THREE-DIMENSIONAL URBAN SOLAR POTENTIAL MAPS
Case Study of the i-Scope Project

by

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Solar maps as web cartographic products that provide information on solar potential of surfaces on the Earth have been exploited in decision making, awareness raising, and promoting the use of solar energy. Web based solar maps of cities have become popular services as the use of solar energy is especially attractive in urban environments. The article discusses the concept and aspects of urban solar potential maps on the example of the i-Scope project as a case study. The i-Scope roof solar potential service built on 3-D urban information models was piloted in eight European cities. To obtain precise data on solar irradiation, a good quality digital surface model is required. A cost efficient innovative method for generation of digital surface model from stereophotogrammetry for urban areas where no advanced source data (e. g. LiDAR) exist is developed. The method works for flat, shed and gable roofs and provides sufficient accuracy of digital surface model .

Key words: *solar map, 3-D urban information models, digital surface model, city geography markup language*

Introduction

Renewable energy can bring a number of benefits to humanity and natural environment. These can be [1]: social: improved health, consumer choice, greater self-reliance, work opportunities, and technological advances, environmental: reduced air pollution, lower GHG emissions, lower impact on watersheds, reduced transportation of energy resource, and maintaining natural resources in the long term, and economic: job creation, cost reduction, and economic diversification. Countries thus generally tend to increase the exploitation of renewable energy sources. For example, according to the Energy sector development strategy of Serbia for the period by 2025, a short term goal is to increase the existing share of renewable energy sources in gross final consumption of 20.1% to 27% in 2020. The recent drop in costs of solar technology has generated an increasing interest in exploitation of solar energy in particular. It is the largest energy resource on Earth and the International Energy Agency estimates that the sun could also be the world's largest source of electricity by 2050 [2, 3]. It has induced a number of studies on solar potential of particular geographic areas and mapping of suitable locations for installing solar panels [4-7]. Of a particular interest is to obtain information on solar potential in urban environments due to the advantages of producing energy

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closer to consumers. A number of research studies dealing with models and methodologies for estimating solar potential of buildings and suitability of roofs for installation of photovoltaic (PV) systems have been conducted [8-11].

There have been a number of initiatives to bring solar energy closer to citizens, business, and public local communities in recent years, and many of them use web solar maps as a tool to achieve that aim. The term *solar map* here refers to a web cartographic interactive tool that provides various information related to solar potential of buildings or open land as well as the benefits related to exploitation of that potential. The information helps potential users to plan their investments in solar technology or to include solar energy aspect in their projects and planning.

There are a number of urban solar maps developed and published recently [12, 13]. They were produced with different methods and provide various level of information, from very basic (*e. g.* irradiation levels), to advanced (*e. g.* output of solar systems, financial considerations, installers, *etc.*) [12]. It is expected that many more cities will develop their solar maps in the nearest future.

This paper examines a model for urban solar maps on the example of the i-Scope project as a case study. The i-Scope project (co-funded through the CIP-ICT-PSP programme of the European Commission) delivered an open platform based on interoperable 3-D urban information models (UIM) on top of which it developed three *smart city* services within different domains: solar potential assessment, routing for diversely impaired persons, and urban noise mapping. The i-Scope service for accurate assessment of solar energy potential will be of interest for this study. The service uses a 3-D web map to deliver information to the users. The i-Scope platform was piloted and validated within a number of European cities/counties: Baia Mare (Romania), La Valleta (Malta), Indjija (Serbia), Trento and Lazio region (Italy), Newcastle (UK), and Zadar and Zagreb (Croatia). The procedure applied in the i-Scope platform for generating of solar potential using r.sun algorithm and the data used for the purpose is described.

The i-Scope 3-D UIM are based on cityGML (geography markup language) open data model. To obtain precise solar potential data, level of details (LoD) that represents roofs well is required. The paper presents the innovative method for generation of 3-D roof models for flat, shed and gable roofs in a cost efficient way. The method is based on filtration of raw data from stereophotogrammetry and was applied in the i-Scope pilot in Indjija, Serbia.

