for every hemisphere direction separately.

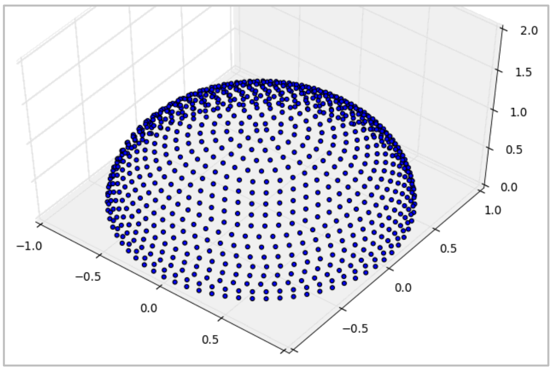

Figure 5: Hemisphere represented by sample points.

The sky view factor for each point is calculated as the ratio between the number of visible hemisphere points and the total number of hemisphere points.

$$sky\ view\ factor = \frac{number\ of\ visible\ hemishere\ points}{total\ number\ of\ hemishere\ points}$$

e. Finally, solar position is calculated. For each surface point, the IDs of the hemisphere directions, which are visible, are stored in an array. To detect whether a surface point is shaded at a certain time, the position of the sun is computed for a specific time of the day and the closest hemisphere direction is determined. If the ID of this hemisphere direction is contained in the array of the surface point, the point is considered not to be shaded at that time of the day. For each surface point this is performed 8760 times, which corresponds to the number of hours per year. The information of whether a surface point is shaded at a certain hour is stored as a Boolean value, either “True = is shaded” or “False = is not shaded”.

3.2 Solar Irradiance Algorithm by Šúri and Hofierka (2004)

This algorithm is applied in many studies and an open source GIS environment is employed. Computation is quick and local meteorological data can be adapted to the model. It is robust, and requires few input parameters (Gueymard, 2012).

The process of computing solar irradiance (clear sky) begins with the determination of the extraterrestrial irradiance, which varies during the year. After the position of the sun is calculated with respect to time, the day and the latitude of the location of interest, the beam and diffuse component of solar irradiance on a horizontal surface can be determined for the time of interest with respect to the Linke turbidity. By incorporating the slope and the surface, the incidence angle of solar rays on this surface can be computed. With this angle, the horizontal radiation components are adjusted according to the orientation of the surface (Šúri and Hofierka, 2004). In this model, only shadowing of the beam component is taken into account, and not of the diffuse irradiance.

3.3 Solar Irradiance Algorithm by Duffie and Beckman (2006)

It is calculated in four main steps. At first, the sun position is calculated depending on the location coordinates and time. Then the direct normal irradiance is calculated considering the sinus of the solar elevation angle, global horizontal and diffuse horizontal irradiances that can be found in the weather data. Then, based on the sun position vector and the normal vector to the surface, the incidence angle of the beam irradiance is computed and the shadowing of the beam irradiance is included as calculated previously. The sky view factor is applied to diffuse irradiance.

Afterwards, an anisotropic sky model, known as the Hay-Davies-Klucher-Reindl model is used to take into account circumsolar diffuse irradiance and horizon-brightening (Duffie and Beckman, 2006). Finally, hourly direct and diffuse radiation are calculated.

3.4 Assumptions

Both algorithms calculate only direct and diffuse solar radiation. In order to have a comparative evaluation, all relevant parameters are considered identical. About 96 hemisphere points were created to determine the sky view factor and to identify if each surface is visible to particular hemisphere points (and to solar position) throughout each hour of a year. A point grid of 5m resolution is created on the building surfaces. The measured weather data of a weather station are used as inputs to both algorithms.

4 VISUALIZATION AND DISCUSSION OF RESULTS

In order to perform a quick comparative evaluation of the irradiance results, both algorithms were run on 95 buildings (having 650 surfaces) in a neighborhood in the City of Karlsruhe in Germany. Then in order to test the applicability of the implemented model, we ran it for about 12000 LoD2 buildings in another district of the same city.

The direct and diffuse radiation were first calculated for each point on the building surface, which were then aggregated for each surface to display the hourly averaged irradiance throughout the year (W/m²). In analyzing the results of the first method, we found the minimum and maximum values to be 25 and 136 W/m² (Figure 6), whereas in the second method, the values were 8 and 127 W/m² (Figure 7), respectively.

Some surfaces displayed exactly the same results for both algorithms. We observe that the initial method estimates higher solar irradiances (up to 78%) on the surfaces that are partially shaded by neighboring surfaces (Figure 8).

