Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: application to Piedmont Region (Italy)

Luca Bergamasco, Pietro Asinari

Department of Energetics, Politecnico di Torino,
Corso Duca degli Abruzzi 24, Torino, Italy

Abstract

During the last few years the photovoltaic energy market has seen an outstanding growth. According to the new Directive on renewable energies of the European Commission (2009/28/EC), the European Union should reach a 20% share of the total energy consumption from renewable sources by 2020. The national overall targets impose for Italy a 17% renewable share, in case of failure the gap would be filled by importation of renewable energy from non-UE countries. The abitious national targets and thus the continuously increasing interest on renewable fuels, require simple but reliable methods for the energy potential assessment over large-scale territories. Considering roof-top integrated PV systems, the assessment of the PV energy potential passes through the evaluation of the roof surface area available for installations. In the present paper a methodology for estimating the PV solar energy potential is presented, together with its application to Piedmont Region (North-Western Italy). The roof area suitable for solar applications, is calculated through the analysis of available GIS data. The solar radiation maps are taken from the database of the Joint Research Centre of the European Commission. Different solar energy exploitation scenarios are proposed with the relative perspective results and confidence interval. Further developments and applications of the presented methodology are finally discussed.

Keywords: Photovoltaic; Roof-top PV systems; Renewable Energy; GIS

Nomenclature

N	Number of	[–]
S	Surface	[m^2]
P	Population	[–]
D	Density	[·/km^2]
C	Coefficient	[–]
η	Efficiency	[–]
μ	Exp. distribution rate parameter	[–]
H	Global irradiation	[Wh/m^2]
T	Temperature	[°C]
Π	Electric energy potential	[Wh]

Subscripts & Superscripts

inhab	Inhabitants
m	Mean
tot	Total
avail	Available
bui	Building
res	Resident, residential
ind	Industrial
mun	Municipality

pro	Province
pop	Population
mod	Module
amb	Ambient
MC	Mono-crystalline
PC	Poly-crystalline
TF	Thin Film

Abbreviations

GIS	Geographic Information System
BIPV	Building integrated PV system
EEA	European Environment Agency
CTRN	Numerical Technical Regional Map
VMAP	Vector Map
DEM	Digital Elevation Model
ESRA	European Solar Radiation Atlas
ISTAT	National Institute for Statistics
HVAC	Heating Ventil. and Air Cond. systems
STC	Standard Test Conditions
AM	Air mass coefficient

1. Introduction

The interest on renewable energies is growing day by day, as fossil fuels become always more expensive and difficult to find. Furthermore, the latest environmental disasters caused by the oil drilling and transportation, have further focused the attention of the entire world on the risks connected to fossil fuels. In the last April 2010, the explosion and sinking of the *Deepwater Horizon* oil rig in the Gulf of Mexico, and the start of the subsequent massive oil leak, is a clear example. During the last years, many attempts have been made to contain and control the scale of the environmental disasters, but the common sensation that fossil resources are "rapidly" going towards the end is widespreading. One of most interesting, among the *"green resources"*, is the solar energy. The employment of the solar radiations has a wide range of applications, nevertheless the interest of solar engineering is mainly focused on thermal processes and photovoltaic applications. Particularly, taking into account the photovoltaic solar energy conversion, the building-integrated PV systems (BIPV) hold an important slice of the energy market (besides other common applications, i.e. *PV farms*). Integrated systems should be in general preferred to massive installations, for a rational use of the natural resources. In Italy, the continuous and uncontrolled installation of PV farms over the territory (highly profitable due to the economic incentives (Conto Energia 2010, [1])), is indeed jeopardizing the natural landscape and occupying more and more agricultural terrains. The increasing rate of these installations and the subsequent consequences are drawing the attention of the public opinion and are cause of alarm. In Italy, the large exploitation of the photovoltaic solar energy is at the beginning and actually there exist no regulation of the PV installations. The number of installations in Piedmont is growing insomuch as in July (2010) the Regional Council has approved a draft law to regulate the land use and to accommodate photovoltaic systems on the ground (Regional Council of Piedmont website [2]). This moratorium against the photovoltaic disfiguring, has been thought to both regulate the installations and promote the BIPV systems. The energy policy of the actual administration indeed foresees to motivate the installations on buildings or anyhow on already compromised marginal areas.

