Remote Sensing and GIS in planning photovoltaic potential of urban areas

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Abstract
The last guidelines approved by Italian government to financially support the solar Photovoltaic (PV) Energy production development include specific indications for more advantageously funding installations exploiting roofs/covers surfaces mainly located in urban or industrial areas. Since the 3D heterogeneity, albedo, atmospheric turbidity and casting shadows significantly influence here the local solar irradiance, the implemented methodology allowed us to suitably account for these distributed factors by means active (LIDAR) and passive satellite/airborne remote sensing techniques and advanced GIS modelling tools in order to support more realistic estimates of PV potential at roofs level in urban areas.

Keywords: GIS & remote sensing, photovoltaic, rooftop PV systems, solar radiation, LIDAR, linke atmospheric turbidity.

Introduction
In order to avoid competition with other strategic uses of soils, such as, for example, those natural and agricultural, in various Italian Government decrees (mainly in the 4th and 5th), the so-called feed-in-schemas (“Quarto/Quinto Conto Energia”, C.E.) concerning incentives for the photovoltaic (PV), there is a clear orientation to further support and develop the diffusion of PV systems on the roofs of buildings compared to those installed on the ground.

The decree aims to support the development and the installation of PV systems on buildings and barns roofs, while there aren’t additional incentives for those to be installed on the ground: all this to avoid soil consumption, especially in rural land [Murgante and Danese, 2011; Fichera et al., 2012, Modica et al., 2012], which could have implications for the food industry, strategic in the near future [Murgante et al., 2011].

The national photovoltaic power trend shows (Fig. 1):
- increase of the absolute and yearly mean of installed PV power (MWp), total number
and mean power value of installations (1st ÷ 5th C.E.);

- the growth of mean PV power for installation between 1st ÷ 4th C.E., which implies the exploitation of wider areas (mainly on ground), potentially interested by other competitive strategic uses (i.e. agricultural, semi-natural, etc.);

- more advantageous Government financial support for PV installation on roofs and coverage in respect to ground plants (from 5th C.E., including asbestos covers removal), to invert this trend.

Figure 1 - Left graph: total installed power and yearly increase rate for each Feed-in-scheme (“Conto Energia”, C.E.). Right graph: total number and mean power value of installations during each C.E. (Source: GSE, “Gestore dei Servizi Energetici”, http://www.gse.it/en).

The general framework of the above mentioned national initiatives is represented by the EU directive for 2020 (Directive 2009/28/EC), which contains recommendations about renewable energy sources (RES): the solar energy exploitation is just one of the main challenges, especially in terms of sustainability and economic impacts [Jäger-Waldau, 2007; Arán Carròn et al., 2008].

To cope with the issues related to an effective exploitation of RES, it is fundamental to have the availability of methodologies and tools, able to support the assessment of the implementable potential [Izquierdo et al., 2008]. In general, until now, in order to map the solar radiation for supporting PV potential assessment using GIS [Caiaffa, 2003; Šúri and Hofierka, 2004; Huld et al., 2005; Caiaffa et al., 2012], the evaluation of the solar irradiance has been carried out on the basis of orientation and exposure parameters, derived from the representation of natural elevations, digitally stored in DEM (Digital Elevation Model) or DTM (Digital Terrain Model); currently, to achieve more realistic estimates in urban areas [Cebeccauer et al., 2007; Pellegrino et al., 2008; Ordóñez et al., 2010; Bergamasco and Asinari, 2011a; Balena et al., 2012], especially in the perspective of roofs exploitation for PV power, it is necessary to take into account a more detailed representation of building covers and their own 3D geometric and radiometric parameters. In most cases there is a lack of information available about the real roof surfaces.

