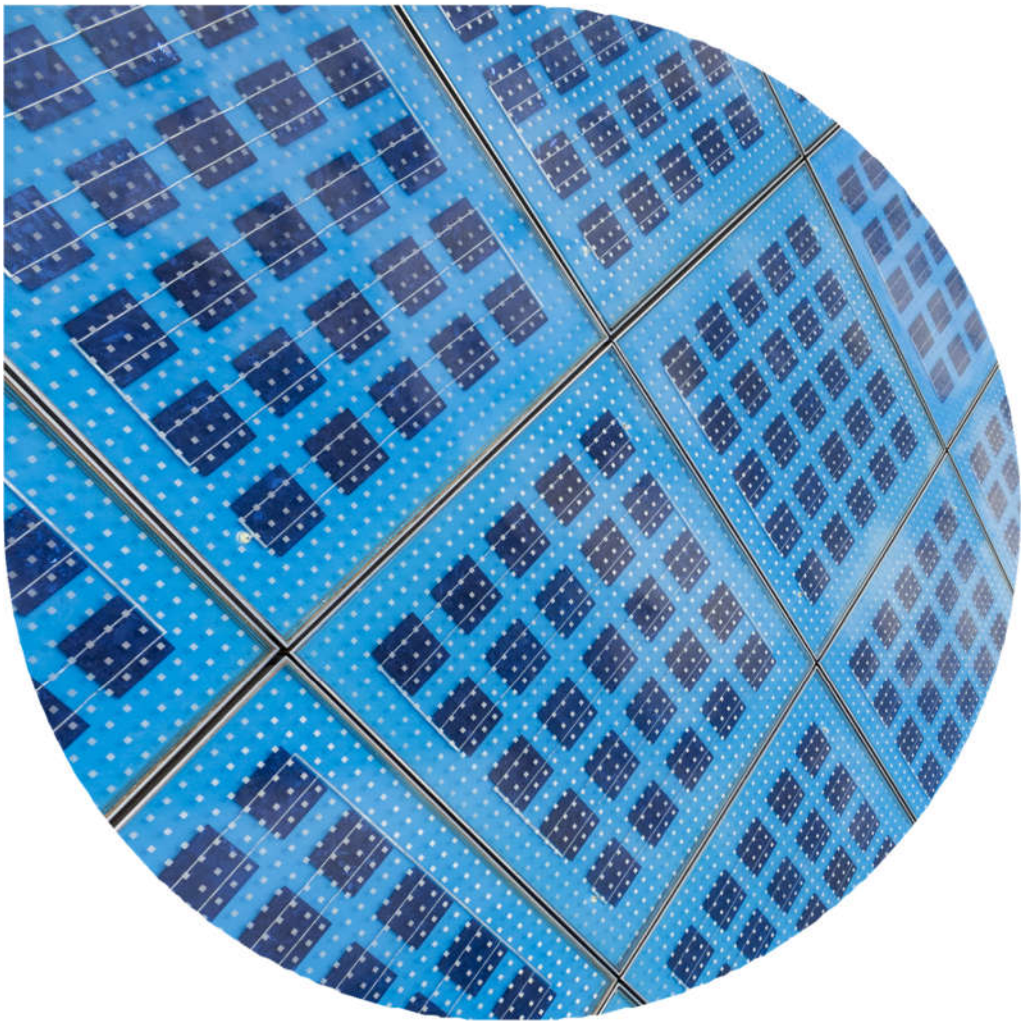

Mapping solar potential in pilot municipalities

Deliverable D II.1

SOLAR ADRIA

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List of abbreviations

AI – artificial intelligence
DEM- Digital Elevation model
DTM – Digital Terrain Model
DSM – Digital Surface Model
3D – Tri-dimensional
2D - Two-dimensional
EU – European Union
GIS -Geographical Information System
GHI - Global Horizontal Irradiation
GRASS -Geographic Resources Analysis Support System
GUI – Graphical User Interface
JRC – Joint Research Centre
Land Cover -CCI Land Cover Climate Change Initiative
LIDAR - Light Detection and Ranging
ML -Machine Learning
NPV – Net Present Value
OECD -Organisation for Economic Co-operation and Development
OSGeo The Open-Source Geospatial Foundation
OSM – Open Street Map
PV -photovoltaic
PVGIS – Photovoltaic Geographical Information system
RoR – Rate of Return
RPV – Rooftop Photovoltaics
SVF- Sky View Factor
UAV – Unmanned Aerial Vehicle
US – United States

Glossary

Irradiation - amount of solar radiation obtained per unit area by a given surface (W/m2) sum of energy per
Radiation - radiant energy emitted from the Sun
GDAL- transfer library for raster and vector geospatial data
HRN EN – Croatian norms for energy
CORINE Land Cover (CLC) - land cover database of European Union
MATLAB – programming and numeric computing platform for data analysis, development of algorithms and creation of models
ArcGIS - software that allows handling and analysing geographic information by visualizing geographical statistics through layer building maps
GRASS GIS - free Geographic Information System (GIS) software used for geospatial data management and analysis, image processing, spatial data visualisation etc.

Introduction

Deployment of photovoltaics (PV) on building rooftops can play a significant role in the transition to a low-carbon energy system. Even though rich in natural potential, this development has been slow in Adriatic region. Therefore, it is evident that the tools and actions are needed to mobilise this untapped potential. Understanding the potential of rooftops in urban areas for production of electricity from sun energy is important at various scales, from improvement of local economic conditions at the scale of a household up to decarbonisation goals at national level.

Based on existing experience in the field and available data, we created a model for visualisation and estimation of solar potential of pilot cities as indication of rooftop suitability for PV installation. Solar potential is displayed in form of solar maps that are a strong visual tool to communicate the massage, especially towards city officials considering creation of policies for PV stimulation and urban planning. Knowing the solar potential can enable property owners and other stakeholders to identify opportunities for electricity production. It can also make them aware of the risks and enable them to make informed decisions about installation of PV.

Finally, we provide description of model development. Based on our approach, other public authorities can conduct initial scanning, develop a solar potential model and shape polices that support PV development at the places with untapped potential.

CHAPTER 1

Models for solar energy mapping – an overview

Solar potential can be defined as potential suitability of a given surface for a PV system installation expressed by irradiance the given surface receives throughout the year (in kW/m^2). It is usually presented in a form of a solar potential map for analysed area. From the solar potential, electricity generation by a PV system on a given rooftop can be calculated. Solar and PV potentials depend on the underlying irradiance model that is being used. Today there are many methodological approaches and different models for modelling solar potential. They differ in source and quality of input data, scale, underlying assumptions, methods, and computer software used to process input data. As the computational science is developing, so are the possibilities for faster and better solar potential estimates. Based on the overview of models and methodologies applied in different cases across the globe, we recommend the design of Solar Adria model most suitable for the region. Such model should be easy to use, based on available data and replicable. However, despite striving to simplicity, the model still requires some level of expertise, especially in data processing.

1 Models and methodologies for solar potential mapping

The literature review reveals extensive studies of the solar energy potential in the last decade, based on numerous methods applied at various locations and scales (from few houses to whole countries). In Europe development is driven by EU goals for decarbonisation and recognition that the PV could be an important contributor to achievement of that aim. The solar potential of the building should provide an answer if a building is suitable for PV construction, however urban structures have complicated features and after a general analysis an onsite inspection of the roof is still needed. The comparison of different models and methodologies is a difficult task since the examined cases are based on different datasets, methods, approaches, spatial and temporal resolution etc. For example, higher spatial and temporal resolution allow precise estimation of potential, but often data are not available at such scales. On the other hand, high resolution data can mean large computational time and a need for an expert that can process the data.

Hierarchical approach for solar potential has been widely accepted over the years (*Mavsar et al. 2019, Walch et al. 2019, Fakhraian et al, 2021).* This approach, in most of the cases, describes the potential by four categories (Figure 1-1):

1. **Physical potential** – maximum amount of solar energy (total solar radiation) that reaches certain surface. Solar radiation is estimated based on meteorological data (e.g. monthly radiation, monthly clearness index) and can be obtained from ground-based meteorological stations, satellite observations or from different solar models by calculating the needed data from other available

data sources. Satellite data is preferable to measurement station data due to the better spatial coverage, increased resolution, and low missing data ratio (*Fakhraian et. al, 2021*).

2. **Geographic potential** –available solar radiation on surface (calculated by excluding zones for other uses and taking in consideration constrains like slope, aspect, shading from neighbouring buildings…). The input can be obtained from statistical institutions (the number of buildings and the population in the urban areas), statistical construction data, Corine Land Cover, cadastral data, LiDAR data, GIS data which can be modified using ArcGIS tools and Google satellite images or digital urban maps obtained from Google Earth (Fakhraian et. al, 2021).

3. **Technical potential** – electricity generation considering technical characteristics of the equipment used for conversion of energy (efficiency and system performance of PV). In addition to the technical characteristics of photovoltaics, the space needed between photovoltaic modules to avoid shadowing is another important factor for determining the technical potential.

4. **Economic potential** - electricity generation considering price of electricity and other economical parameters such as installation costs, maintenance costs, installation lifetime, interest rate, operational cost, as well as cost constraints, societal constraints, and government regulations.

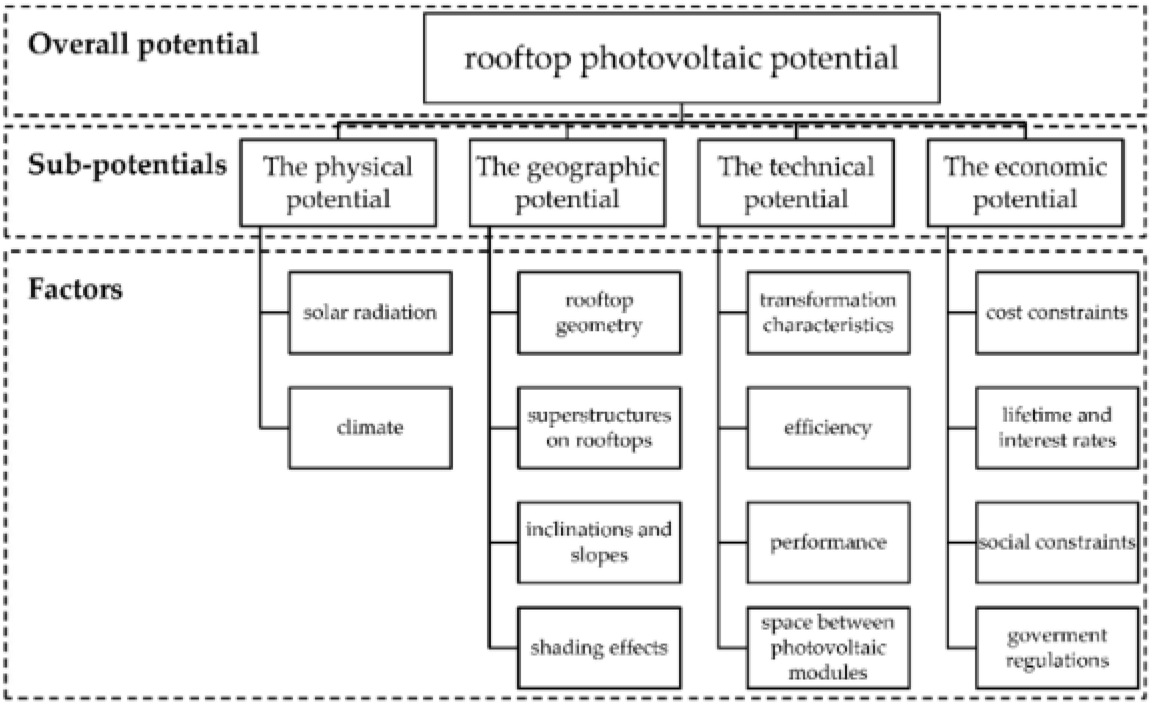

Figure 1-1 Essential factors for rooftop PV potential determination (Source: Fakhraian et. al, 2021)

Freitas et al. (2015) indicate that the more levels of potential a model can perform, the easier it is to communicate the advantages of building integrated solar systems to the general public and to help policy-making processes by identifying all available energy resources of a country and the most interesting areas within a city.