We also observe that both algorithms calculate almost the same solar irradiance on the roof surfaces.

It is found out that the second algorithm calculates slightly higher solar irradiances (up to 36%) on the north oriented surfaces (Figure 9).

It is evident that tilted surfaces (directing towards the sun) will receive more irradiance than flat surfaces. In case of flat roofs (e.g., where slope is

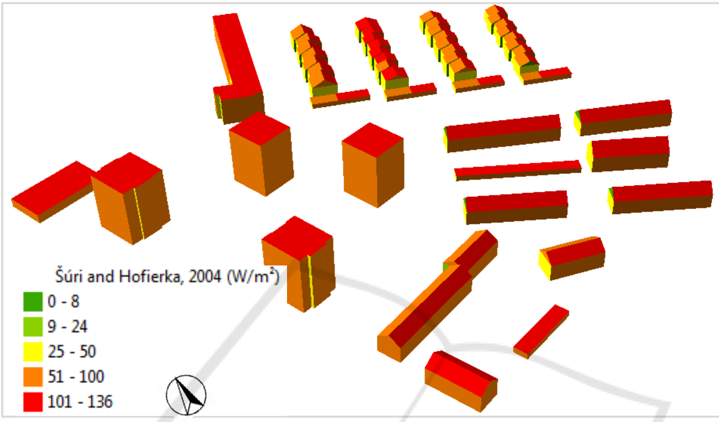

Figure 6: Hourly average solar irradiation on horizontal and vertical surfaces after Šúri and Hofierka (2004).

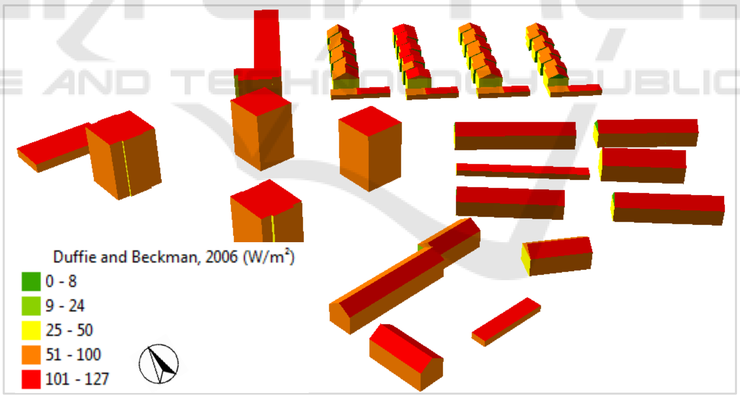

Figure 7: Hourly average solar irradiation on horizontal and vertical surfaces after Duffie and Beckman (2006).

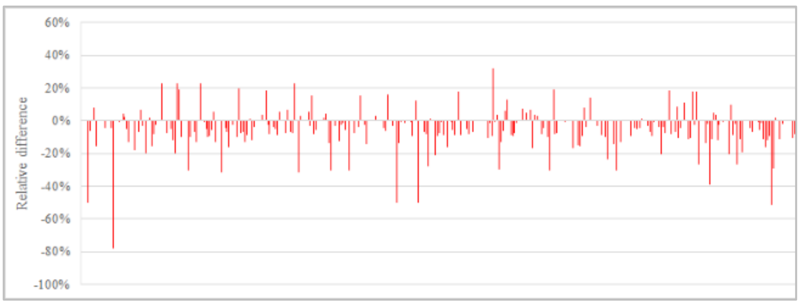

Figure 8: Relative difference of irradiance results on some surfaces detected by the two algorithms.

<20°), the PV installations are normally optimized by tilting the panels so that they can receive maximum solar radiation and thus can optimize energy production for the PV panels. Therefore, the calculation of irradiance on such tilted surfaces (analogous to the PV installation surfaces) is very important. The second method can be adapted to calculate radiation on such surfaces. For example, we found that the irradiance on a tilted surface is 140 W/m², which is higher than the radiation calculated earlier on the actual roof surface (127 W/m²), which has a slope less than <20° (Figure 10).

Both models were run on the same virtual machine with standard configurations. The run time of both models with 95 buildings was almost the same (approximately 4 minutes). The multi-processing functions of python helped to improve the model run time.