To fill this gap, different approaches has been proposed: Izquierdo et al. [2008, 2011] have developed a methodology based on crossed sampling of GIS layers and cadastral data; also Wiginton et al. [2010] have used a GIS-based approach, by means a specific tool, in order to perform a suitable feature extraction; Kabir et al. [2010] have exploited satellite image. A relevant and original contribution is that proposed by Bergamasco and Asinari [2011b], which have developed a specific methodology for the detailed roof analysis.
Considering these previous experiences and to confirm our thesis, our work has consisted in the characterisation of roofs shape and arrangement (slope, orientation, tilt angle, etc.) for better assessing the available solar radiation, as potential power exploitable by PV. To this end, a hierarchical methodology has been implemented. Such a kind of approach, as demonstrated by Izquierdo et al. [2008] is one of the most suitable to deal with the aims of our research work. In Figure 2 is reported a flow-chart showing the main methodological steps of the approach described in this paper.

The main goal of this work was to preliminarily test the feasibility of a GIS based methodology for solar radiation evaluation, using Remote Sensing (RS) data (LIDAR-derived DSM and satellite images) to support the PV potential assessment in urban areas. In this framework, a first evaluation of available radiation over the entire territory of Avellino municipality was accomplished by means a standard approach: it was referred to the most productive (in term of PV power) months (June and July) and based on the assumption of unique values of the atmospheric turbidity and without reflected contribution. Then, a delimited sub-area was considered to implement a refined procedure to account for spatial distribution of atmospheric turbidity and albedo (obtained from satellite images), and reflected component.

In this context, the primary goal of the research was related to perform a feasibility analysis: thus, some processing restrictions were introduced (test areas and time span selected for solar radiation assessment), to cope with the availability of data (i.e. satellite remotely sensed images). Moreover, the software implementation of operative procedures were out of the scope of the present work.
In order to exploit the good practice of data reuse, the present study was conducted using data coming from an existing airborne LIDAR (LIght Detection and Ranging) survey, already used for another research project. Thus, the case study here described was located in the area of the Municipality of Avellino, in the Campania region (Southern Italy). Avellino (40°54′55″N 14°47′23″E, 348 m a.s.l., 42 km NE of Naples, Total population: 52,700) is situated in a plain called “Conca di Avellino” and surrounded by mountains: Massiccio del Partenio (Monti di Avella, Montevergine and Pizzo d’Alvano) on NO and Monti Picentini on SE. Due to the Highway A16 and to other major roads, Avellino also represents an important hub on the road from Salerno to Benevento and from Naples. In order to improve the extensive evaluation of roof solar PV-systems potential, it is necessary to take into account the real surface available as well as the orientation and inclination. In this perspective, the assessment of the covers potentially exploitable for PV production, represents a fundamental task, whose effectiveness depends from a reliable 3D model of buildings and/or other man-made objects in the area of interest.

The recent improvements of RS techniques (sensors, platforms and systems) make them very attractive and capable to contribute to the above mentioned surveying tasks, in terms of geometric resolution, operability and accuracy. In particular, active LIDAR has emerged as an effective technology for the acquisition of high quality Digital Surface Models (DSM), due to its capability to generate 3D dense terrain point cloud data with high accuracy [Axelsson, 1999]. Recent advances of airborne laser scanning systems and techniques have opened a new way of directly measuring elevation or generating DSM, with high vertical and horizontal accuracies. Compared with traditional methodologies (e.g., aerial photogrammetry), LIDAR has advantages in measuring 3D objects on the Earth Surface, in terms of density of measured points, accuracy, effectiveness, processing automation and fast delivery time.

Referring to the case-study here described, LIDAR technology [Baltsavias, 1999] has been exploited to produce a more detailed and effective characterization of the urban environment at building and coverage level, in order to support a reliable assessment of roofs PV potential. In this context, the structure and heterogeneity of the urban environment have been also considered in terms of other significant environmental parameters, such as albedo, atmospheric turbidity and shading. These, in general, have a strong influence on the local solar irradiance, as primary source for PV production. Therefore, to reach the above mentioned goals, it is necessary to account, in an appropriate way, for these factors relating to the atmospheric transparency and to the contribution of reflected irradiance over the whole spectrum (albedo) due to the surrounding areas.