State-of-the-art review of modelling solar power in urban environments is provided by Freitas et al. (2015) and Fakhraian et al. (2021). They present the variety of the technologies but underline that the appropriate methodology should be selected based on end-goal and level of details required.

Freitas at al. (2015) provide a detail description of i) empirical solar radiation models, and ii) computational solar radiation models. Empirical models use data from meteorological stations or satellites to provide solar irradiance on horizontal plane. The simplest models consider radiation to be the entire sky view and that global solar irradiance has three components: direct beam, isotropic diffuse and diffusely reflected from the ground. Then there are more realistic anisotropic models that define anisotropy index. Among empirical solar radiation models there is great diversity in performance depending on conditions. In the literature (Freitas et al, 2015) the Perez model is considered as the best performing model.

Physically based solar radiation alone is not enough for estimation of potential due to obstructions of sunlight. In that sense, computational modelling of the physical context is applied. Computational models are described through i) concepts and numerical methods, ii) solar potential urban-oriented models, and iii) web-based maps. Most relevant concepts are shown in Table 1-1.

Table 1-1 Most relevant concepts and numerical solar radiation models (Source: Freitas et al. 2015)

Tool	Purpose	Related solar potential
GOSOL	Simulation software that can analyse energy balance on surfaces. Provides an outline of obstructions so shading patterns can be visualised. It uses building data source of German housing types.	Physical/ geographical
SHADOWPACK	Contour maps of shading evaluations for the direct radiation (modest shading evaluations).	Physical
ATM	Image processing framework can generate topoclimatologies for large areas at arbitrary time intervals.	Geographical
Solei-32	Potential energy income to slopes with different orientations and cloudiness, shadow from surrounding topography.	Geographical
Sky view factor (SVF)	Percentage of visible sky for diffuse radiation calculation. Introduced to classify obstructions resulting either from self-shadowing by the slope itself (shading) or from adjacent terrain (shadowing).	Physical/ geographical
SolarFlux	Topographic GIS capabilities deliver total direct and diffuse radiation, direct sun duration, SVF and fisheye projections of sky obstructions. AML program. Errors in DEM have great impact on solar irradiance.	Geographical
Kumar et al.	Direct clear-sky short-wave radiation for the DEM of a large area, latitude and time interval. AML program.	Physical/ geographical
RADIANCE	Software employs light-backwards ray-tracing algorithm for direct radiation, diffuse and specular reflections from urban obstructions in a volumetric 3D model. Applies Perez diffuse radiation model and considers both diffuse and specular reflections from urban obstructions.	Physical
Cumulative sky approach	Global irradiance at the centroid of a scheme of patches 145 patches subtending a similar solid angle. Included in RADIANCE in form of GenCumulativeSky.	Physical
Daysim	RADIANCE based daylight analysis software. Illuminance profile at each point in and around buildings using a daylight coefficient and RADIANCE based backward ray-tracing.	Physical
ArcGIS Solar Analyst	ArcView GIS extension delivers a set of various radiation maps, fisheye equivalent photograph and a viewshed analysis. The most relevant inputs for the model are location, elevation, orientation, and atmospheric transmission. It is flexible in terms of temporal and spatial resolution.	Geographical

SRAD	Circumsolar radiation derived from within 5 degrees of the direct solar beam and an isotropic portion of the diffuse, monthly average cloudiness and sky view factor.	Physical
Solar Envelopes	A zoning device to achieve the largest volume that a building can occupy, regulates the development within limits of solar obstruction.	Physical
Albedo calculator and Albedo viewer	Simulation of albedos within 3D urban structures and web database. GUI based applications.	Physical
ESRA clear-sky model	Beam irradiance at ground level from satellite images and data fitting techniques. Uses Heliostat approach to derive info from satellite images.	Physical/ geographical
r.sun	Irradiance raster maps, reflectance, and shadow maps for horizontal or inclined surfaces, fitting to overcast and clear-sky conditions. Uses raster maps of terrain, latitude, turbidity, radiation, and clear-sky index to produce irradiance maps. Optimised for European climate condition. Its most relevant contribution is PVGIS online database.	Physical/ geographical
RayMan	Detailed simulation for the short- and long-wave radiation flux densities from the three-dimensional surroundings. Build for human thermal comfort analysis.	Physical/ geographical
Preferable sky window	Sky section which has the greatest daylight potential in a horizontal plan located inside a building	Physical
Tooke et al.	Fraction of incoming radiation that is transmitted through the semi-transparent vegetation canopy	Physical
Solar3DBR	Google SketchUp plug-in for shading factor and the solar radiation determination on surfaces of 3D models	Physical/ geographical
SORAM	Direct and diffuse solar radiation incident on a sloping PV cell in an urban environment by ray-tracing.	Physical/ geographical

Tools such as the Solar Analyst of the software ArcGIS or r.sun of the open-source GRASS-GIS platform have been utilized to develop a large number of cadastres for photovoltaic and solar thermal systems for locations all around the globe. These tools serve to calculate theoretical solar radiation potentials based on geographic and geometric parameters such as latitude, longitude, altitude, aspect and slope of surfaces and further basic parameters to account for the atmosphere. This theoretical calculation corresponds to the solar radiation under clear-sky conditions. To calculate solar radiation estimations under real-sky conditions, the tools include the possibility of integrating measured data to indirectly consider clouds and improve the solar radiation prediction. The calculation of the effect of shadowing of near and distant objects using DEMs is also possible, and one of the major assets of GIS-based calculation methods, particularly when studying mountainous territories or urban areas, in comparison to studies based solely on satellite imagery.

To associate 3D urban construction to calculation based on physical based formulation of solar radiation, more complex models are needed. All-in-one models contain tools that couple modules for solar radiation treatment with design interface or 3D object representation in a single software. They allow reliable quality assessment at small and medium scale and feature user friendly environment (Freitas et al, 2015). All-in-one models are TOWNSCOPE and SOLENE. TOWNSCOPE software consists of 3D urban information system coupled with solar evaluation tools, morphological and wind risk analysis tool. Once the 3D model is completed, the data processing tools calculate the direct, diffuse and reflected solar radiation at any point or face defined by user. SOLENE is an asset of numerical models for simulation of natural light in the urban morphologies. It is suitable for smaller units (set of buildings, streets, small district).

While previous models receive the 3D objects but also have their own designed models, CAD plug-in based 3D models receive plugins from other software able to conduct radiation analysis. Their advantage is that they are very versatile, perform with great detail and are user friendly (Freitas et al, 2015). CAD plug-in models are Skelion and Autodesk ecotect analysis. Skelion is a plug in for Google ScetchUP. It simulates the electrical output of a number of PV components added to a certain design. Georeferenced buildings are imported from Google Earth. Solar radiation and the subsequent electrical PV production estimates are acquired from PVGIS database or PVWatts. Autodesk ecotect analysis can be applied for solar radiation of windows and surfaces showing different incident radiation calculated over any period using latitude, longitude, and climate files input.

GIS based models are designed to obtain spatially and temporally resolved solar radiation estimates on the ground over large geographic areas. Traditional GIS radiation models such as ESRI ArcGIS Solar Analyst and GRASS GISS r.sun can operate only on two-dimensional raster maps that supply surface elevation. Such 2D raster maps are not able to represent complex geometries such as vertical surfaces and overhangs. Therefore, the future of the modelling is in 3D models and well estimating potential on facades. Thanks to UAV technology and 3D reconstruction technologies, oblique airborne photometry-based 3D city models have become widely available (Liang et al, 2020).

GIS -based models are considered as good models to predict the physical potential of the solar resource at a large scale (Feitas et. al. 2015), and widely used for spatial assessments of solar energy (Camargo & Stoeglehner, 2018). They rely on GIS to represent the outputs of radiation algorithms applied to the surface data. The main characteristics of these models are summarised in the table Table 1-2.

Table 1-2 Overview of GIS based models (Source: adapted from Feitas et al., 2015)

Approach	Characteristics
Carneiro et. al	• 2.5D urban surface model (2.5DSUM) • Data: LIDAR data, 2D vectorial digital maps of building footprints, altimetric information about building hights, MeteoNorm database (average monthly radiation) • Radiation is calculated using Hay and SVF model • Software: GIS, Matlab • Appropriate for flat and tilted roofs
v.sun	• 3D model • Data: photogrammetry, satellite images (raster maps for solar radiation). • Radiation is calculated using r.sun model • Software: GRASS GIS • Appropriate for flat rooftops, facades
Jakubiec and Reinhart	• 3D model • Data: LIDAR, oblique images, Boston Logan TMY3 • Radiation is calculated using Perez model and cumulative sky method • Software: radiance/Daysim • Appropriate for detailed rooftops, tilted surfaces
SOL	• Data: photogrammetry (georeferenced LIDAR data cloud sampled to 1x1m2 raster), SolTerm database from radiation • Radiation is calculated using Kumar model and SVF • Software: Matlab, ArcGIS • Appropriate for detailed rooftops, tilted surfaces, facades

There are multiple GIS tools to support assessments of solar energy resources and wide range of methodologies that have been used to approach the topic for diverse study areas in different spatial resolutions (Camargo & Stoeglehner, 2018).

The development of GIS applications and remote sensing data such as LIDAR (Light Detection And Ranging) have become useful tools with promising results. However, the lack of data in some regions, the high cost of accessing the data sources, and time-consuming procedures, have made this progress bounded, which led to the lack of urban solar energy production potential maps on global scales. In this sense, web-based free access data such as free satellite images from Google are seen as an opportunity to carry out actions (Fakhraian et. Al, 2021).

Application of LIDAR for modelling solar potential has been widely used at urban scale. LiDAR is an active remote sensing technology that captures surfaces topographies in high detail and can be used for accurate automatic solar irradiance estimations. The steps in application of LIDAR data for determining roof suitability and potential shows Figure 1-2.