The incentive to the large scale utilization of building integrated modules however supposes the knowledge of the technical and economic territorial potential. Several works have been carried out on building integrated PV system installations (Castro et al. [3], Sorensen [4]), but generally the available roof surface area is assumed to
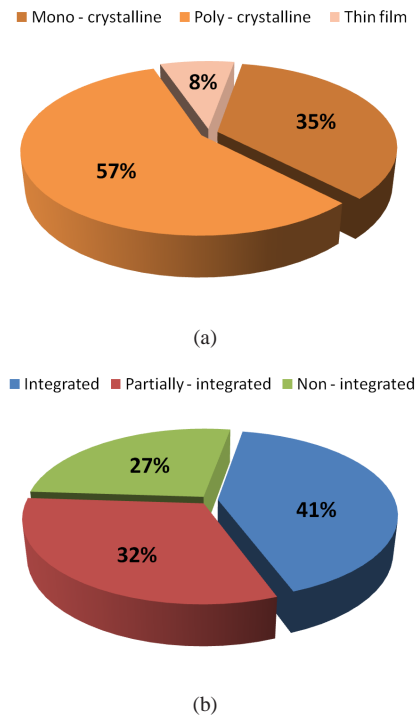

(a)

(b)

Figure 1: Subdivision of the electric power production [%] by different module technology (a) and different system-integration (b) over Piedmont Region in 2009 [10].

be an input. Furthermore, the detail of the available surface for PV installations is the *built-up area*, evaluated through maps of the land use (i.e. Corine Land Cover, of the European Environment Agency (EEA website [5])). This lack of methodology for the assessment of the available roof surface area, has been partially filled by some recent papers. A first scalable methodology for the roof surface assessment based on crossed-processing and sampling of various GIS data has been proposed together with its application to Spain in 2008 (Izquierdo et al. [6]). Very recent papers discuss similar methodologies and their relative applications to different geographical regions (Kabir et al. [7], Wiginton et al. [8]). The increasing literature on the topic reveals the growth of interest for the widespread exploitation of the solar power by means of building-integrated systems.

In Italy, in 2009, the total electrical energy consumption has been of about 320 TWh ([9],[10]), on the other hand the total production has been of about 275 TWh, corresponding to a 14% deficit ca. The paucity of the production has been balanced through importation from abroad. The only Piedmont Region in 2009 has seen a production of 24.5 TWh ca. against a demand of 26

TWh ca. (deficit of 6% ca.). Considering the only photovoltaic production, Piedmont produced 50.2 GWh, corresponding to 7.5% ca. of the total photovoltaic production in Italy. The energy production is subdivided on different module technologies and different kind of installations/integration[1]. (Fig. 1(a), 1(b)). It is important to notice that in the only Piedmont, the number of installations and the installed power in 2009 has been more than twice that of 2008 (respectively +118% and +149%), [10]. The present paper deals with the PV solar potential assessment over the Piedmont region through the evaluation of the roof surface available for grid connected building-integrated PV installations (BIPV). For the sake of clearness, the term BIPV generally refers to roofs and façades, in the paper we use it to refer to roof-top integrated PV systems only. The work is organized as follows: the general outlines of the methodology are first presented. Subsequently, the procedure for the assessment is discussed in detail together with the various data processing. The results are presented progressively: from the municipal to the regional scale. Different scenarios for the solar energy exploitation are presented together with their confidence interval and finally, the conclusions on the present work are drawn and perspective developments of the methodology are proposed.