This paper describes the development of an innovative approach, based on active and passive RS, to extensively assess a set of buildings cover parameters, in order to support the evaluation and mapping of PV potential from roofs. In particular: a) to take account of the diffuse and reflected solar irradiance including cloud cover, have been also exploited products and features provided by PVGIS web-GIS application (JRC-IET, http://re.jrc.ec.europa.eu/pvgis), developed by EU for PV diffusion; b) from LIDAR data have been extracted specific geometric parameters of roofs (suitable surface, orientation, etc.) for every building in the area of interest; c) reflectance/albedo properties and atmosphere turbidity maps have been derived from RS data.
**Materials and methods**

**Solar irradiance**

In urban areas the wide variability in 3D objects and in environmental factors, from which depend atmospheric turbidity and shading, strongly influence the local solar irradiance. To assess the potential PV production, in correspondence of buildings it is necessary to consider effects on solar irradiance (W/m²) that constitutes the PV source. These effects are:

- Solar position;
- PV surface arrangement (slope, aspect, orientation, tilt angle);
- Atmospheric Turbidity (*Linke Turbidity factor, T*ₗₖ [Linke, 1922]);
- 3D heterogeneity and mutual shading;
- Contribution from neighbourhood reflectance.

The solar irradiance [Zaksek et al., 2005] that reaches the Earth, out of the atmosphere, on a plane perpendicular to the rays (normal extra-terrestrial irradiance *G₀*), has an average amount of about 1360 W/m², with variations up to about 7%, mainly depending from the variable Earth-Sun distance (modelled on the basis of Julian day in the year).

As reported in Figure 3 the main components of the solar irradiance at ground level are the direct (or beam) and diffuse, while the reflected one would be significant especially in case of high albedos surfaces and complex 3D features, as in urban or high relief areas.

![Figure 3 - Solar irradiance and its components.](image)

The beam irradiance incident on a PV surface at ground can be expressed as:

\[
B_{hc} = G₀ \exp \left\{ -0.8662 T_{Lk} m \delta_R (m) \right\} \cos \theta_i \quad [1]
\]

where *T*ₗₖ is the Linke turbidity factor; *m* is the relative optical air mass depending on the sun height angle and altimetry [Kasten and Young, 1989]; *δ*R (m) is the Rayleigh molecular optical thickness. Finally, θi is the angle between the sun direction and the perpendicular to the surface considered, whose cosine is directly dependent on its inclination and orientation angles.
\[ \cos \theta_i = \sin \theta_a \cos \theta_s + \cos \theta_a \sin \theta_s \{ \cos (\phi_a - \phi_s) \} \]

where:
\( \theta_a, \phi_a = \) PV surface inclination and orientation (azimuth) angles;
\( \theta_s, \phi_s = \) sun zenith and azimuth.

The diffuse component on a horizontal surface \( D_{hc} \) [W.m\(^{-2}\)] is assessed as a product of \( G_0 \), a diffuse transmission function \( T_n \) dependent only on the Linke turbidity factor \( T_{LK} \), and a diffuse solar altitude function \( F_d \) dependent only on the solar zenith angle \( \theta_s \) [Scharmer and Greif, 2000]:

\[ D_{hc} = G_0 T_n (T_{LK}) F_d (\theta_s) \]

The estimate of the transmission function \( T_n (T_{LK}) \) gives a theoretical diffuse irradiance on a horizontal surface, with the Sun vertically overhead for the air mass Linke turbidity factor. The following second order polynomial expression is used:

\[ T_n (T_{LK}) = -0.015843 + 0.030543 T_{LK} + 0.0003797 T_{LK}^2 \]

The solar altitude function is evaluated using the expression:

\[ F_d (\theta_s) = A_1 + A_2 \cos \theta_s + A_3 \cos^2 \theta_s \]

where the values of the coefficients \( A_1, A_2, A_3 \) are only dependent on \( T_{LK} \).