The paper aims at discussing the concept and technical aspects of the i-Scope solar potential map as a paradigm of efficient and comprehensive system for generation and communication of information related to solar potential at urban level.

Data and methodology

Calculation of solar irradiation by using GRASS r.sun algorithm

The information on the solar potential of roofs is generated in two steps [14]. In the first step, total clear-sky solar irradiation is calculated using r.sun model embedded in GRASS GIS free and open-source software. The model is developed by Hofierka and Šuri [15]. It is a complex and flexible solar radiation model that calculates direct (beam), diffuse and reflected solar irradiance or irradiation for both clear-sky and cloudy conditions.

The input data used to run the model are as follows.

– The DSM – raster file containing elevation data of a city including buildings and roofs. Each pixel contains its elevation value.

– The digital terrain model (DTM) – raster file containing elevation data on the area surrounding the city. This is useful when a city is surrounded by relief that can affect solar irradiation.

A number of additional parameters need to be set.

– Linke turbidity coefficient – it describes the reduction in the transparency of air resulting both from the scattering of light by tiny particles suspended in the air and from the absorption of light by water vapor. The default value of 3.0 is used for the i-Scope service which is considered near the average annual value for urban areas.
– Ground albedo – it is the ratio of total reflected radiation from the surface to incident radiation upon it. The albedo values range from 0 for no reflection (in the case of perfectly black surface) to 1 for perfect reflection of (a white surface). The default value of 0.2 is used that corresponds with a typical urban environment.
– Time step – calculation of solar irradiation for large areas continuously from sunrise to sunset is impractical due to high required processing power and the time consumed. Instead, solar irradiation is simulated at specific time intervals using a time step. The time step used is 30 minutes. Since the Sun moves 15° each hour, it means that solar simulation is being done at each 7.5° the Sun moves in the sky.

Before performing calculation of irradiation, the system generated a set of intermediate maps.

– Horizon maps – a horizon map is raster map with the horizon height in radians for the points in the elevation map (DSM or DTM) in a single direction. Multiple directions are computed using a 15° rotational step around the horizon which means that 24 maps are generated in total from 0-360°. These maps are calculated using r.horizon model in GRASS GIS used to speed up the computation of the solar irradiation maps and also to permit processing big maps in smaller chunks.
– Slope map – computed from the elevation map (DSM or DTM) and contains degrees of inclination from the horizontal plane for the pixels in the elevation map. It describes inclination of the roofs.
– Aspect map – computed from the elevation map (DSM or DTM) and contains azimuth in degrees for the slopes of the pixels in the elevation map. This map describes direction of the roofs.

During the testing and evaluation phase of the project pilot cities highlighted that the annual irradiation values returned from the system were too high due to the use of the clear-sky radiations. The overestimation was corrected by introducing the Insolation Clearness index in the calculation. It is a dimensionless parameter in the range of 0 to 1. This was done on the client side to avoid recalculation of all the maps. The monthly insolation clearness index was retrieved from Atmospheric Science Data Center. It presents the ratio of the monthly average amount of the total solar radiation incident on a horizontal surface at the surface of the Earth and the monthly average incoming top-of-atmosphere radiation for a given month, averaged for that month over the 22-year period (Jul 1983 to Jun 2005) [16]. The data is available at https://eosweb.larc.nasa.gov/cgi-bin/sse/subset.cgi.

The DEM and DSM data

Geometric quality of the input data is critical for the estimation of clear-sky solar irradiation. A level of details in 3-D models of buildings depends on geometric resolution of DSM. It is especially important to take into account when particular roof elements (*e. g.* chimneys) produce shadowing effect that influences roof solar potential estimation. The effect of DSM resolution on estimation of clear-sky solar irradiation is not high in the case of diffuse irradiance, but can be significant when it comes to direct and total radiation during summer months [17].