2. Methodology

The assessment of the photovoltaic solar energy potential requires the evaluation of the *physical potential* (useful solar radiation), *geographical potential* (roof surface available) and *technical potential* (PV system efficiency). The estimated theoretical PV potential is achieved proceeding through a hierarchical assessment methodology (Fig. 2). Generally, in large scale analysis like this, a certain level of approximation has always to be accepted, thus the effort is to be done to contain the errors as much as possible, in order to achieve reliable results. The evaluation of the various potentials requires to take into account a wide range of different parameters. In the present study, it has been decided to counter the risk of misleading results evaluating different scenarios for each uncertainty, in a sort of parametrical study. The initial stage of the analysis, corresponding to the collection of the various data is of fundamental importance as the accuracy of the final results

---

[1]The level of integration of the PV modules is generally referred to three main typologies: *non-integrated*, for ground-mounted systems (i.e. PV farms), *partially-integrated* if the systems are intalled on buildings by means of additional structures, *integrated* if the modules are intalled directly on building features (i.e. roofs, façades)
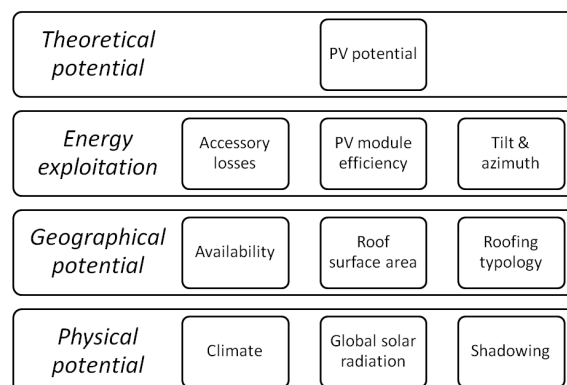

Figure 2: Scheme of the hierarchical methodology: the assessment foresees the estimation of the physical, geographical and technical potential (energy exploitation). The theoretical PV potential is achieved aggregating the data obtained through the various levels.

depends in great measure on the precision of the original data (as well as on the accuracy of the analysis and on the number of affecting parameters taken into account). A review of the available data necessary for the analysis has allowed an overview on the maximum precision achievable and on the sources of the various data types. In the matter of solar radiation data, it has been decided to refer to the maps provided by the Joint Research Centre of the European Commission ([16]) (freely available for public use). The geographical and cadastral analysis is carried out basing on the Numerical Technical Regional Map of Piedmont CTRN (Carta Tecnica Regionale Numerica). The update of the sections of the map is different over the region, the newest (current) version presents updates from 1991 to 2005. This is actually the most precise territorial data available and suitable for a large scale processing. For the sake of clarity, it has to be told that in Italy, all the cadastral data are held at the municipal level by the local cadastres. There have not been unification of the cadastral data at higher level until now and furthermore, all the data have not been computerized yet. There are nevertheless some projects, currently ongoing, aiming to digitalize and associate the cadastral data to the numerical maps. Such a document would allow the possibility to have all the cadastral information associated to the entities present in the numerical maps (i.e. height of buildings, number of resident persons per building, etc.).

All the analysis on the maps are performed in a commercial GIS software, ESRI ArcGIS 9.3. The data is successively exported for the processing, which has been

performed in MATLAB.

2.1. Solar radiation data

The solar radiation maps for Europe are freely available on the website of the Joint Research Centre (JRC) of the European Commission ([16]). The solar radiation database has been developed from the climatologic data available in the *European Solar Radiation Atlas, ESRA* (ESRA website [15]), homogenized for Europe. The algorithm used to build the database, accounts for beam, diffuse and reflected components of solar irradiation. Basically, the irradiation is computed by integration of the irradiance values measured at imposed time intervals during the day. For each time interval the effect of sky obstruction (shadowing by local terrain features) is computed by means of the Digital Elevation Model (DEM). For the sake of completeness, the calculation steps in the construction of the model are briefly reported hereafter, for the details on the algorithm refer to M. Šúri et al. ([11]), M. Šúri and Hofierka ([12]), M. Šúri et al. ([13]). The model has been developed through the following steps:

1. computation of clear-sky global irradiation on a horizontal surface;

2. calculation and spatial interpolation of clear-sky index and computation of raster maps of global irradiation on a horizontal surface;

3. computation of the diffuse and beam components of overcast global irradiation and raster maps of global irradiation on inclined surfaces;

4. accuracy assessment and comparison with *ESRA* interpolated maps.