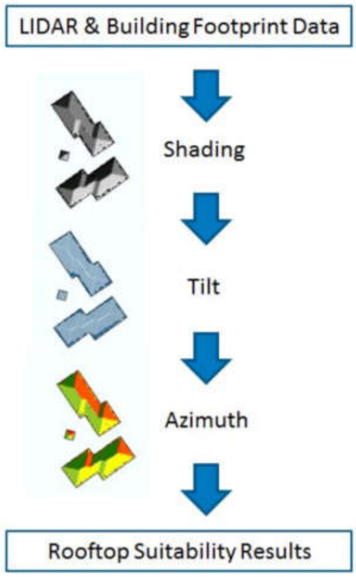

Figure 1-2 Determining suitability of roof area for PV based on LIDAR (Source: NREL, 2016)

Apart of physical models (used to compute the solar radiation) and geographic information systems (GIS), state of the art data processing techniques for estimating rooftop photovoltaics (RPV) potentials include image processing and machine learning (ML). Currently the trend is directed towards increasing spatial and temporal resolution, using larger and more accurate datasets for analysis through data driven estimations enabled by machine learning, scalable algorithms, and powerful computational engines (Walach et. al, 2020). The analysis of different models' application over the years performed by Walach et al. (2019) shows that the largest differences between the models are caused by the source of solar radiation input data, the computation of shading effects on rooftops and the estimation of available roof area for PV installation, later being the most uncertain parameter.

According to Fakhraian et. al. (2021) tools and approaches used to build the database and determine solar photovoltaic potential can be classified into 6 approaches:

- Statistical Sampling Approach
- Mathematical Approach
- Digital Modelling Approach and Commercial Software Packages
- Optimization Approach
- Artificial Intelligence in Commercial Software Packages Approach
- Artificial Intelligence Approach

With the development of technology and improvement in data accessibility, we can see application of advanced modelling as well as artificial intelligence. The study from Fakhraian et. al. (2021) found that in the years after 2015, the most applied approach was the artificial intelligence (AI), followed by digital modelling approaches and their related commercial software packages. For example, AI approach is taken within DeepRoof system (Lee, et al 2019) that analyses satellite imagery with convolutional neural networks (CNNs) to calculate solar energy potential and can eliminate the need for solar potential evaluations. The positive side of this approach is that satellite data is less expensive to collect and covers a wider geographical range than LIDAR data. On the otherside, expertise in image processing is needed. The supervised learning Support Vector Machine algorithm method is used to estimate the monthly global solar radiation and the geographical potential such as available roof area, roof slope, and shadowing effects on the roofs using LiDAR data, different land uses from the CORINE land cover data in vector polygon format, population density and building residential typology. The combination of MATLAB® and solar radiation analysis tools in geographic information system, as well as LIDAR data, were also frequently used. For example, a combination of GIS, solar models, and random forests machine learning algorithm was used to estimate the potential for rooftop PV solar energy in Switzerland based on Digital Orthophoto Map and LiDAR data.

The overview of some approaches to solar potential mapping from the literature is provided in Annex 1.

Economic potential has gained much more attention after 2015 (Fakhraian et. al, 2021). This is a result of interest of building owners in economic aspects of PV, since they are considering investing in rooftop photovoltaic installations if this is economically justifiable. The economic potential takes in account technical generation of electricity, the hourly price of electricity on the market, the investment cost, the installed power of PV system (Mavsar et al., 2019).

2 Solar maps

Solar potential is usually represented in 2D maps, 2.5D or 3D urban models and is in many cases showcased within web-based platform. The maps provide a specific information for a specific location. Information usually includes solar radiation, estimated PV system size, projected electricity production. The information that should also be available to the end user to benefit from the maps is costs of PV and corresponding savings.

Today there are also web applications for calculation of solar radiation and photovoltaic (PV) system energy production. State of the art examples include PVGIS, PVWatts, Mapdwell.

PVGIS solar radiation tool[1], developed by JRC, allows the visualisation of the solar radiation data with resolution of 1km. The tool calculates solar radiation using the r.sun model, using ground-based measurements. The user should first choose the start and end year for the output and input the coordinates of the area. Then there is a number of options which data to calculate. The tool has also other tabs that allow further calculations of performance of systems (grid connected, tracking, off grid).
The interface allows the user to input nominal peak power, estimated losses, orientation, inclination, mounting type, technology used etc. The output includes optimal panel inclination for a given location, monthly and yearly radiation maps, daily irradiance profiles, climatic parameters, and potential PV production. The results of the monthly radiation calculations are shown only as graphs, although the tabulated values can be downloaded in CSV or PDF format.

The solar irradiation for Starigrad and Koper for 2015 and 2016 is shown in Figure 2-1.

[1] https://ec.europa.eu/jrc/en/pvgis

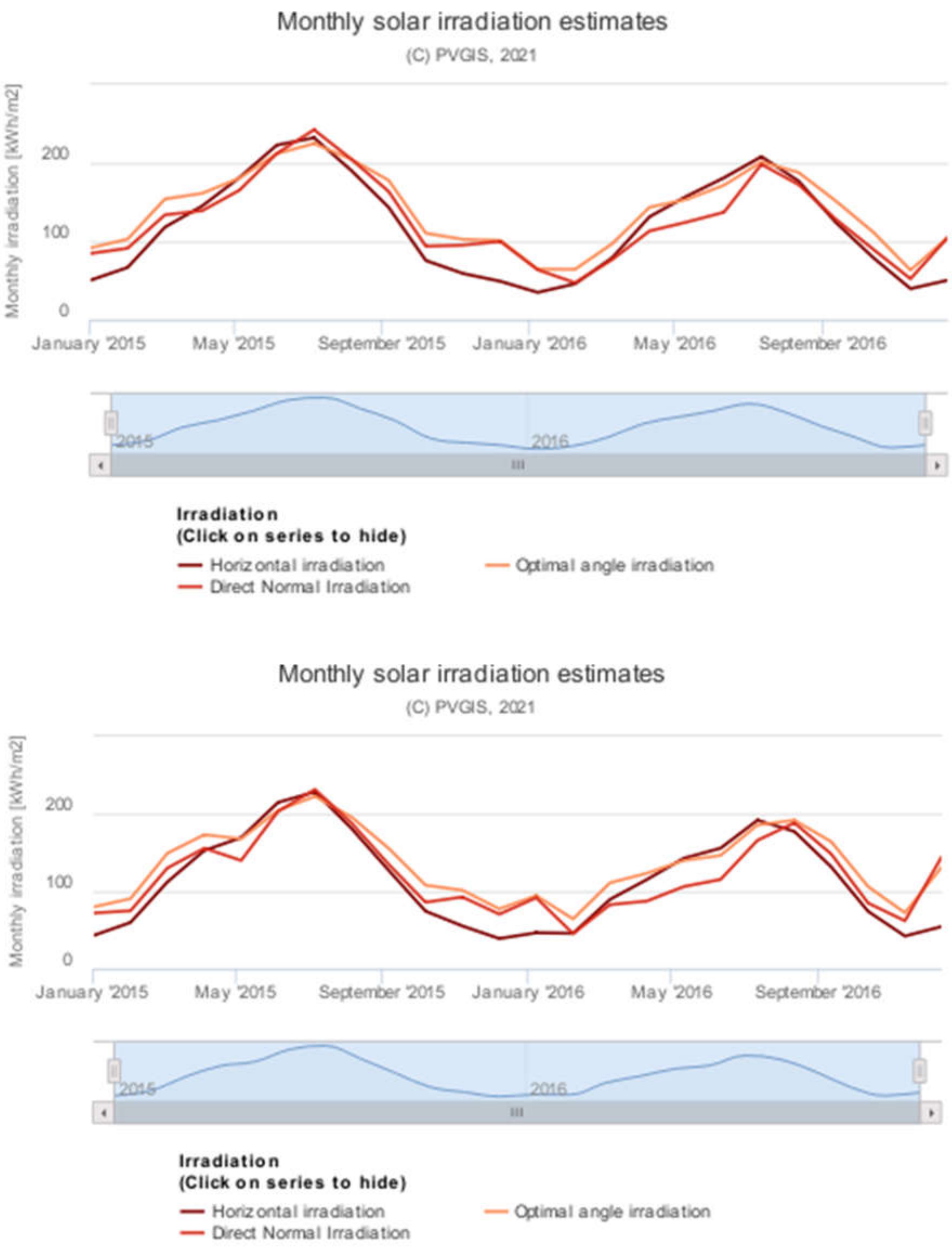

Figure 2-1 Monthly solar irradiation estimated based on PVGIS a) Starigrad, b) Koper

PVWatts[2] estimates annual PV production and its value (in US dollars) and allows input of local electricity costs, tilt, surface azimuth, tracking mode, DC rating and de-rating factor. In My Backyard incorporated in PVWatts tool, estimates the electricity produced by a PV system over a year, including hourly AC output, its value, payback and contribution to the load profile. An hourly satellite-derived data set with a spatial resolution of 10 km is used to calculate the solar resource.

[2] https://pvwatts.nrel.gov/

Mapdwell Solar System maps[3] (for US) show financial, technical, and environmental information for selected roof (cost to owner [$], monthly revenue [$], system size [kW], payback period [yr], and carbon offset). A coloured code also help visualizing roofs defined as "poor", "average", "good" and "optimal" or not available at all.

Another example is Google project Sunroof[4] which uses GIS data, 3D modelling derived from arial imagery, and shading calculations to predict PV energy generation potential at a rooftop. It provides information on hours of sunlight (yearly), area available for installation (roof patterns, shadowing) recommended solar installation size (kW), CO_2 savings. This is standalone model, available only for USA area.

Examples of some solar maps worldwide are provided in the Table 2-1. Due to diversity in the approaches, some basic info is given for each map. Examples are shown for Bolzano, Bristol and Helsinki (Figure 2-2, Figure 2-3, Figure 2-4).

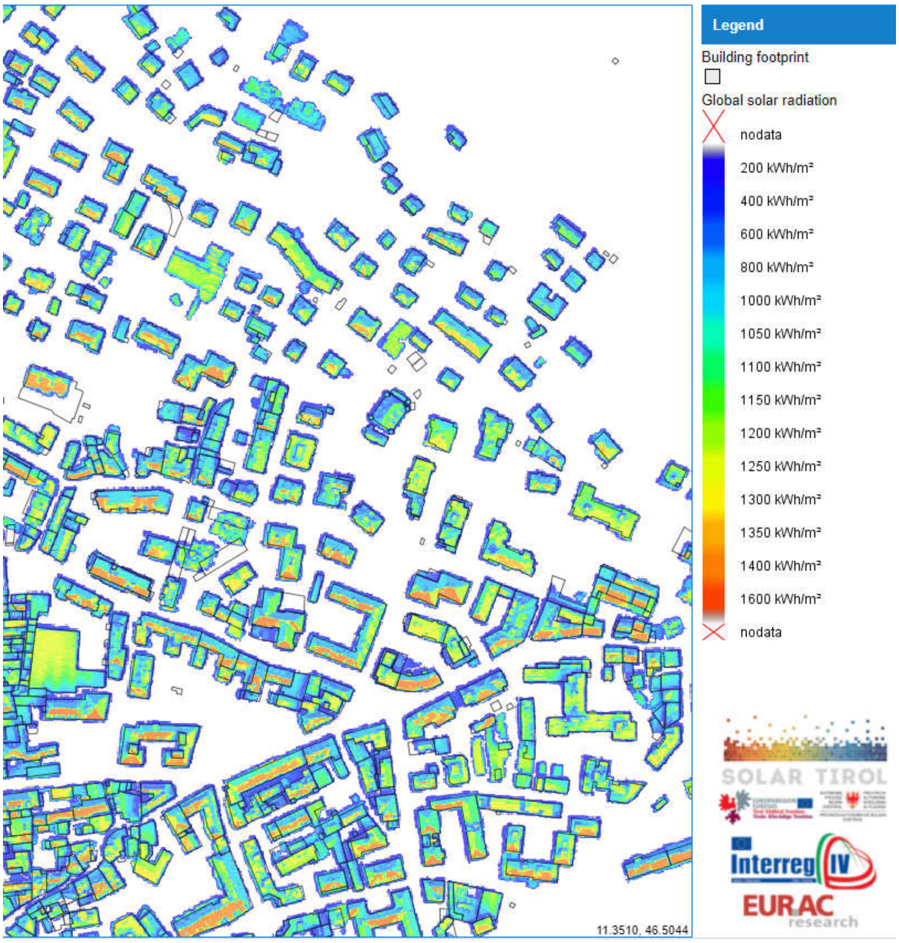

Figure 2-2 Example of solar map for city of Bolzano

[3] https://mapdwell.com/en
[4] https://sunroof.withgoogle.com/

Table 2-1 Examples of solar maps worldwide (URL valid on 13.09.2021)