Based on the results, it is difficult to justify which method is more accurate and suitable for PV potential analyses, although both of them considered similar input datasets and assumptions. Nevertheless, observing the evidence that the method by Duffie and Beckman (2006) performs more realistic calculations for the surfaces which are next to shaded surfaces (confirmed after site inspection) and the flexibility of assessing the irradiance on tilted surfaces, this method is more suitable for photovoltaic assessment in urban areas. Therefore, the algorithm proposed by Duffie and Beckman (2006) was applied to around 12000 LoD2 buildings (consisting of approximately 96000 surfaces and 442000 points) in the city of Karlsruhe in Germany to calculate hourly irradiance on the tilted and vertical surfaces. It took approximately 7 hours to complete the analysis.

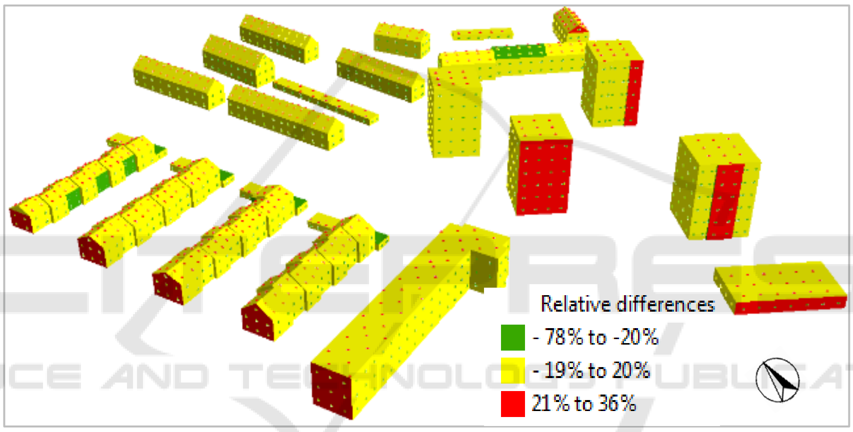

Figure 9: Relative difference in solar irradiance on the wall and roof surfaces observed by the two methods. The grid points are displayed on the surface on which solar radiation is calculated first.

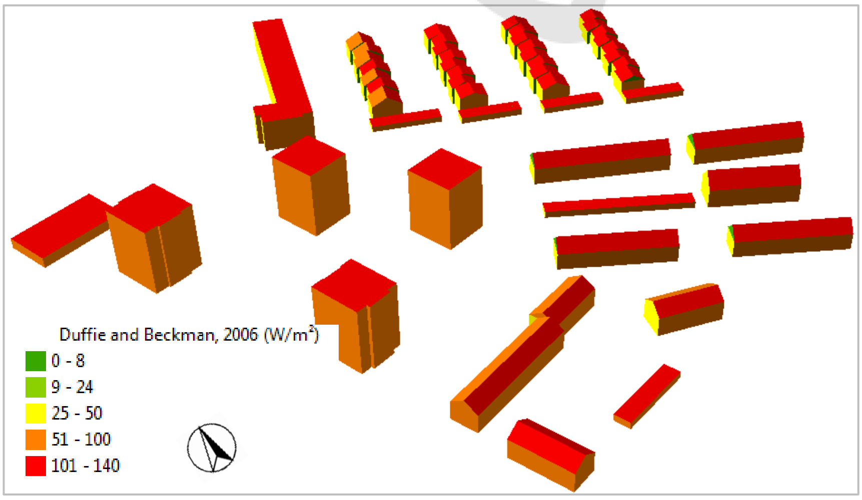

Figure 10: Hourly average solar irradiation over a year on tilted surfaces (where slope was <20°) after Duffie and Beckman (2006).

Figure 11 illustrates the hourly average solar irradiance over a year on the vertical and tilted surfaces of the buildings. The surfaces that strike out in red are those that have few neighbouring buildings obstructing sunlight. Generally, these are tilted rooftops and this visualization quickly identifies the best sun exposure.

5 CONCLUSIONS

Two solar irradiation algorithms were tested in this study to perform a comparative evaluation of irradiation results with a view to assess PV potential in a city or district. For this reason, CityGML data and an open source software infrastructure was used to perform a quick but robust calculation of direct and diffuse radiation of different building surfaces. Moreover, with the semantic relationship among the points, surfaces and buildings within the CityGML data, it was possible to aggregate the results on different spatial and/or temporal (hourly, monthly, yearly, etc.) resolutions. The testing of the model with about 12000 LoD2 buildings in the city of Karlsruhe showed the applicability of these algorithms at a city scale.