On the website it is also possible to interrogate an interactive tool, the Photovoltaic Geographical Information System (PVGIS), and to obtain the solar radiation (kW/m^2) and the photovoltaic electricity potential (kWh) in a certain location (and for an assigned installed peak power), calculated on the basis of the desired parameters (i.e. module technology, mounting options, tracking options, etc.). The utility provides daily and monthly mean values and the yearly sum. The database has already been used to analyse regional and national solar energy resource and to assess the photovoltaic (PV) potential in European Union member states (Marcel Šúri et al., [14]). For the purpose of the present study, in order to obtain the solar radiation data at the municipal detail, the raster maps are the most suitable tool. Among the available maps on the website, the following are taken into account in the present paper:
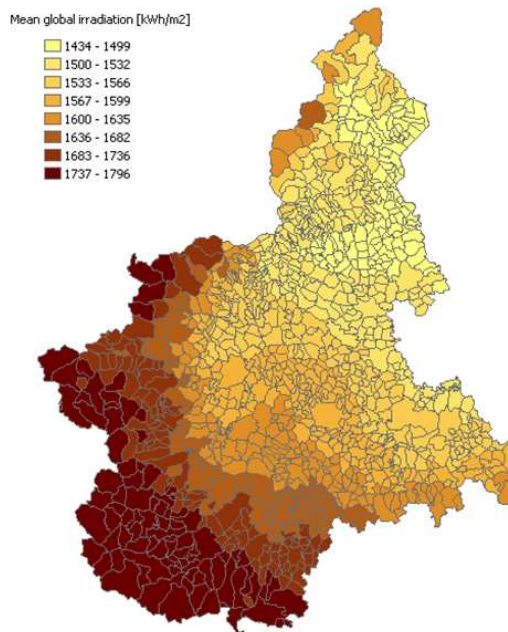
Figure 3: Yearly sum of global irradiation on the Piedmont region [kWh/m^2]. The colors refer to the mean global radiation per municipality. These values are the interpolated among all the cell-values of the solar radiation map falling within the municipality.

- yearly sum of global irradiation on optimally-inclined surface (kW/m^2);

- optimum inclination angle of equator-facing PV modules to maximise yearly energy yields ($°$).

The raster maps are in format ESRI ascii grid, and the original map projection is geographic, ellipsoid WGS84. The rasters cover the extent within the following bounds: North 72° N, South 32°30' N, West 27° W, East 45° E. Each map consists of 474 rows and 864 columns, for a total of 409536 cells. The grid cell size has a resolution of 5 arc-minutes (corresponding to 0.083333°), obtained aggregating the original data with 1 km resolution. All the raster maps have been vectorized and the geo-reference system (and projection) has been modified in order to match that of the Piedmont vector map. Each map has been thus overlayed to the Piedmont numerical map and clipped by the regional borders (Fig. 3). Each data layer (solar radiation and optimum inclination angles) has been joined to the Piedmont vector map assigning to each municipality the corresponding property. Particularly, the interpolated value of the pixels within the municipality is taken.

4

Figure 4: Comparison of the Piedmont numerical map (a) with the *Google Earth*™ image (b) for the same location. The snapshots show a view of Politecnico di Torino and neighborhood. In the view from the numerical map (a) it is possible to see the edge where two sections have been merged.

2.2. Territorial analysis

The CTRN of Piedmont Region is a vectorial map (*VMAP*), consisting of 70 *"sheets"* in scale 1:50000, obtained from the digitalization of the original CTR paper map. Each sheet is divided into 16 *"sections"* in scale 1:10000, for a total of 1120 sections. Actually, there exist no aggregated versions, the map is indeed in the form of compressed files, for a total of 21 GB ca. (subdivided in 45 CD-roms). The formats available are: *e00* format, an ESRI proprietary format to be used by means of GIS sofware, *dxf* format for AutoDesk, ESRI *shape3D* (this last only for the Dora river basin, until now). In the present work the *e00* format is used. All the 3191 *e00* files have been filtered and extracted from the CD-roms for the processing, the actual size of the compressed data is 9.6 GB ca. All files have been extracted to *coverages*. The coverage is a file containing multiple sub-files for points, lines and polygons. The sub-files have been filtered and, for our purpose, only those containing polygons have been selected. These files have then been converted to the most common *shp* file-type. This latter format, the *shapefile* is a *meta-data* format, which is able to store multiple informations for the same object. It is organized into geometries, which are geo-referenced polygons called *entities*. Each entity corresponds to an object, such as buildings, roads, rivers, etc. Each polygon stores a certain quantity of available informations, as for example its area and perimeter or its intended use. The storage of informations is achieved by means of at least three interconnected files (in this case there is a fourth optional file):

- *shp* file, geometries;

- *shx* file, indexes of the geometries;

- *dbf* file, attribute database;

- *prj* file, reference system (optional).