Solar map	URL	Description
Los Angeles Country	http://solarmap.lacounty.gov/	Map shows four levels of potential. Information available: roof area, area fit for solar, solar pV potential (up to kW), electricity produced (kWh/year), electricity savings ($/year), carbon savings (lbs/year). Printable report includes rough estimation of cost and explanation of calculations.
City of Vienna	https://www.wien.gv.at/umweltgut/public/grafik.aspx?ThemePage=9	Map shows two levels of potential- good and very good. Information available: installed PV, the address, roof area (m²), energy generation kWh_{el} /year.
Northern Virginia	https://nvrc.maps.arcgis.com/apps/webappviewer/index.html?id=ef5c5dc969f341cc986cd431d94cdfe9	Map shows exact potential. Information available: roof area, area fit for solar, solar pV size (up to kW), electricity produced (kWh/year), electricity savings ($/year), carbon savings (t/year).
New York City	http://www.nycsolarmap.com/	Data represented at the level of neighbourhood, not individual houses.
Auckland	https://solarpower.cer.auckland.ac.nz/	Map shows nine levels of potential (solar radiation kwh/m²/year). Information available: annual solar radiation (kWh/roof), annual energy generation (kWh/roof), annual revenue savings ($/roof), NPV.
Chicago	https://www.elevatenp.org/chi-solar-map/#15/41.92687/-87.70687	Map shows six levels of potential. Information available: property type, solar pV capacity (up to kW), electricity generation (kWh/year), carbon offset (t/year).
Osnabrück	http://geo.osnabrueck.de/solar/	Four main divisions: not possible, very low potential (<650 kW/a), some potential and good potential PV. Good for PV roof potential divided into 5 categories (flat roof, tilted E, S, N, W). Information available: area for PV (m²), electricity generation (kWh/year), carbon offset (t/year), installed capacity (per roof).
Bristol	https://www.arcgis.com/apps/mapviewer/index.html?webmap=2364a7046a62417d8a92eec4494d5a45 https://opendata.bristol.gov.uk/explore/dataset/solar-potential/map/?location=17,51.458,-2.59491&basemap=jawg.streets	Map shows three levels of potential (low, average, high) (Figure 2-3). Information available: unshaded roof area (m²), PV generation (kWh/yr), insolation (kWh/m²), emission savings (kg CO_2/yr), system size (kW), suitability.
London	https://maps.london.gov.uk/lsom/	Map shows est. annual output per roof (kWh) – 11 categories. Information available: annual input (kWh), installed potential (kW), potential per m² (kWh/m²), viable area for installation (m²), carbon savings (kg). Explanation provided.
Lisbon	https://www.solis-lisboa.pt/mapa-solar-de-li/	Indication of shadows and solar radiation.
Wroclaw	https://gis.um.wroc.pl/imap/?gpmap=MapaSolarna&locale=en	Information available: installed capacity (Wh), electricity production (kWh)
Koprivnica	https://www.arcgis.com/apps/MapJournal/index.html?appid=03da64a0ce8940e4ba63a4ce9e59be7a	Solar potential shown in (kWh/m2 (0->1300), not average per roof but on parts of the roof different potentials.
Velika Gorica	http://solarnigrad.info/	Information available: total roof area, type of roof (tilted or not), electricity production annual, CO_2 savings, ROR.
Tirol	http://webgis.eurac.edu/solartirol/	Gradation of solar potential from 0-1300 kWh/m². Information available: for each part of the roof insolation, area, energy yield. Example provided for city of Bolzano (Figure 2-2)
Calgary	https://maps.calgary.ca/SolarPotential/	Map shows four levels of potential in terms of yield (kWh/m²/day) – low-high. Data not averaged per roof, but exact potential is shown.
Municipalities in Germany	https://solar.tetraeder.com/en_v2/municipalities/spm/	Potential shown in three maps: 1. four levels of potential (very from suitable to not suitable)- represented for whole roof one value. 2. Potential levels at each roof from low to strong 3. Suitable roof parts – three levels of solar radiation. Allows user to configure.
Helsinki	https://kartta.hel.fi/3d/solar/#/	3D map, also shows the potential of facades (Figure 2-4). Information available: radiation (kWh global, diffuse, direct).
Long Island, US	https://tnc.maps.arcgis.com/apps/webappviewer/index.html?id=d61dfb3bad544dbea16397e08f084ff1	Demonstrates energy generation potential (MWon sg.ft) for low-impact sites for commercial and utility-scale solar arrays. Results shown for: large rooftops, parking lots, previously disturbed lands (ground mounted) and combined.

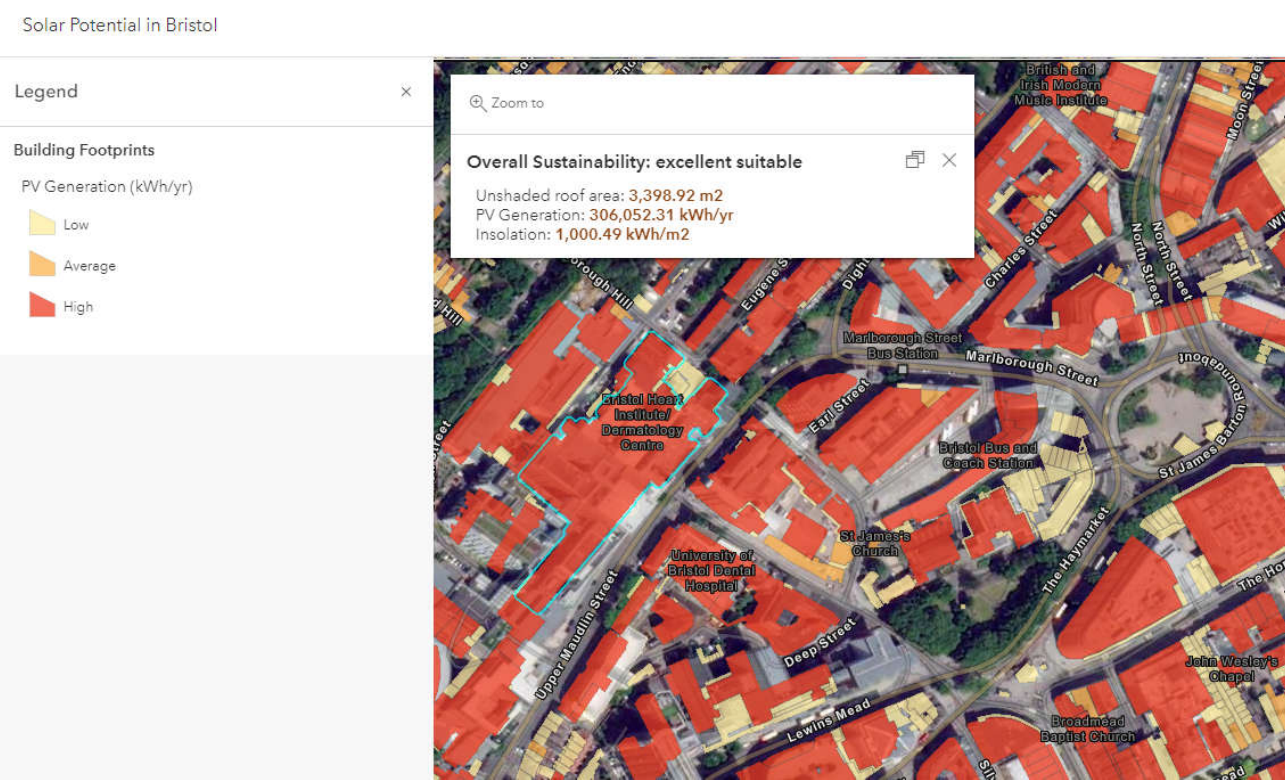

Figure 2-3 Example of solar map for city of Bristol

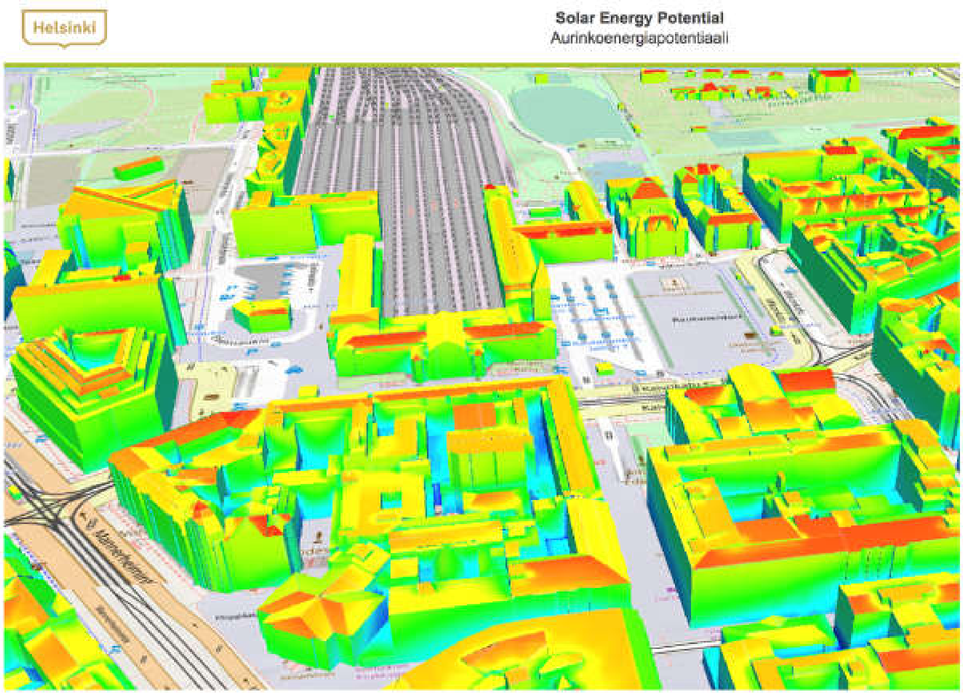

Figure 2-4 Solar energy model on Helsinki 3D+ (Source: Ruohomäki et al, 2018)

CHAPTER 2

Solar potential mapping in pilot areas

Framing an appropriate methodology for solar potential mapping will depend on target audience, spatiotemporal resolution, available datasets, methods, computational competences etc. In this chapter we describe the selected approach and method for solar potential mapping for pilot municipalities Starigrad and Koper with an aim to provide a tool to promote and enable better decisions on PV installations.