Several limitations are also evident in this study. For instance, reflected radiation was not calculated. It can be added by calculating the ground view factor. Increasing the number of hemisphere points will improve the model accuracy but will also increase the run time. Therefore, in the future, the results can be tested with a varying number of hemisphere points and grid points. Consideration of shading due to vegetation or chimneys will also improve the calculation of solar irradiance.

As a continuation of this study, considering the amount of solar radiation received by the sun, the PV potential in terms of electrical energy (kWh), investment costs (Euro) and levelized cost of energy (LCOE) on the horizontal, vertical and tilted surfaces will be calculated. The results can be integrated into

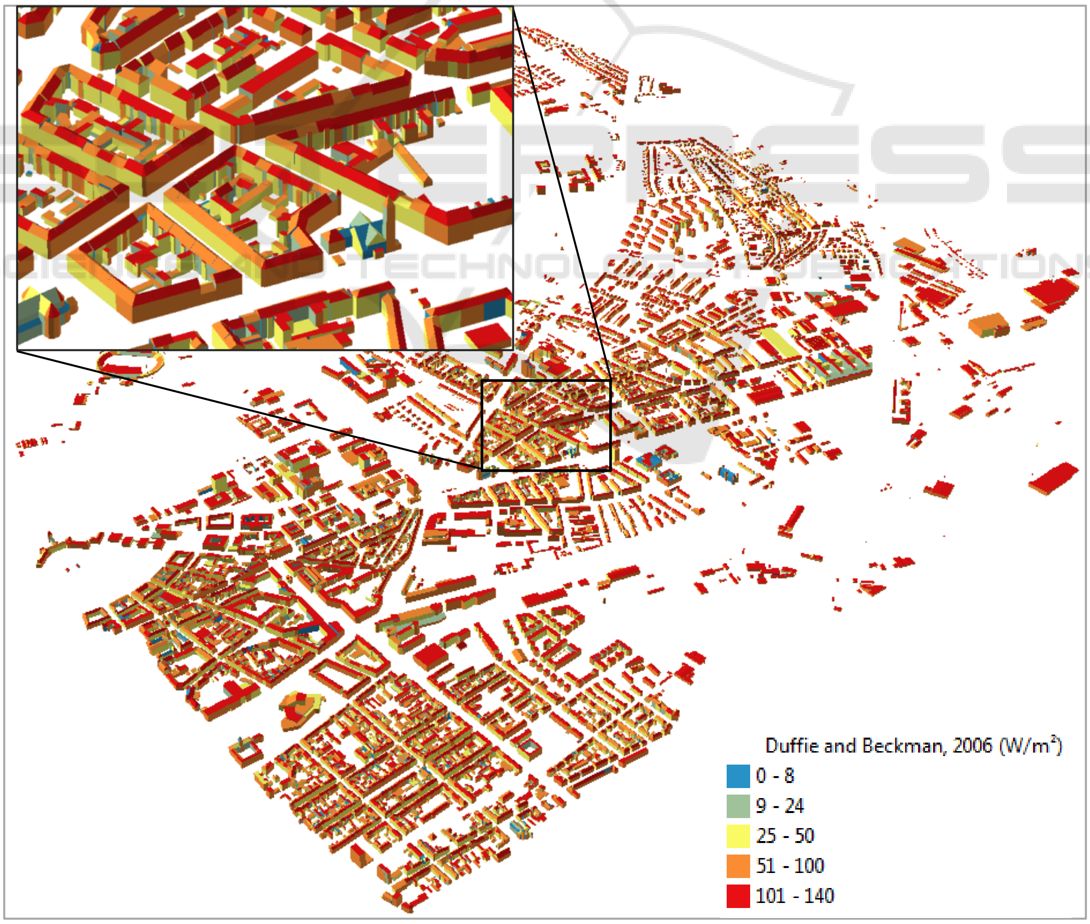

Figure 11: Hourly average solar irradiation (W/m²) over a year on tilted (where slope was <20°) and vertical surfaces after Duffie and Beckman (2006) on 12000 LoD2 buildings in Karlsruhe, Germany.

a web platform, in order to visualize in 3D and to allow the decision makers and citizens to ascertain the solar irradiance and techno-economic PV potentials in a flexible manner.

ACKNOWLEDGEMENTS

We would like to thank City of Karlsruhe for the permission of using CityGML data and the project "Smart and Low Carbon Cities" of EDF R&D for funding the research. We are also grateful to Manfred Wieland for his initial contribution in coding and the three anonymous reviewers for their constructive comments on our manuscript.

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