The model used for estimating the clear-sky diffuse irradiance on an inclined surface \( D_{ic} \) (W.m\(^{-2}\)) distinguishes between sunlit, potentially sunlit and shadowed surfaces [Hofierka and Suri, 2002], determined on the basis of 3D model and actual sun position.

Figure 4 shows the daily trends (left) of global and diffuse irradiance on a 35° sloping surface, south (0°) oriented, for the Avellino site, calculated on the basis of the local average of atmospheric turbidity [Linke, 1922; Remund et al., 2003] for June and derived from time series data (JRC-IET).

The same diagram also shows the direct irradiance in a state of “clear sky” for the identical site: in the right side, the average monthly trend of the diffuse fraction is shown. As it is possible to observe, the diffuse percentage consistence is relevant and up to about 35-55% of the total, with peaks in the winter months.

The other factors, which have a significant effect on solar energy intercepted by a PV surface, is the geometric arrangement in terms of slope and aspect, that needs to be maintained as much as possible perpendicular to the sun, in order to maximize the global intercepted irradiance.

The graphs in Figure 5, obtained by means PVGIS too, clearly show how - for the studied site and south orientation - the optimal inclination angle varies during the year with the
height of the sun (right side of Fig. 5). For fixed PV installations, the optimal value is about 33°. This corresponds to the total irradiance trend of the black curve (in the graph on the left), resulting in a cumulative annual maximum value. In the same graph are also reported the specific values of irradiance on horizontal (blue) and vertical (violet) inclined PV surfaces.

Figure. 4 - Hourly solar irradiance and percentage of monthly average diffuse in the Avellino area in June, on the basis of monthly average atmospheric turbidity derived from recorded time series (source: PVGIS, http://re.jrc.ec.europa.eu/pvgis/).

Figure. 5 - Estimated monthly radiation (irradiation) on surfaces with different inclination and orientation to the south (left graph) and optimal angle (right graph) for the location of Avellino (source: PVGIS, http://re.jrc.ec.europa.eu/pvgis/).

In Figure 6 is reported an example of PVGIS web interface, which provides maps of yearly solar radiation in Kwh/m² over natural surfaces obtained from DEM/DTM; tables reporting the related values estimated for the area of interest (in this case, Avellino Municipality). In this application the assessment of global urban irradiance is significantly overestimated, especially that related to roofs/coverage in terms of size/structure.
Commonly, the photovoltaic potential is extensively assessed by GIS techniques, according to estimated irradiance on the ground and considering the natural altimetry parameters obtained from DEM or DTM [Cebecauer et al., 2007]. The results coming from such a typology of models are generally different from those obtained from detailed 3D models, capable to accurately describe roofs surfaces usable for PV-systems installation.

In this context, therefore, a DSM obtained by LIDAR [Ackermann, 1996; Baltsavias, 1999] surveys can be more profitably used for covers identification and characterization, in terms of useful surface and related arrangement parameters, which are crucial for a more realistic estimate of the PV potential.

**LIDAR Data**

The 3D reconstruction of terrain and urban built-up within the area of interest has been obtained by means LIDAR specific techniques and methodologies [Borfecchia et al., 2010], processing a set of data on purpose acquired for the area of Avellino. The survey has been conducted by means of the **altm3100** LIDAR system (developed by **Optech**, Canada), with acquisition frequency of 100 kHz and flying by helicopter at an average altitude of 900-1000 meters above the ground, having a speed compatible with the expected resolution (Fig. 7).