3 Model selected for mapping

As shown in the previous chapter, there are various models and algorithms used for solar potential modelling, but they all follow the same general steps. These steps include definition of goals and objectives of the model, selection and preparation of input data, computation of radiation models and analysis, and finally presentation of results.

Model must be based on appropriate available data, ideally easy to use and the results should be easy to understand. Since we are dealing with models, in general, the quality of the model results will depend on the quality of the input data and skills of the analyst processing the data. Higher temporal and spatial resolution of input data will provide more accurate results but at the same time can be hard to process and demand more computational skills and time. The choice and precision of the input data used should be based on the user expectations and goals of the model.

In this chapter we present the Solar Adria approach to estimating the solar potential in pilot areas. We first define the goals of the model and based on them pick the appropriate scope for modelling based on categorization by Fakhraian et al. 2021 (see figure Figure 1-1). Following this, we chose a model from the above review (Table 1-1) that meets the requirements and for which suitable data could be acquired. Project teams' familiarity with software also played a role in selection of the model and modelling environment.

3.1 Goals and objectives of the model

Models of solar radiation for Starigrad and Koper are among the primary tools through which the Solar Adria project's goals will be realised. The project aims to increase the understanding of the participatory urban planning as a mean for deployment of solar energy projects in urban areas and to strengthen the knowledge capacity of target groups and their dialogue. To this end the objectives of the model are:

- To promote solar energy by showcasing the high overall potential of solar energy in the pilot municipalities, as well as individual building potential, in a clear and easy to understand way,

- To provide the municipality an interactive tool through which they will be able to engage other stakeholders in a dialogue about solar power and plan projects more easily,
- To identify possible (built) locations for solar energy development.

It is evident that the **primary purpose of the model is to serve as a first-step or an initiator of the decision to install a solar power plant** on a building and as a promotional tool, while provision of exact detailed (technical and economic) data on the level of individual roof is secondary. This does not mean that the provided data is not accurate, but the user should bear in mind that the model is generated for the whole municipality, applying universal factors in calculations (more on this in the chapter Model limitations). Following Fakhraian et. al (2021), the model must be at a geographic level of precision. It must calculate available solar radiation on surface, considering constrains like slope, aspect, shading from neighbouring buildings, superstructure on roof and other elements. To make the model information more tangible for residents, we additionally included approximations of technical potential per roof by applying factors to the geographic potential accounting for minimum PV area and roof type differences (flat vs. tilted). The major steps of the approach are illustrated in Figure 3 1.

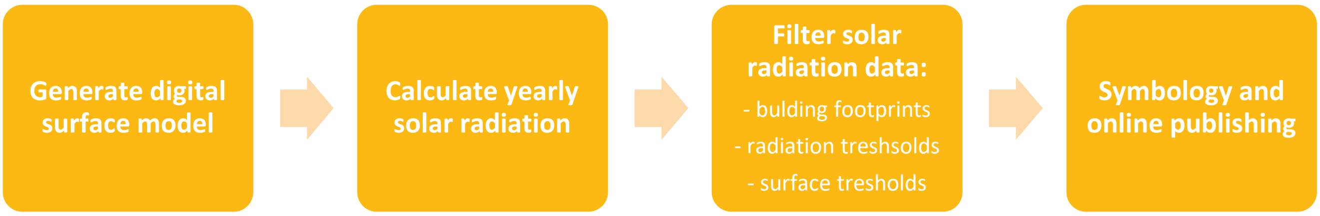

Figure 3-1: General workflow of creating solar potential maps.

3.2 Input data (sources)

The key input data to generate solar radiation data is a digital surface model (DSM), which represents the surfaces for which solar radiation should be calculated. A DSM typically includes all above ground structures such as trees, buildings, and other elements, which are also sources of shading. To obtain a detailed DSM (0.5 x 0.5 m) we used high resolution LIDAR data from which we generated a DSM using only first return points. For Starigrad we obtained LIDAR data from custom scanning for the purposes of the project (by UAV SenseFly eBee RTK Drone), while we used publicly available data for Koper. The average point spacing for Koper is 0.3 m, while for Starigrad it is 0.15 m, indicating slightly better resolution of points for Starigrad.

The second input data, building footprints, was used to filter and limit the solar radiation data to areas of interest, which are all buildings (rooftops). For Koper we used national building cadastre, which is publicly available. Since for Croatia national building cadastre is not available, for Starigrad, we used OpenStreetMap data, which we slightly corrected and filled based on up-to-date satellite imagery as it was not complete.

EUKI Solar Adria also supports installation of PV at other available urban surfaces such as parking lots and brownfields. However, we do not have data of such sites and we would have to detect them from satellite images and insert them manually, what would be time-consuming. Through consultations with municipalities, we decided to only focus on roofs in the model.

The input data and sources are shown in Table 3-1.

Table 3-1 Main input data for the model

Component	Sources of DATA	Source Koper	Source Starigrad
Digital surface model (DSM)	• Generated from LIDAR data (first return points). Raster in 0,5 x 0,5 m resolution.	Direkcija Republike Slovenije za vode, portal eVode: www.evode.gov.si/index.php?id=87	Custom dataset, provided by company Tripodij Geodezija
Building footprints	• Cadastre (Koper) • OpenStreetMap, satellite imagery (Starigrad)	Geodetska uprava Republike Slovenije, portal e-geodetski podatki: www.e-prostor.gov.si/brezplacni-podatki/	OpenStreetMap, www.openstreetmap.org; Državna geodetska uprava: www.geoportal.dgu.hr/#/menu/podaci-i-servisi

3.3 Software and process

Following the review of available data and models that are capable of estimating geographic solar, we chose to generate the model in ArcGIS Pro 2.8 (ArcGIS Solar analyst), which was also chosen because the research team is familiar and proficient with the software, the interface is user friendly and has a wide suite of web-based applications that enables us to prepare an on-line viewing application to share with other stakeholders. ArcGIS Pro is not an open-source software and requires a user to acquire a software license. Alternatively, open-source software like QGIS with its analysis tools can be used.

In the first step we prepared the DSMs. For both Starigrad and Koper we used first return points of both LIDAR datasets to generate a raster with a 0.5 x 0.5-meter cell size. This size was chosen as we estimate that it is precise enough to account for various roof-top structures (dormers, chimneys, windows, skylights, etc.) and still within reasonable file size and processing time.

We used the DSMs as an input for Area Solar Radiation geoprocessing tool (ESRI, nd) within the ArcGIS Spatial Analyst toolbox to calculate the solar radiation within a year on a monthly interval, producing output for each interval (month). The outputs are in a form of global radiation rasters in same resolution as input DSM, which include both direct and diffuse radiation calculated for each raster cell. Each interval (month) is output as a separate raster band, meaning 12 raster bands were generated. Each cells' value is expressed in Wh/m^2. To create yearly radiation, all monthly rasters were added together.

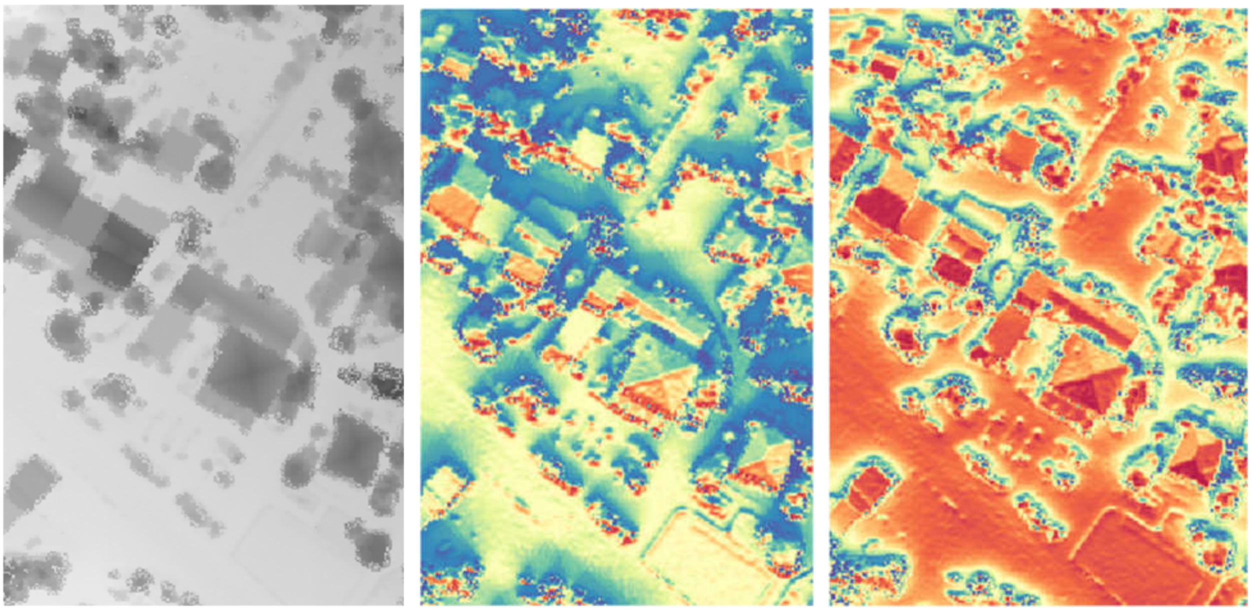

Figure 3 2: Digital surface model (left), solar radiation for January (middle), solar radiation for whole year (right)

The yearly radiation raster was first clipped to building footprints. For Slovenia we used the publicly available building cadaster data without any changes. For Starigrad, we downloaded OSM data from Geofabrik[5]. We validated the data using digital ortophoto imagery from year 2020, repositioned the existing building outlines to better match it and manually filled in the missing buildings. We also corrected the most obvious geometry errors from OSM data.

We further used the DSM to generate a slope map, which was used to differentiate between a tilted and flat roof. The information on type of roof was used to better estimate the available area for PV modules installation, as flat roof systems occupy more space/kW due to separation between the rows that must be included to take in account mutual shading of PV modules. We considered roofs with up to 13,5° slope as flat, others as tilted.

In the next step, a series of filters was applied to solar radiation map (clipped to buildings) to calculate the potential power and area for PV installation[6]:

- The rasters were transformed from Wh/m^2 into kWh/m^2,
- Cells below 900 kWh/m^2 were discarded, as this is considered a threshold below which PV is inefficient,
- Contiguous cells of 900 kWh/m^2 below 20 m^2 for tilted roofs and below 40 m^2 for flat roofs were discarded, as this is considered the minimum PV area for an efficient system (solar expert input).

Following this procedure, only theoretically useable raster cells within each building outline remained in the raster (Figure 3-2).