The *shp* files have then been merged and organized in a *file geodatabase*, a new ESRI compressed database format for large scale analysis. The data size at this point is 4 GB ca. Now it is possible to work and perform the analysis on the shapefiles of the entire region. The map can be directly interrogated and several studies can be performed. It is possible to filter or select entities by attributes or intended use, for instance. The strategy of the present study is to assess the roof surface area available for intallations per municipality. The municipality is indeed considered the smallest unity for the analysis. In order to associate each polygon to its administrative domain, a new shapefile containing the polygons representing the administrative limits of the municipalities has been layed upon the Regional map (obviously according to the same geo-referenced coordinate system and projections). In this way it has been possible to associate each entity of the CTRN to the municipality it belongs to. The association has been performed basing on the spatial location of the polygons. The criteria foresees that a polygon is associated to the relative municipality only if it falls completely inside. If a polygon falls in more than one administrative limit, the polygon is associated to the first municipality encountered by the algorithm. Another possible criteria could have been to associate a polygon to the municipality where the most of the area falls into. In both cases an error occurs, because it should be kept in mind that:

- the shape of the polygons representing the administrative limits is slightly simplified;

- an ambiguous building (falling on the administrative limit), in the reality, is not necessarily assigned to a certain municipality only basing on the spatial location;

- the obtained data cannot be verified, as neither the local administrations nor the cadastre, systematically provide this kind of informations.

The entity of the error due to the association algorithm will be discussed in the section dedicated to the methodologic uncertainties. After the association of the polygons to the municipalities, the entities have been filtered to calculate the number of residential and industrial buildings per municipality and the total roof surface area available. A brief clarification on the term "building" is mandatory. In the paper this term refers to a polygon characterized by a certain intended use (i.e. groups of adjacent residential or industrial structures).

2.3. Residential and industrial roofing

2.3.1. Residential

In Italy, especially in the north, the most employed roof typology is the double-pitched (in the southern regions flat roofs are also common). Actually, there exist no data about the roof-type distribution. Here we assume that the representative residential roofing typology over the Piedmont Region is double-pitched (Fig. 5(a)). The slope of the pitch is usually calculated according to the maximum theoretical snow-load (besides the roofing material). The slope of the roofs is indeed steeper in the mountains. In Piedmont the slope of the pitches can be assumed to range between 30 and 45% (17 to 24° ca.). This consideration allow to calculate the effective roof surface area. It should indeed be noticed that the building areas extrapolated from the CTRN are the 2D projections of the real roof surface. These areas are hence supposed to be corrected by their own slope. We assume a characteristic inclination angle for residential roofing of 20° (θ_{res} = 20°), and correct the area by a $cos(\theta_{res})$ factor. If we then assume that, given the slope of the pitched-roof, the fixed installation is realized so that the best inclination angle, or *tilt angle* (angle of inclination of the array from horizontal, 0° = horizontal, 90° = vertical, Fig. 5(b)) is achieved (by means of apposite supports), the solar radiation exploitation is maximized.

It should be reminded that an increased tilt will favour the power output in the winter months, which is often

(a)