The flight plan was designed to cover the entire municipality, aiming to the optimal delineation of urbanized areas through an adequate impulse density of the laser data (at least 4 return pulses/m²) and multi-returns handle capability. Such configuration is able
to ensure the effective spatial identification of building cover features (yellow objects in Fig. 7), contextually with vegetation discrimination through specific processing procedures [Elshehaby and El-Deen Taha, 2009]. The processing schema is reported in Figure 8, jointly with the LIDAR data storage arrangement (1 km x 1 km tiles).

After the acquisition and the pre-processing tasks, the obtained points clouds show a distribution density higher than four measured-points per square meter, jointly with a decimetre vertical accuracy. In particular, these data were characterized by the following parameters: Horizontal uncertainty $H_{\text{Max}} \leq 40$ cm; Vertical uncertainty $V_{\text{Max}} \leq 2 H_{\text{Max}}$; Density DSM/DTM $\geq 4$ points per m².

The final products, in a interoperable format, were organized into files containing data as points clouds (format .las), for a total of 48 tiles with 1 km x 1 km size (Fig. 8), covering the entire extension of Avellino Municipality (~ 42 km²).

For each tile at least two control lines normally acquired at the mean direction of the main strips were carried out. These acquisitions, defined as “tie-lines”, were performed every 10 km circa and served as a check for the proper workability of the scanning system as well as to determine and correct possible instrument drifts. This was carried out to reduce the maximum distances (less than 25 km) between the helicopter and the GPS master-station.
on the ground. The measurements were performed only during periods of the day in which occurred simultaneously the following conditions: Position Dilution of Precision (PDOP) < 3 and number of seen satellites > 6, with an elevation mask of 15°. The UTM-WGS84 was the adopted geodetic reference system. Finally, for all relevant operations, were used as Ground Reference Stations (GRS) the IGM 95 (the Italian geodetic national network) cornerstones.

By processing and mosaicking LIDAR data, as points clouds (filtering/classification as reported in schema included in Fig. 8), were obtained DTM and DSM of the area of interest. These digital models are depicted in Figure 9-a, as images in grey tones: lighter tones represent higher altitudes. DTM describes the natural elevation shape, including hills (Avellino is located at 300 m a.s.l.) and hydrological features; DSM provides the representation of anthropic structures and infrastructures (e.g., the layout of A16 motorway) and residential/industrial buildings. Then, by LIDAR data processing [Ricci et al., 2011] it has been possible to extensively extract the 3D model of each building within the urban area (Fig. 9b), including the related cover parameters (orientation and inclination) used for the radiation map assessment [Borfecchia et al., 2013]. Such 3D model made possible not only the accurate characterization of roof surfaces (area, inclination, orientation, etc.), but
also the extensive assessment of mutual shadowing and occlusion of 3D structures. This has allowed to better evaluate the solar radiation, for supporting a more precise assessment of PV potential related to roofs covers in the areas of interest.

Figure 9 - DTM/DSM extracted from LIDAR “points clouds” (a) and Buildings 3D model produced by LIDAR data processing (b).

**DSM and irradiance over municipality territory**

In order to obtain the irradiance values over Avellino territory from DSM/DTM LIDAR products, estimates have been carried out taking into account the Linke atmospheric turbidity [Linke, 1922] monthly values, for the site, derived from historical series available at PVGIS site. The cumulative radiation was accomplished using formulas [3] and [1] for direct and diffuse components, with surfaces arrangement maps derived from DSM and taking into account the daily and monthly trends of sun height variable through related optical air mass $m$ and arrangement angles. The 3D model was exploited through ray-tracing algorithm to account for sun occlusions occurring during some periods. All the hourly contributions, evaluated using the variable sun height, were summarized on the basis
of an half hour sampling, to obtain the daily amounts which have been used to assess the relative monthly total.

On the left of Figure 10 the direct component is mapped, under form of grey shadows, with a maximum of about 293 kWh/m², whilst the right part depicts the diffuse component distribution (maximum = ~83 kWh/m²). In the direct component map, the self and reciprocal shading effects of 3D infrastructures and building described in DSM, are more evident in the less urbanized areas.