[5] www.geofabrik.de

[6] Factors/numbers without citations are based on project team's experience with developing solar power plants. We consider these numbers most accurately reflect conditions on the sites

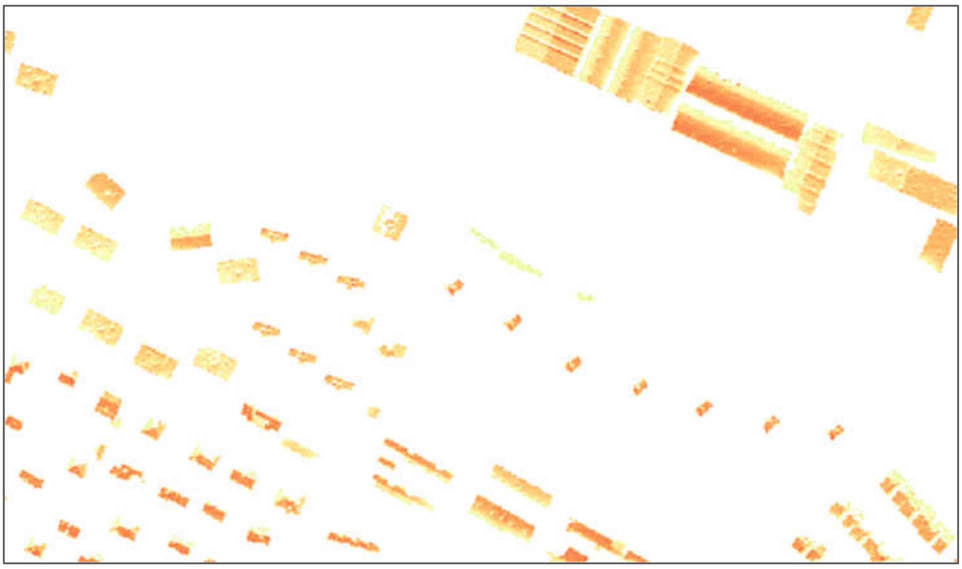

Figure 3-2: Solar radiation data after filtering

These above-mentioned steps were required for calculation of area for PV solar plant that could be theoretically installed on the building, production capacity and ranking of the buildings based on their suitability for PV installation.

The following information was calculated[7]:

- Calculation of average solar radiation of remaining cells (above 900 kWh/m^2) per building,
- Calculation of usable area for PV, by multiplying total area of suitable cells with 0,8 to incorporate misfit between the area and PV module geometry and the needs for addition infrastructure (powerlines, service pathways…),
- Calculation of possible installed capacity, by multiplying the area of favourable radiation with factors (150 W/m^2 for tilted, 80 W/m^2 for flat roofs)
- Calculation of possible generated electricity of the theoretical PV, using the formula from HRN EN norm:

$$E_{pv} = \frac{(E_{sol} * P_{pk} * f_{perf})}{I_{ref}}$$

  where E_{sol} is yearly radiation of PV system, P_{pk} is possible installed capacity, F_{perf} is efficiency factor of PV system (0,75 used) and I_{ref} is 1000 W/m^2,
- Calculation of the share of average household yearly energy consumption that the PV could provide (using 2809 kWh for Croatia (EIHP, 2019) and 4400 kWh for Slovenia (SURS, 2021)
- Calculation of possible carbon savings, by multiplying possible generated electricity with publicly available CO_2 emission factors (234,81 kg CO_2/MWh, OG 98/21).

It is important to note that parts of the roof can have different solar irradiation depending on an orientation, slope, and shading etc. This is visible in Figure 3-2, while later these data are aggregated to average yearly solar radiation. Based on average yearly solar radiation, the buildings were classified into four suitability classes, ranging from not suitable (below the thresholds) to high suitability (Table 3-2).

[7] See footnote 6.

Table 3-2 Classes of suitability

Ranking	Condition
Not suitable	Average radiation below 900 kWh/m^2 or too small area (below 20 m^2/40 m^2 for tilted/flat roof)
Low suitability	Average radiation between 900 and 1010 kWh/m^2
Good suitability	Average radiation between 1010 and 1125 kWh/m^2
High suitability	Average radiation above 1125 kWh/m^2

For each class of suitability, a corresponding colour was assigned, ranging from grey (transparent) for not suitable to red for high suitability (
Figure 3-3).

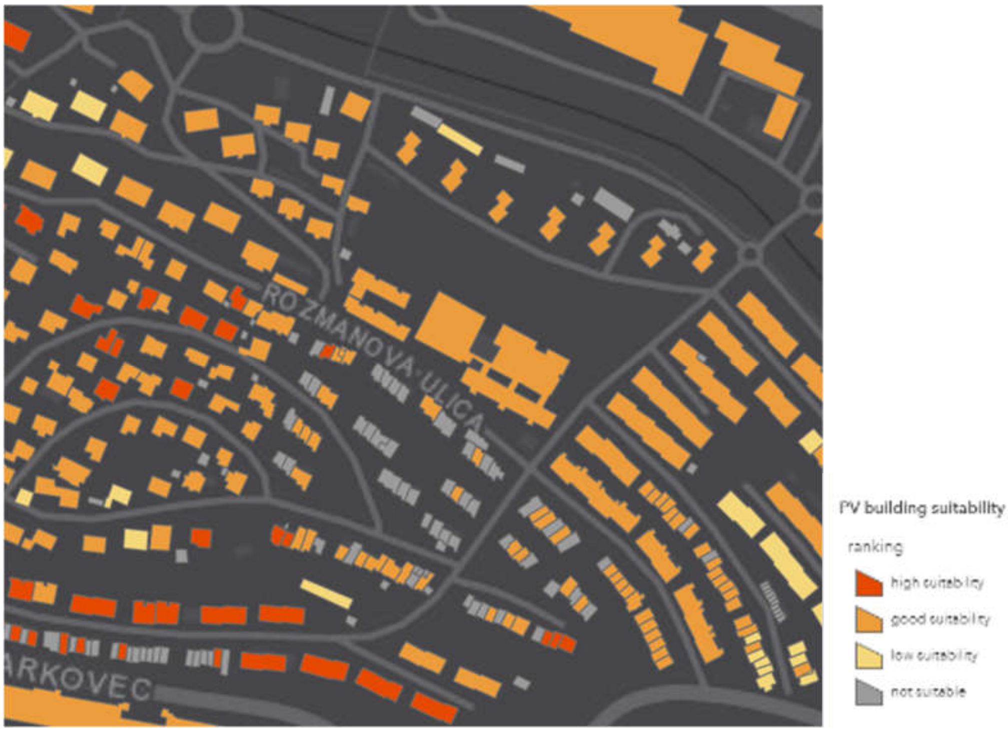

Figure 3-3: Model with applied symbology (example of Koper)

4 Results: solar potential for Koper and Starigrad municipality

The final models were published online in both English and local languages.
English versions available at:
https://experience.arcgis.com/experience/128fe14264e348cbaa9668c90a04b62b for Starigrad and
https://experience.arcgis.com/experience/d82a5297696840bcb907756482da895b for Koper

The online viewer (Figure 4-1) is designed to allow the user to freely explore the modelled area and acquire key information for each building. Additionally, layer with cultural heritage is added as an indicator of possible limitations. This layer marks the areas where development of PV could be difficult due to preservation of original architecture of the building, including the roof. For the roofs within the cultural heritage zone, a special permit is needed. Depending on the characteristics, the project can be accepted or rejected by a local conservation office.

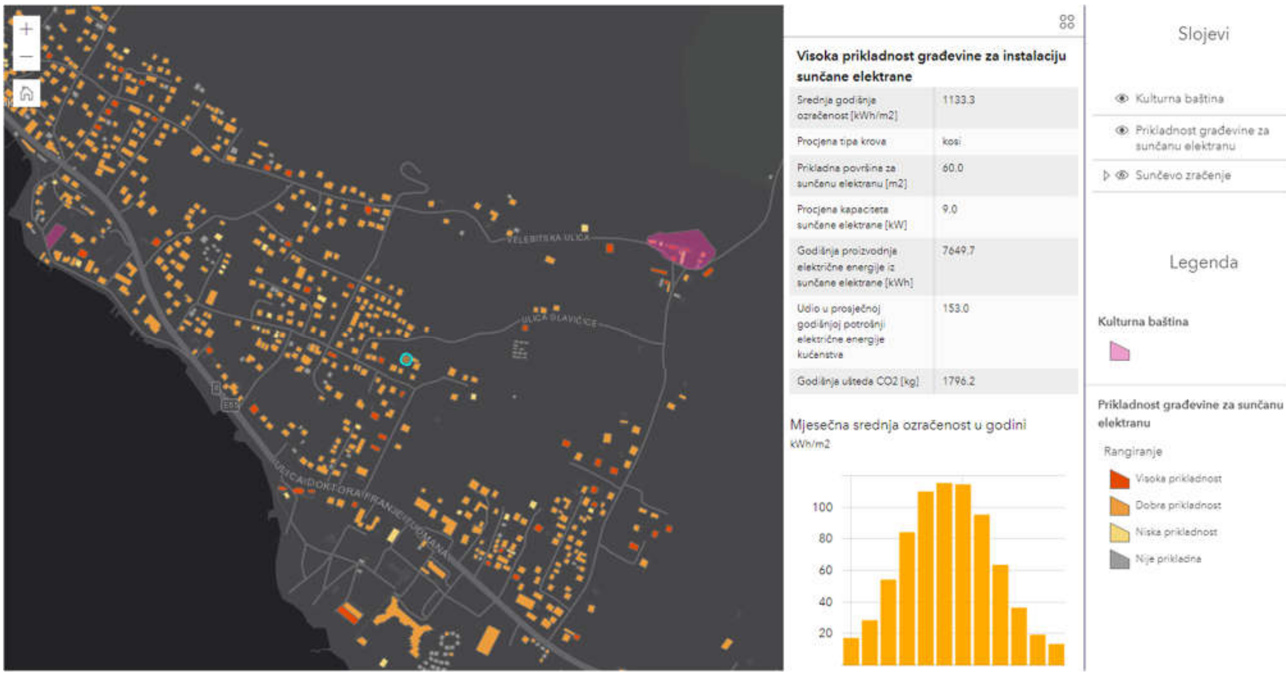

Figure 4-1: Online viewer of Starigrad model in Croatian

When comparing both models, it is evident that they both get similar amount of solar radiation (Table 4-1). Because Koper is a larger city it is also understandable that the mean and total usable area for PV is larger than for Starigrad, which mainly consists of single-family houses. Due to larger mean area, the theoretical mean PV capacity is also larger in Koper, leading also to more production.

Table 4-1: Comparison of models for Koper and Starigrad

	Starigrad	Koper
Mean yearly radiation	1074,3 kWh/m^2	1077,7 kWh/m^2
Mean usable area	62,9 m^2	97,1 m^2
Total usable area	110640,2 m^2	1429752,0 m^2
Mean PV capacity	8,2 kW	12,1 kW
Total capacity	14509,1 kW	178737,7 kW
Mean yearly el. prod	6644,5 kWh	9765,0 kWh
Total el. production	11,7 GWh	143,7 GWh
Number of average households to provide	4160	32619

The estimated PV production in Koper would account for about 45% of total electricity use in the municipality (data from 2013; Mestna občina Koper, 2019). In total, this PV production could provide for 160% of households in Koper. While we do not have data on electricity use in Starigrad, the model predicts that the estimated PV production could provide for 110% of households in the modelled area. In both countries the most buildings are evaluated with good suitability.

Table 4-2: Comparison of indicators per building suitability.