There is a number of methods and techniques that enable generation of DEM and DSM in various spatial scales including: manual, automatic and semi-automatic acquisition from digital stereo photogrammetry, airborne laser scanning (LiDAR), digitalization of contours from existing topographic maps, radar interferometry, *etc.* The sources and resolution of DEM and DSM data for the i-Scope pilot cities are presented in tab. 1. [18]. Due to the increasing demand on various spatial information, some cities (*e. g.* Vienna) have already had comprehensive urban spatial datasets including high quality 3-D data on buildings. Some other cities (*e. g.* Trento) expressed the intention to acquire more accurate data in the nearest future.

Table 1. The sources and resolution of DSM and DEM data for the i-Scope pilot cities

Pilot city	DSM		DEM	
	Data source	Resolution	Data source	Resolution
Trento	Regular grid filtered from raw Lidar data	1 m	Regular grid filtered from raw Lidar data	1 m
Indjija	DSM of roofs generated automatically from stereophotogrametry and filtered, raster	1 m	DTM generated automatically from stereophotogrammetry, raster	1 m
Cerveteri – Lazio	DBT (Spatial Database) compliant to the reference national technical specifications	n. a.	DBT (Spatial Database) compliant to the reference national technical specifications	n. a.
Newcastle	Point grid generated from Lidar	One point per 0.5 square meter ±15cm for horizontal and vertical accuracy	Point grid renerated from Lidar	One point per 0.5 square meter ±15cm for horizontal and vertical accuracy
Zagreb	LoD 2 AutoCAD dwg (3-D) collected with photogrammetric method	n. a.	LoD 0 AutoCAD dwg (3-D) collected with photogrammetric method	n. a.
Zadar	LoD 2 AutoCAD dwg (3-D) collected with photogrammetric method	n. a.	LoD 0 AutoCAD dwg (3-D) collected with photogrammetric method	n. a.
Vienna	Airborne laser scanning	15 points per square meter	DEM of Vienna	2.5 m resolution
	City model of Vienna LOD1 and LOD 2, in CityGRID XML format.	n. a.		
	DSM of Vienna raster data	0.5 m resolution		

Automated generation of 3-D roof model

High quality DSM is essential for creating reliable urban solar potential maps. Methodology for creating DSM should be efficient but inexpensive. In that sense, a methodology for generation of DSM from single stereopairs of digital airborne photo sensors is developed for Indjija pilot since there was no other suitable data sources for 3-D city model. The raw DSM was generated in SOCET Set software, however, the result was noisy, fig. 1 left, and with low vertical accuracy and precision. The noise is mostly the result of irregularities of roof surfaces (*e. g.* chimneys, antennas, trees, *etc.*). It was necessary to develop a filtering method to reach the acceptable DSM quality.

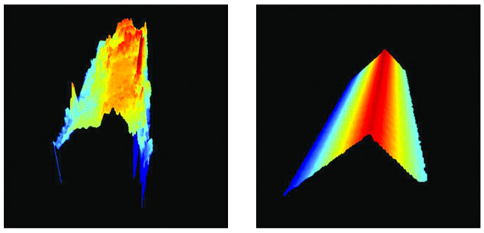

Figure 1. An example of raw DSM of the 2-plane roof used in the experiment (left) and final 3-D model of 2-planes roof (right)

The methodology was applicable to shed (single-plain) roofs and gable (2-plane) roofs. There were 2208 roofs (or 21% of all roofs in Indjija) of the former type and 4506 (or 42% of all roofs in Indjija) belonging to the later group. The rest of 37% roofs were more complex and it was not possible to generate DSM for them following this methodology.

Apart of the raw DSM generated automatically from stereophotogrammetry, vector polygons representing outlines of the buildings with an attribute indicating whether the roof of a building is single or 2-plane were required.

The algorithm consists of 2 parts: discrimination of single-plane and 2-plane roofs (according to the polygon attribute) and filtration of the DSM. In case of single plane roof, the DSM was filtered by defining first order polynomial trend surface [19] using least squares method (LSM). For each *roof* a vector point cloud was derived from the raw DSM. The LSM was used to define trend surface and for each point residuals and Cook's distances [20] were calculated. After points with residuals greater than the threshold adopted for Cook's distance had been deleted, new trend surface was calculated. This way, the outliers were detected and removed. The process was repeated until residuals were below 0.5, fig. 2.