![Figure 10 - DSM-based distribution maps of direct (left) and diffuse (right) cumulate solar radiation (Wh/m²), related to June and July 2012 for the Avellino municipality (violet boundaries).](image)

**Solar irradiance over the covers and roofs**

Then, in order to estimate solar irradiance over the covers and roofs of Avellino, the previous calculation of solar irradiance related to June and July month was restricted to covers which have been previously characterized in terms of size and related parameters (slope, aspect) derived from DSM, taking into account the variability of solar position (elevation, azimuth angles, etc.) as above described. In general, different roof surfaces are characterized by unique value of slope and aspect angles, so that it is possible to evaluate their specific cumulative radiation values for a selected day or for monthly periods during the year. This can be observed in Figure 11 and, in particular, in the lower-right box included as detailed-view, where it is possible to detect changes in cumulate radiation calculated (only direct and diffuse contribution, fixed values for albedo = 0.2 and monthly T_{LX} ) for each roof with different orientation and inclination, characterized by uniform values for flat roofs and by mutual shading effects. The different geometric elements and surfaces of roofs were obtained from the DSM, for each of which has been estimated (by GIS techniques) the cumulative radiation exploitable for the PV production.
Figure 11 - Total solar irradiance (kWh/m²) calculated for buildings’ roofs of Avellino town, during June and July 2012. The detailed-view shows roofs characterization obtained from DSM LIDAR.

Improved model

The next step was to try to refine the previously described approach, by introducing the reflected component in irradiance evaluation on PV surface. The spatial distribution of this component can be significant in urbanized areas, jointly with a better assessment of atmospheric turbidity (which allows to properly account for concentrated turbidity and pollutant sources, typical in densely built-up regions, which are often subjected to traffic). To this end, a specific sub-area of interest was selected to implement and test the refined procedure. This area corresponds to 2 tiles of the 48 total of LIDAR survey. The improved model, here developed and tested, deals with a complete assessment of solar irradiance including the additional reflectance component, that may significantly increase in urban environment.

Atmospheric Turbidity

To evaluate the cumulative sun irradiance, as previously described, tools and data available on PVGIS website have been used: the atmospheric Linke Turbidity ($T_{LK}$) parameter has been calculated for the reference month and related to Avellino location. The monthly average turbidity punctual values, in terms of Linke factor, is provided by PVGIS, where its estimation is derived from the global atlas implemented by Remund et al. [2003], mainly based on ground-based measurements acquired by meteorological stations. Although the atmospheric transparency of Avellino study area (about 42 km², with a nearly rectangular size of about 7x6 km) is well characterized by a single point value, in general urban
heterogeneity and pollutant concentrated sources (traffic, heating, etc.) may cause a spatial variability of turbidity; thus, its distribution assessment is required for model improving. In this perspective, to better estimate the local solar irradiance, we tried to assess the $T_{LK}$ distribution by using MODIS (Moderate Resolution Image Spectrometer) satellite-derived atmospheric products, such as $AOD/Ång$ (Aerosol Optical Depth/Ångström Coefficient), and related reflectance maps.

In particular, the monthly mean (reference period: 2005−2012) of satellite derived atmospheric turbidity parameters ($AOD$ and $Ång$, Fig. 12) were compared with the related values of $T_{LK}$ obtained from PVGIS for the Avellino site (Fig. 13).
It is possible to observe a substantial accordance between \( \text{Ång} \) and \( T_{LK} \) monthly-means trends. Based on the linear relationship [Jacovides, 1997; Elminir et al., 2001] that links \( T_{LK} \) and the above mentioned turbidity parameters (particularly \( \text{Ång} \)), a regression model was calibrated for the Avellino site (Fig. 14):

\[
T_{LK} = 5.553 \cdot AOD + 1.64811 \text{Ång} + 0.368189 \ [6]
\]

where: \( R^2 = 0.682; R_{adj}^2 = 0.612; \) P-value (F) = 0.0057

![Figure 14 - Predicted (modelled) TL\(_{LK}\) (from MODIS AOD and \( \text{Ång} \) coefficients) versus measured TL: monthly mean trend for the Avellino area.](image)

It is important to note that the \( AOD \) and \( \text{Ång} \) monthly-means values were derived using morning and afternoon acquisitions (7-16-2012) from MODIS Terra and Aqua satellites, in order to better account for daily variations.