Number of buildings	Starigrad	Koper
high suitability	160	2621
good suitability	1531	11182
low suitability	68	915
not suitable	375	8700
Total area [m²]	**Starigrad**	**Koper**
high suitability	7486	152296
good suitability	99924	1219728
low suitability	3229	57727
Total PV capacity [kW]	**Starigrad**	**Koper**
high suitability	1122	22548
good suitability	13004	148415
low suitability	381	7773

5 Model limitations and verification

The solar potential identified in previous chapters is intended to be an estimate based on available data and can be improved by better spatial resolution and precise input data. The analysis was run on a fairly large area so certain trade-offs between precision (individual roof level) and universality (municipality level) had to be made. The model is made to generally fit and adequately describe most roofs. Therefore, the estimates are rough and can be used for general consideration of roofs suitability while further investigations at site should be performed by experts for selected roofs.

Based on available meteorological data (ARSO, 2021; DHMZ, 2021), we estimate that the weather is generally clear or slightly cloudy. This was included in the calculation of solar radiation by an atmosphere transmittivity factor (0,5) in the Area Solar Radiation tool.

The largest limitation of the model is the geographic inaccuracy of building footprints and their match with LIDAR dataset. Building footprints are generally constructed from geodetic measurements and orthophoto interpretation, while LIDAR is created using airborne scanning. While in Slovenia the building cadastre is precise and corresponds to LIDAR well, in Croatia building cadaster is not available meaning other sources had to be used. To avoid laborious manual delineating, we used OSM data as a starting point and slightly corrected it and filled the missing parts. The main problem in Slovenian dataset is that the definition of a building does not necessarily correspond to a topological structure we are modelling (a house) – for example, underground garage extending beyond the actual apartment building on top is still considered a building in the cadastre (Figure 5-1).

Figure 5-1: Imprecisions in building footprint data.

It is important to emphasize that the results are expressed per building unit in cadastre. This means that certain buildings that are in reality a single structure but represented as multiple units in cadastre (such as row of houses) could have a better suitability if modelled as one unit instead of as multiple ones. We however chose to keep individual cadastre units as it is more likely to represent the different ownership of the actual buildings. In the survey conducted in first phase of the Solar Adria project, building ownership was found to be one of the most important factors when deciding about installation of rooftop solar systems. This is also the reason why we abstracted the individual viable radiation raster cells to individual buildings, as we consider a building to be the unit about which a decision to install a solar power plant will be taken (besides making the model simpler and easier to grasp). This is also why building units of the same shape can have different suitability, as the radiation might differ based on local shading/orientation conditions.

To verify the model, we compared our modelled estimates of theoretically possible PV system capacity with Slovenian register of solar power plants in Koper. The model both underestimated and overestimated the capacities by 24% on average. Taking all solar power plants together (summarized), the model underestimated the overall installed capacity by 7%. It is understandable that compression of individual power plants and modelled values varies more, as the model is created through generalizations. We consider the accuracy suitable for the purpose of the model, which is to generate interest among citizens for PV installation.

Further, the model does not take any account of structural properties of buildings, which could be a limiting factor in some cases. It also does not include grid connections and capacities.

The focus of our approach are rooftop PVs, that are in general poorly developed in Adriatic region. However, the recent trends in evaluating solar potential of buildings also considered vertical elements (facades). Representation of vertical elements is one of the most challenging issues that is out of the scope of our study. This issue should be addressed at some point in the future.

6 In brief: Step by step guide for solar mapping

One of the goals of the project is potential replicability of Solar Adria approach in other municipalities of Adriatic region. Therefore, we summarise the previously described methodology in several steps to guide the interested municipalities through the process of solar potential map development. The workflow is presented in Figure 6-1.

STEP 1. DATA COLLECTION

For solar potential maps two basic data sets are required:

1) **LIDAR data.** For Slovenia LIDAR data are available at national level while for Croatia the LIDAR scanning at national level is still in progress. If data for a desired area are not available, they could be created by application of UAV. Airborne LIDAR scanning service by UAV is offered today by many companies. The LIDAR data are provided in digital format and should be processed in GIS environment.
2) **Building footprints.** If not available at national level (e.g. building cadastre), one option is to use Open Street Map (OSM) building footprints. It is very likely that some building will not be recorded while area of the others will not be correct. The manual adjustments can improve the data. This practice is reasonable for smaller settlements, but for a large ones manual adjustment of building footprints would demand to much time and workforce.

STEP 2. LIDAR DATA PROCESSING → DSM

LIDAR data are processed within the ArcGIS to create Digital Surface model (DSM) which is a 2D raster map with 0.5 m x 0.5 m cell size. The DSM contains elevation information for all objects and ground features, including buildings and trees, which could be sources of shading. Area Solar Radiation tool within the Spatial Analyst toolbox of ArcGIS is applied to calculate monthly irradiation based on the DSM. The final output is 0,5m x 0,5m cell size raster with yearly radiation (sum of 12 monthly radiations). If ArcGIS is not available, see Table 1-1 for other options, including free open-source ones like QGIS.

STEP 3. CROPPING MAP TO BUILDING FOOTPRINT

The building footprint layer is uploaded, and the DSM and irradiation maps are cropped to building footprints. The result is a map with data limited only to roof areas. It provides information how much solar energy hits a given rooftop in a year.

STEP 4. APPLICATION OF THRESHOLDS

To determine the roof suitability, certain thresholds are applied related to shading (tilt, azimuth from DSM), minimum irradiation (900 kWh/m^2/y), roof slope (flat roof =< 13,5°[8]), minimum size of the roof (20m^2 for flat and 40m^2 tilted) etc. The shading effect of the trees and other building was addressed through solar potential maps. Areas of different radiation within the single roof are most likely exposed to shading effect, resulting in lower solar potential. The result is exclusion of roof areas with unfavourable characteristics while the remaining roof areas are classified in three categories based on the level of suitability.
Additional filters can be applied as for example cultural heritage buildings and zones.

STEP 5. CALCULATION OF YEARLY ELECTRICITY PRODUCTION FROM A ROOF

Based on roof area available for PV installation, yearly irradiation on a surface and tilt, approximate installed capacity for a roof is calculated. Based on installed capacity and the efficiency of the technology, an approximate yearly production of electricity is calculated.

8 Subject to local characteristics

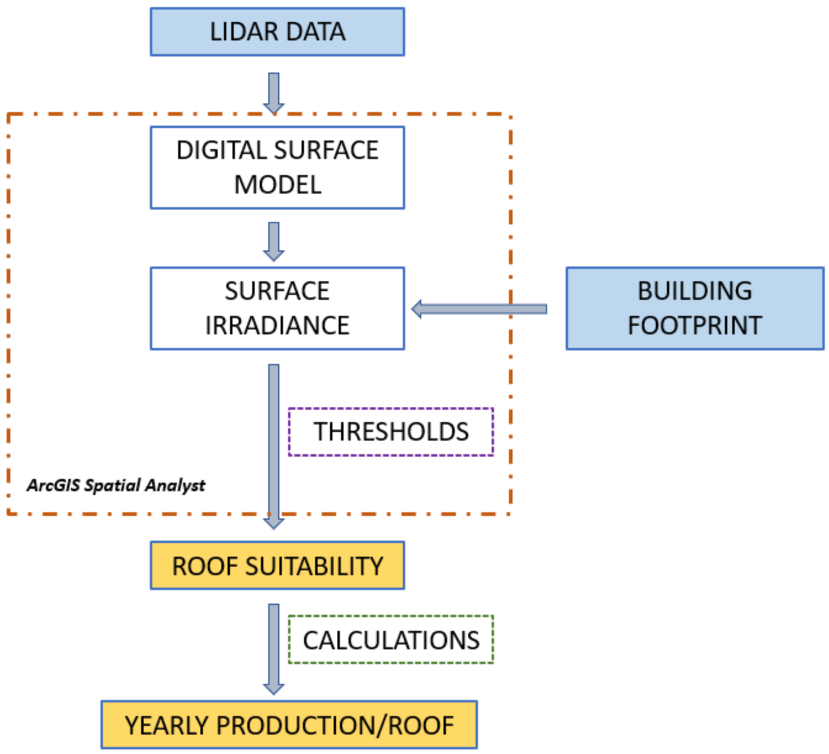

Figure 6-1 Detailed workflow description for solar potential mapping

Conclusion

The assessment of solar potential in the urban environment can be an important instrument that enables policy makers to make informed decisions regarding renewable energy deployment in the city. The fast-decreasing cost of photovoltaics makes this topic interesting also for the citizens that are now capable and ready to invest in PV.

There is a great diversity of methods and tools available for solar potential estimation. The review of models clearly indicates that web-based models provide a good information on solar potential and convey the message on suitability well to the end user. Based on already existing approaches in solar potential mapping, within the EUKI Solar Adria project we developed a methodology specific for estimation and representation of solar potential for Koper and Starigrad municipalities. Solar potential is displayed in form of solar maps available online at project website. The results indicate that Koper and Starigrad both get similar amount of solar radiation. Due to its size, in Koper the mean and total usable area for PV is larger than in Starigrad, which mainly consists of single-family houses. Due to larger mean area, the theoretical mean PV capacity is also larger in Koper, leading also to more potential electricity production. The municipalities can now understand how appropriate their territory for solar development is, where the potential lays and how much can be exploited. Accordingly, based on findings, they can frame policies that promote and mobilise the identified solar and PV potential.

Solar potential is based on a remote evaluation tool (topographical surveys, models) and results may be inaccurate at the level of a single building due to various constrains that can appear in any step of the process. The model limitations are primarily related to quality of input data. Inaccuracy of building footprints is the main limitation in estimation of roof solar potential. Therefore, solar maps for pilot cities area are indication of solar potential and are no substitute for an on-site assessment performed by a certified professional. The model provides some basic calculation while detailed calculation requires advanced technical knowledge on solar potential which is too demanding for an average user. Having this in mind, the primary purpose of the model is to serve as a first-step or an initiator of the decision to install a solar power plant on a building and as a promotional tool.

The solar radiation models crated in the Solar Adria project demonstrate the initial hypothesis that coastal municipalities in Adriatic region have a high potential for roof solar power plants utilization. We calculated the overall and roof-specific potentials for PV. In both municipalities the available surface and theoretical installed power could provide more electricity than is needed by the households. Of course, PV production and electricity use are not always in sync, but the model clearly shows that there is a lot of unused potential in both municipalities that could be better utilised. The following phases of the project will look into ways of encouraging development of rooftop solar.

The step-by-step procedure for model development is provided in order to encourage other municipalities to engage in solar potential initial screening and shape the polices that support PV development at the places with untapped potential.

Alongside rooftop PV, an interest in development of PV on facades is increasing. Thanks to UAV technology and 3D reconstruction technologies, oblique airborne photometry-based 3D city models have become widely available. Therefore, the future of the modelling is in 3D models and estimation of potential on facades.