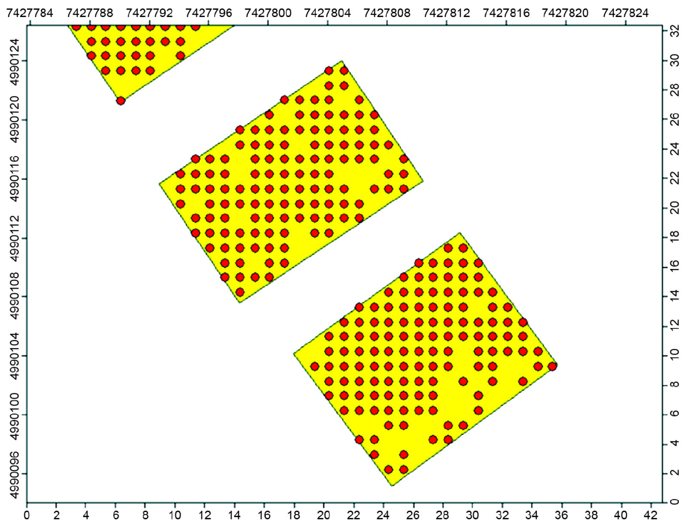

Figure 2. Cloud of remaining points after filtering for each building; final DSM is created from the points

In the case of 2-plane roofs, second order polynom trend surface [19] is calculated using the LSM, fig. 1. The pixels of the trend surface are subsequently clustered in two groups based on their aspect value using hill-climbing method [21]. Finally, a 2-plane roof is reduced to a case of two single plane roofs. In both cases the process is iterative, leading to the smooth roofsurfaces, fig. 1 right. The result is the number of filtered DSMs of roofs representing 3-D roof models that were later used as a base input for the estimation of the solar potential service.

To assess the accuracy of the filtered DSM, aspect and slope of the roof planes calculated from the DSM were compared with the aspect and slope calculated from 3-D roof models produced by manual methods of classical photogrammetry (regarded as the reference parameters). The results are presented in tabs. 2 and 3.

Table 2. Differences in heights, aspect, and slope for the case of single plain roof

	Number of pixels	Minimum	Maximum	Mean	Standard deviation
Height [m]	17395	0.000314	0.379614	0.193921	0.103811
Aspect [°]	17395	0	0.922687	0.001293	0.01794
Slope [°]	17395	0.000228	0.721203	0.248249	0.151658

Table 3. Differences in heights, aspect, and slope for the case of 2-plains roof

	Number of pixels	Minimum	Maximum	Mean	Standard deviation
Height [m]	1065	0.000197	0.486569	0.120322	0.103383
Aspect [°]	1065	0	12.5	1.32686	3.154805
Slope [°]	1065	1.690043	10.583567	4.759772	1.928329

Vertical accuracy for both roof types is around 20 cm. However, mean aspect and slope difference of respectively 0.001293 and 0.248249 decimal degrees in the case of single plane roof are lower than in the case of 2-plains roofs (1.32686 and 4.759772) which have also higher standard deviations of the differences. Nevertheless, we can consider that both 3-D models are produced with the sufficient accuracy for the purpose.

The 3-D UIM

The i-Scope solar service is based upon the concept of 3-D UIM. An UIM is aimed to *integrate multi-dimensional urban aspects like economy, society and environment with 3-D urban model plus temporal dimension* [22].

The i-Scope 3-D UIM is built on cityGML, an open geospatial consortium (OGC) standard. The cityGML is defined as [23]: *a common information model and XML-based encoding for the representation, storage, and exchange of virtual 3-D city and landscape models. CityGML provides a standard model and mechanism for describing 3-D objects with respect to their geometry, topology, semantics and appearance, and defines five different levels of detail. Included are also generalization hierarchies between thematic classes, aggregations, relations between objects, and spatial properties. CityGML is highly scalable and datasets can include different urban entities supporting the general trend toward modelling not only individual buildings but also whole sites, districts, cities, regions, and countries.* The cityGML can provide a common information model with entities relevant to various disciplines [24], with attached information specific for different applications including solar energy exploitation [25].