Then, to improve the spatial ground resolution (10 Km) of the \( T_{LK} \) map obtained from MODIS, an interpolation based on the TOA (Top Of Atmosphere) and TOC (Top Of Canopy) blue reflectance components ratio (0.5 Km of ground resolution, respectively \( R_{TOA} \) and \( R_{TOC} \)) was carried out:

\[
T_{LK_{0.5Km}} = T_{LK_{10Km}} \frac{R_{TOA}}{R_{TOC}} \ [7]
\]

The spatial correlation between \( R_{TOA}/R_{TOC} \) ratio and the \( T_{LK} \) maps was preliminarily checked (\( 0.5<=R^2 \)) at 10 Km of ground resolution. Due also to the contribution of the MODIS
morning acquisitions, the $T_{Lk}$ maximum values are located mainly over the vegetated areas; nevertheless, some high spots has resulted in correspondence of some industrial settlements or main roads, as is possible to observe in Figure 15, where the Landsat ETM+ true colour image of Avellino Municipality is placed side by side to the $T_{Lk}$ map.

![Figure 15](image)

Figure 15 - On the right side: $TL$ map (500 m spatial resolution) assessed from $AOD$ and $Ång$ distribution detected on 7-16-2012 (morning/afternoon) by means of MODIS sensor over the Avellino area. On the left side: Landsat ETM+ true colour image with Avellino boundaries superimposed (red line).

**Reflected component**

The reflected component of solar irradiance is particularly significant in urban areas, due to the complexity of 3D-geometries and to the different reflectance properties of artificial surfaces, which are able to play an important role. Thus, such reflected component for the area of interest has been derived from wide band hemispherical map, called albedo (Fig. 16), at suitable spatial resolution of 30 m on ground.

In order to produce the map of local albedo, a multispectral Landsat ETM+ satellite image (June 2012) has been processed, using the reflectance channels in the Visible (RGB), NIR and SWIR ranges.

The atmospheric correction has been performed on the basis of atmospheric visibility value of 30 km. Moreover, it is possible to observe that the highest values are in correspondence to urban and industrial areas, whereas densely vegetated areas and roads show lower reflectance values.

Figure 17 reports the cumulate solar irradiance map (values in Wh/m$^2$-day, estimated for 7-16-2012), including the three components: direct, diffuse, reflected. Here the maximum value of reflected component is about 1/6 of that of diffuse one.
Results: solar radiation on roof surfaces

The preliminary approach, previously described, has allowed to obtain the global solar radiation cumulate map (kWh/m² day/month), over the entire area of Avellino municipality (as shown in Fig. 10). Then, for a specific sub-area a refined methodology has been implemented and tested, to account for the reflectance component of the solar irradiance over the PV surface and for the spatial distribution of the $T_{IK}$ factor. By specific software tools available within both commercial and open source suites, these values have been
estimated for 7-16-2012, using DSM and DTM obtained by LIDAR data. Further, Landsat ETM+ data have been exploited for albedo estimation, as necessary step for the reflected component assessment. The related $T_{LK}$ map has been assessed by means of 4 Km MODIS $AOD$ and $Ang$ thematic maps, after a suitable interpolation performed using the atmospherically corrected ($TOC$) and uncorrected ($TOA$) blue reflectance components (MODIS sensor, 500 m ground resolution).