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Annex I Approaches to solar mapping

Approach reference	Description	Tools	Input data
Prieto et. al., 2019	City level - Vitoria-Gasteiz, Spain Easy replicable approach, based on open data and non-commercial tools. The model is not taking in account morphology of the building or shape (only horizontal surface). Radiation threshold - 800 kW/m2/year. Result is 3D model of solar potential, annual cumulative incident radiation per square meter for roofs (Kwh/m2/year).	LASTools; QGIS; QGIS plugins (UMEP Tools, SEBE tools) CityGLM Generation toolà generates 3D model	• LIDAR → DSM, DTM • weather data-EnergyPlus • cadastre data (shp)
Walch et al., 2020.	National level, Switzerland. Exclude roofs with a small available area < 8 m2 (minimal economic feasibility), all north-facing roofs with an aspect angle 90 > ° from south. Annual Gt of 1000 kWh/m2 used in other studies is found to be very sensitive to small changes in the estimate. Result: solar potential (monthly predicted values (in kWh/m2) + available area for PVàtechnical potential for electricity generation. The strength of the method lies in the combination of physical models with GIS and machine learning	GIS (sky view, shading, panel placement). Data mining approachà Machine learning (pixel maps, enhance shading, effects of superstructures).	• Meteosat Second Generation (MSG) satellite observations using the Heliomont algorithm- meteorological data • Building data (national dataset) • LIDAR →DTM, DSM • PV performance • Temperature maps
Jurasz et. Al, 2020	City level – Wroclaw, Poland. Slope, shading, and orientation taken in consideration (from DSM). For angles ranging from 0 to 15° PV installations mounted in rows with a tilt angle of 3° whereas for greater angles PV will be mounted directly parallel to the roof. Results: maximal installed capacity of the city (MW).	Artificial intelligence algorithms (artificial neural network applied for solar radiation) GIS tools	• LIDAR→DSM • BDOT10k database→ buildings layer • meteorological dana →SoDa
Bodis et al., 2019.	EU level Results: available rooftop area, levelised electricity cost (LCOE), weighted average cost of capital (WACC) (technical (GWh/year) and	GIS PVGIS	• European urban atlas + CORINE → European settlement map • CM SAF- satellite→ solar radiation map

	economic rooftop solar electricity potential.		• ESM image →building cadastre • CMWF ERA-5 reanalysis → solar radiation
Florio et. Al., 2021	District level, Geneva, Switzerland Result: 3D model, conomic estimation of PV integration into the grid, an hourly resolution simulation for building energy generation and consumption.	RADIANCE (Daysim)à irradiance simulation CitySim Solver	• LIDARà DSM • Weatherà EnergyPlus • Copernicus Land Monitoring Service 2020 (DEM) à Building Height 2012
Faiz et. Al, 2020	Residential complex, India. Result: amount of energy generated (kWh/m2/annualy) E = A * r * H * PR E = Energy (kWh) A = Total Solar Panel Area (m²) r = Solar Panel Yield (%) H = Annual Average radiation on Tilted Panels (shadings not included)* PR = Performance Ratio, Coefficient for losses (range between 0.9 and 0.5, default value = 0.75)	PIX4D MAPPER, PHOTOMOD UAS, ArcGIS 3D featuresàGoogle ERDAS IMAGINE (inbuilt AutoCAD software Bentley MicroStation)à procart600	• LANDSAT, UAV images, DGPS survey→ generation of DEM/DSM
Kausika et. Al, 2015	City Apeldoorn, the Netherlands. Takes in account slope and orientation The criteria for suitable roofs: • Slope: less than or equal to 38° • Solar radiation: greater than 70%of the annual maximum received in the area -600kWh/m2 • Orientation: (a) South facing (optimal) (b) other orientations. A value of 150Wp/m2 has been taken as the PV power density that can be installed. Result: City capacity (MW) and yield (GWh/y) in relation to consumption.	ArcGIS- AREA SOLAR RADIATION TOOL (Spatial Analyst)	• LIDAR • Radiation→ calculated ArcGIS • Building layer
Kausika et. Al, X	Utrecht, the Netherlands. Criterion that only 35% of the roof area is suitable for PV siting (due to presence of dormers, windows, chimney or shading, or potential other use of the roof area	ArcGIS- Solar analyst tool, Slops and orientation calculated à flat and sloping roofs difference	• CityGLM→3D model • Building footprint (government cadastre)

	such as for water detainment) has been used as a constraint. Categorization of roofs: Class 3: if the building surfaces receive more than 90% of the annual average irradiance of the region. Class 2: if the surfaces receive 70-90% Class 1: surfaces receiving 50-70% Class 0: those areas which receive less than 50%. (not suitable). Result: 3D models, potential and the capacity of producing electricity by PV power		
Lee et al., 2019	Data-driven approach alternative to LIDAR, uses widely available satellite images to assess the solar potential of a roof. Results: energy generation potential (MWh/building).	DeepRoof approach	• Satellite images→image classification
Zhong et al., 2021.	City scale- Nanjing, China Rooftop regarded as horizontal plane. Clear sky radiation dana. Cloud cover correction. Shows the total annual acceptable solar radiation and the monthly total solar radiation per hour. Results: rooftop solar PV potential + potential installed capacityà potential power generation.	Deep learning-based method àextract the rooftop area with image semantic segmentation (OBIA). DeepLab V3 algorithm (Google)	• Google Earth images→ rooftops • Land use status • Solar radiation Copernicus Atmosphere monitoring Service (CAMS.3)
Singh & Banerjee 2015.	Mumbai, India. Effect of tilt angle on the plane-of-array insolation received has been studied to make an optimum choice for the tilt angle. Results: installed PV potential (MW)	QGIS image analysis. PVSyst - to estimate effective sunshine hours for the region of interest Liu-Jordan model	• Satelite images→ building footprint • Climate Design Data 2009àsolar irradiance • ASHRAE Handbook
Tarigan, 2018.	Building level, Surabaya, Indonesia. Results: solar energy potential, electricity power generation, greenhouse gas (GHG) emission reduction.	SolarGIS pvPlanner àenergy output Google Sketch up RETScreen à Greenhouse gas (GHG) emission reduction analysis	• Google Earth TM→surface of buildings
Caamano-Martin et. Al., 2012	District, city level- POLIS network (Malmo, Lyon, Lisbon, Vitoria - Gasteiz…)	ESPA System- digitalisation of roof geometries AutoCAD	• Building footprints – city cadastre • LIDAR→DEM, DSM

	Slope, shading calculated Only roofs oriented between 90° east and 90° west were considered. Optimal surface is south oriented, 32º tilted. Only surfaces of at least 50 m2 were considered. Results: 3Dmaps, potential kWh/m2	SketchUp PVSyst - simulation of the electricity produced	• Aerial photos • Global annual radiationà calculated with GIS using DEM
Huang et. al, 2015	District level, Shanghai, China. Suitability- roofs larger than 10m2, slope equal or lower than 45 degrees, aspect south, southeast, southwest facing, or horizontal, 10 MJ/m2/day as the threshold value for the yearly average total solar radiation. Result: monthly average total solar radiation (MJ/m2)	SHORTWAVE-C - GPU based solar radiation model	• LIDAR à DSM • Aerial photography high resolution àNDVI • Cloud cover data- satellite
Chow et.al, 2014	Neighbourhood, Canada Spatial Analyst- the daily and seasonal shifts of the sun angle, elevation, orientation (slope and aspect), and shadows from surrounding features affect the amount of solar radiation received on surface. Result: 3D model, solar potential (Wh/m2), monthly average hourly solar radiation.	ArcGIS -Solar Analysis tools Zonal statistics ScetchUp àCollada ArtSceneà 3D image file hemispherical viewshed approach viewshed method	• High resolution orthophoto • 3D CAD model in Google ScetchUp → into 2D raster DEM model
Tian et. al, 2021.	Galápagos Aspect- not a problem due to equator. Results: estimated PV generation in kWh/m2, annual energy produced by a photovoltaic system.	NREL's Annual Technology Baseline tool	• average annual solar radiation à Global Solar Atlas (Solargis and World Bank Group) • Building footprints
Moudry et. al, 2019.	Family house, Czech Republic Slope and azimuth of the roof were 39° and 0° (south orientation). Result: Measured solar power production (kWh/month) and estimated technical solar potential for 40 PV panels mounted on a family house.	PVGIS ArcGIS- solar radiation toolàhemispherical viewshed algorithm PhotoScan Professional version 1.2.6. (Agisoft)	• Drone- LIDAR→ LAS→ DEM- slope, aspect • Atmospheric Science Data CentreàMonthly values for transmissivity • PVGIS→ diffuse proportion
Santos et al., 2014	Lisbon, Portugal.	ArcGIS' Solar Analyst extension (ESRI)	• Building footprint • LIDAR→ DSM, DTM

	Roof overhangs, chimneys, dormers, antennas, are not taken into account (would require 3D data or additional spectral information). Result: Solar potential of each roof (MWh/m^2): 4 categories of PV potential according to energy produced.	PVGIS	• urban atlas - Landuse • PVGIS àradiation
Song et al, 2018	District level, Bejing, China. Slopes greater than 60° excluded For multi-row PV systems, this type of shading is inevitable. Result: PV electricity potential (GWh/year) in area. Distinguish 5 roof categories.	GIS	• Google Maps and DSM (from Pleiade) → 2D rooftop outlines and 3D rooftop parameter • PVGIS- radiation
Lukač et al, 2014	Part of Maribor, Slovenia Novel PV potential calculation. Result: electrical energy production from buildings' roof (kWh/m2)	Photoscan Heuristic vegetation shadowing, and multiresolution shadowing model	• LIDAR àDEM • solar irradiances à pyranometer measurements
Brito et al, 2019	Lisbon, Portugal Focus on facades. Result: 3D model, average annual irradiance (kWh/m2), total annual irradiance (MWh).	GIS- v.sun, SEBE SOL (algorithm in MATLAB), SURFSUN3D ArcGIS- CityEngineà generation of 3Dmodel	• Lidarà DSM • Solterm database • Meteonorm database
Rodriguez et al,X	Ludwigsburg County,Germany. Results: irradiance, suitable roof area, nominal power, and annual energy yield (technical potential). Tilt angle of 25° facing south for the PV panels when the roof is flat. Minimum roof size 40 m$^{2.}$ Threshold 1000 kWh/m2/year based on 10 years payback period.	PV potential tool in SimStadt	• CityGML file of the region.
Liang et al, 2020	Description of Solar3D. It was developed using a mature graphics rendering engine (OpenSceneGraph) and a full-featured 3D-GIS framework (osgEarth), as a 3D extension of the GRASS GIS r.sun model. AIM: calculate solar radiation on three-dimensional (3D) surfaces in a virtual environment constructed	Solar3D open source software - extends the GRASS GIS r.sun model from 2D to 3D by feeding the model with input, including surface slope, aspect	• 3D-city models • DEMs, DSM

	with combinations of 3D-city models, digital elevation models (DEMs), digital surface models (DSMs) and feature layers.		
Garcia & Polo, 2020	Few buildings, Santiago, Chile. Result: total energy kWh/m2	QGIS - SEBE (Solar Energy Building Structures) model in the Urban Multi-scale Environmental Predictor (UMEP)	• DEM • Global Horizontal Irradiance (GHI) measuredà DHI, DNI • Weather – typical meteorological year developed
Protić et. al. 2017	i-SCOPE platform cities. Result is a 3D city model. Based on 3D Urban Information Model (UIM) concept. An UIM is aimed to "integrate multi-dimensional urban aspects like economy, society and environment with 3D urban model plus temporal dimension. The calculator provides results organized in three sections: 1) Simulated System Information (e.g. annual production, percent of roof coverage, etc.), 2) Economics Factor (e.g. system installation cost, total costs, return on investment, etc.) and 3) Other factors (e.g. annual self-consumption savings and revenues, CO2 reduction, etc.)	GRASS GIS r.sunà total clear-sky solar radiation SOCET Set softwareàraw DSM novaFACTORY softwareàcityGML Sketchup plugin	• DEM, DTM àslope, aspect, horizon map,