The cityGML data was generated using novaFACTORY software with the help of tridicon CityModeller. Buildings are automatically generated with roof recognition up to LoD2 CityGML. The input data needed for the process to run are: building floorplans, DEM, and DSM. When performing generation of cityGML in novaFACTORY to enable proper identification of roof planes, certain requirements in terms of DTM and DSM resolution should be met (D2.3), namely: DTM resolution should be between 5 m and 20 m; DSM resolution should be better than 4 dots per square meter (*i. e.* 0.5 m). In order to obtain LoD1 3-D city model, minimum requirement is 1 dot per square meter. Detection of roofs in LoD2 requires minimum 6 dots per roof area for a simple roof, 12 dots for a gabled roof and 24 dots for a hipped roof.

The CityGML data is stored in the 3-DCityDB, an open source extension to the Oracle or PostgreSQL databases. The calculated values of solar irradiation are stored in database tables within the 3-D CityDB and are connected to cityGML buildings and roof planes.

To perform manual editing of cityGML buildings, a Sketchup plugin is used. It enables Sketchup .skp format export and import in novaFACTORY while editing is performed in Sketchup. When a new building is added to 3-D city model, calculation of solar irradiation can be automatically run again to update the solar service.

Cartographic visualization of the i-Scope 3-D UIM is performed through a web client with a 3-D visualization view component. The 3-D view manages real-time rendering of the terrain and LoD2 cityGML buildings. The requested annual or monthly solar irradiation maps are rendered over the roofs. Retrieval of additional information by clicking on a roof plane is also enabled by web feature service (WFS).

The i-SCOPE Application

The i-Scope solar potential service aims to provide information on city roofs' characteristics that are related to solar energy. The information is delivered to the users through a 3-D web map solution. The i-Scope 3-D Web Client, publicly accessible at http://iscope.graphitech-projects.com/en/, is aimed at rendering 2.5-D terrain and CityGML 3-D buildings, access buildings and layers metadata and start simulation on top of the available data [14]. The web client is composed of two components, the client side interface based on HTML and jQuery and the 3-D visualization view based on Java applet and OpenGL technology.

When 3-D visualization applet is loaded, 3-D city map is displayed (chosen among the pilot cities) with LoD2 [26] 3-D buildings and 2.5-D terrain orthophoto (or OpenStreetMap, depending on the pilot city). Initially, the map of annual irradiation is rendered over the roofs and brings the information in form of a color palette, fig. 3, explained by the related legend. The user can select a particular month and visualize the average irradiation map for the selected month rendered over the entire terrain.

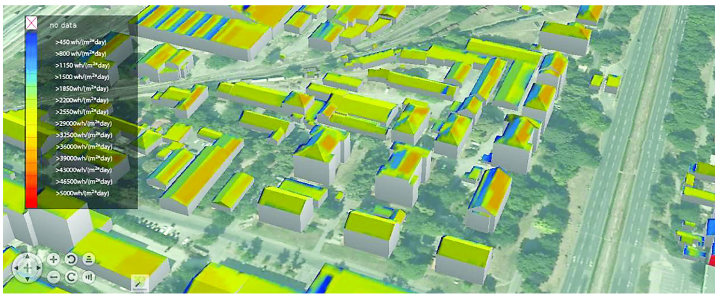

Figure 3. The i-Scope 3-D solar map; the roofs are colored to present annual irradiation

The user can select a roof which triggers loading of the Information window. The Information window provides the information on: average year irradiation [kWhm^{-2}], roof south exposure [%], roof monthly irradiation [kWhm^{-2} per day], address of the building, roof area [m²], average roof irradiation [kWhm^{-2} per day], and full roof annual irradiation [MWh], fig. 4.