Figure 18 shows an example of results produced for the area of Avellino municipality: the detailed map of solar daily radiation (kWh/m$^2$·day), referring to the mid-July day considered. This result was achieved taking into account the two additional factors: $T_{LK}$ and reflected component, in terms of distribution maps for the areas of interest, instead of single values as adopted in the previous calculations (Figs. 10 and 11). In the present map it is possible to clearly distinguish how slope and orientation of different roof surfaces determine the potential solar radiation exploitable for PV production. In this way it would be possible to implement a precise and effective cadastral GeoDatabase of PV potential available for the roof surfaces of each building/infrastructure located within the area of interest, to properly support the policies and the commercial activities in these specific sectors.
Conclusions
The work described in this article represents an innovative approach, based on the integration of active and passive RS techniques and GIS methods, to extensively assess the solar radiation for buildings covers, starting from their effective characterisation based on suitable LIDAR survey. In this case-study the LIDAR data (acquired at suitable resolution of 4 points/m$^2$), were processed to properly estimate area, inclination and aspect of each cover surface potentially exploitable for effective PV power generation in the area of interest (Avellino municipality). The total integrated sun radiation output in kWh/m$^2$ was, therefore, assessed for two typical reference months (June and July), considering: a) direct and diffuse components; b) $T_{LK}$ monthly mean values; c) 3D model for mutual shadows and buildings obstructions evaluation (corresponding to “Basic 3D model in procedure schema of Fig. 2). Such methodology was further refined, taking in to account two additional limiting factors, typical of urbanised areas: the atmospheric transparency and the contribution of reflected irradiance over the whole spectrum, due to the objects surrounding the reference PV surface (see “Refined 3D model” path in procedure schema of Fig. 2). In general, urban areas are characterised by poor air quality with pollution arising from different sources (residential heating and traffic, concentrated along the most congested roads over which the atmospheric transparency decreases). In this context, a $T_{LK}$ map has been produced (500 m of ground resolution, suitably derived from MODIS satellite sensor), allowing to improve the previously PV potential estimation based on unique punctual value.

The reflected component of sun irradiance (Fig. 3) become significant in case of high reflectance/albedos and complex 3D models (low sky-factor) around the reference PV surface, as frequently occurs in densely built areas. For instance, in the selected test area the maximum of the reflected contribution, estimated via ray-tracing and the 3D model, can reach 300 Wh/m$^2$, which is about 1/6 of the diffuse component (Fig. 17). The refined method has been implemented for specific area, day and month, due to resource constraints linked to unavailability of processing and remotely sensed data resources. Nevertheless, it will be make easily extensible to wider areas, allowing the yearly assessment, especially on the basis of forthcoming information provided by the most recent and ongoing RS techniques. Many local Administrations in Italy, such as Municipalities and Provinces, are equipped with informatics tools able to provide to citizens the opportunity to consult the PV energy exploitable. Such applications (essentially web-based) are very important for many reasons, including that to support citizens in designing and planning PV installations on their own houses. This feature is also valuable in the framework of the new policies aiming at developing open data and producing/sharing information by means collaborative mapping (Volunteered geographic information, VGI) and participative approaches [Goodchild, 2007; Modica et al., 2013; Pollino and Modica, 2013].

Thus, the results obtained from the presented work could represent a significant input of such informatics tools and could be linked, for example, with cadastral data, in order to explore the real possibilities of exploitation of buildings covers, from the energy point of view. Another useful function is, then, to provide an effective information, for example, for PV systems installers. Last but not least, the results coming from the present approach can be considered a valuable tool for supporting planners who have to decide whether and where it is possible to exploit PV energy from roofs.

In conclusion, the work aimed at the development of an innovative methodology to
effectively evaluate the PV potential from roofs, in which the usefulness of the GIS tools associated with the integrated use of remote sensing active (LIDAR) and passive (Landsat and MODIS) techniques have allowed a complete characterization of urban environment, in terms of 3D geometries and surfaces properties (albedo and atmospheric turbidity).

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