Figure 4. Detailed information presented for a selected roof

Another functionality provided by the service is roofs' potential calculator which calculates the solar potential of a selected roof surface under certain conditions set by the user. The parameters that need to be set are: desired system peak power [kW], type of PV panel (monocrystalline, polycrystalline, custom), system installation costs: total per W installation cost (panel + additional equipment + installation) [€/W], installation incentive [%]: economic contribution to the installation provided by the municipality, region, province, country, or community in percentage of the total costs (if any), electricity self-consumption [%]: percentage of self-consumed (not feed into the net) over the total produced power, panel efficiency [%]: the efficiency depends on the selected paned typology, kWh buying cost [€], kWh selling value [€], and system loss [%].

The calculator provides results organized in three sections: simulated system information (*e. g.* annual production, percent of roof coverage, *etc.*), economics factor (*e. g.* system installation cost, total costs, return on investment, *etc.*), and other factors (*e. g.* annual self-consumption savings and revenues, CO_2 reduction, *etc.*)

Discussion and conclusions

The importance of estimation of actual solar irradiation is clear when it comes to sustainable environmental and resource planning [27]. On the other hand, due to decreasing costs of the PV technology solar energy becomes very competitive [28] with other energy resources and a good business opportunity. However, any *smart* investment decision is always based on the information on solar potential of the area of interest.

Exploitation of solar energy is particularly attractive in cities because the most suitable location to generate electricity from PV solar panels is at the source of consumption, but there are also other environmental, technical, and economical advantages of installing solar panels on individual rooftops [29].

The i-Scope solar potential estimation service for cities provides functionalities that support decision making with respect to investing in solar energy exploitation. The design of the i-Scope service takes into account all three aspects of the role of solar maps as a decision support tool identified by [12] which they define as a precondition for accelerating a full development of solar energy in cities. These aspects include: the difference in users (politicians, urban planners, investors, real estate owners), scale (city, urban district, building), and soft aspects (raise interest, vitalize the debate, get a common base for discussion). The same study presented comparative analysis of urban solar maps of 19 European and USA cities and a methodology for classification of solar maps using basic, medium, and advanced classes. According to the defined criteria, the i-Scope solution is classified as advanced solar map.

The service is built on 3-D UIM and the communication with the users is achieved through an interactive 3-D map. In this way, the solar potential data can be integrated with other urban information in an appropriate LoD level of the 3-D geometric model which will enable further information retrieval and analysis. Moreover, 3-D interactive maps enable better users' perception and understanding of spatial phenomena and raise users' interest in the map content.

The i-Scope solar service can be also useful to professionals (*e. g.* architects, planners) allowing them to make experiments in a highly realistic virtual 3-D environment and search for an optimal solution. For example, specific architectural designs are developed in order to make use of solar energy to create passive buildings [30]. Designed building models can be easily integrated into 3-D cityGML and calculation of solar irradiation would be performed with respect to the new situation.

The accuracy of information on solar potential depends on the geometric quality of 3-D city model. There are a number of advanced techniques that enable generation of high resolution DSM and DEM as the input data for building LoD2 cityGML. Since it can be foreseen that the 3-D city models (like the one described) will play an increasingly important role in our daily lives and become an essential part of the modern city spatial data infrastructure [31], it is expected that cities will increase investments in regular 3-D data acquisitions. In this paper, it is showed that the methodology based on filtering raw DSM automatically generated from stereophotogrammetry can provide sufficient accuracy in 3-D roof modelling for shad and gable roofs. This approach can significantly decrease costs of 3-D city model generation since it decreases the need for manual 3-D digitalization of roofs from stereophotogrammetry or laser scanning.

Future work is needed to focus on further automation of filtering of DSM generated from stereophotogrammetry by developing an automatic method of roof type discrimination. The possible approach is application of point cloud segmentation methods (*e. g.* [32, 33]). This would additionally facilitate implementation of urban solar potential information services.

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