(b)
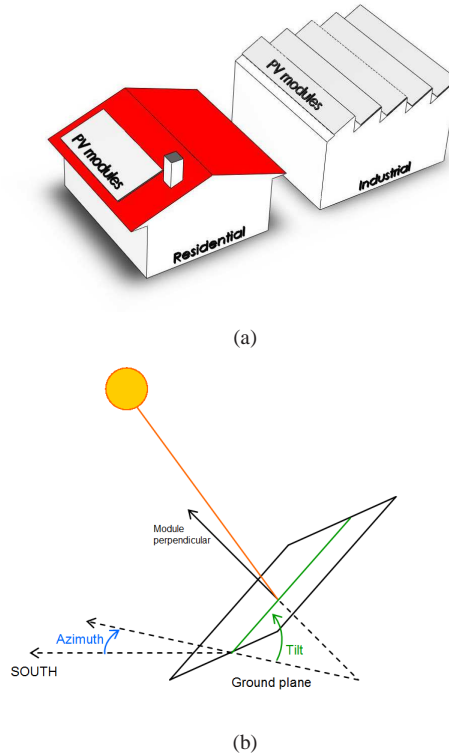
Figure 5: Schematic example of the representative roof typologies for residential and industrial buildings in Piedmont with roof-top integrated PV installations (a). Definition of the *tilt* and *azimuth* angles for PV applications (b).

desired for solar water heating instead, and a decreased tilt will favor power output in summer months. The optimal installation angle is a mean value, calculated to maximize the yearly energy yield. Another key factor to take into account in order to get the highest energy production from a photovoltaic system within a set geographic area has to do with maximizing the exposure to direct sunlight. It is necessary to avoid shade and expose the modules towards the sun, therefore realizing the module installation according to the best *azimuth angle* (angle of the panel with respect to the south, 0° = South, Fig. 5(b)). Considering fixed mounted, integrated PV systems, the installation azimuth should be that of the longitudinal roof axis, which is randomly different from the best (towards the south). In order to evaluate the losses due to the incorrect azimuth angle of the installation, the roof axes should be known. The territorial/cadastral data available at today, do not provide this kind of information. In order to overcome the problem, a corrective coefficient has been introduced, the *azimuthal coefficient, C_{AZ}*. The value of this coef-

Table 1: Summary table of the coefficients and angles of eq. (1). *Azimuthal coefficient C_{AZ}, roof-type coefficient C_{RT}, feature coefficient C_F, solar-thermal coefficient C_{ST}. The pitch inclination angle θ is 20° for residential and 30° for industrial roofing.*

Coefficient	Residential	Industrial
C_{AZ}	0.90	0.90
C_{RT}	0.50	0.75
C_F	0.70	0.90
C_{ST}	0.90	1.00
C_{TOT}	0.28	0.60

ficient has been evaluated using the PVGIS tool: in a set condition, the value of the azimuthal angle has been made varying from 0 to 90° for all the provinces of the Piedmont region, and the calculated power outputs have been used to evaluate the influence of the azimuth angle on the PV output. The mean value of the power outputs has been divided by the maximum value for each province. Sampling the eight provinces it has been assumed for this coefficient a value of 0.9 ($C_{AZ} = 0.9$). In the present paper it has been also decided to consider the installation of the modules only on one of the two pitches of each roof, which is a reasonable approximation. This consideration leads to decrease the roof surface available per building of 50% (*roof-type coefficient* $C_{RT} = 0.5$). Furthermore the roof surface available for installations has been considered to be 70% of the total pitch, considering the space already occupied by chimneys, aerials or windows (corrective *feature coefficient* $C_F = 0.7$). Precautionary we consider also that a 10% of the roof surface may not be available because already occupied by solar-thermal systems (corrective *solar-thermal coefficient* $C_{ST} = 0.9$). Considering all the above coefficients, their product yields the total corrective coefficient C_{TOT} (Tab. 1). The roof surface available is finally calculated by the following equation (1):

$$S_{roof}^{avail} = C_{AZ} \cdot C_{RT} \cdot C_F \cdot C_{ST} \cdot \frac{S_{roof}}{cos(\theta_{res})} \qquad (1)$$

2.3.2. Industrial

The industrial roofing is generally different from that of residential buildings. Despite the roof surface available can still be evaluated by means of equation (1), the different typology impose different values of the corrective coefficients and inclination angle. In particular, we consider that the most common roof typology for industrial applications is the pitched-roofing (Fig. 5(a)),

which is perfectly suitable for integrated PV installations. The *roof-type coefficient* C_{RT} is in this case assumed to be 0.75 (considering a 25% of the roof without sheds), the *feature coefficient* C_F equal to 0.9 (for chimneys or HVAC systems) and *solar-thermal coefficient* $C_{ST} = 1$ (generally industrial roofing is not used for solar-thermal systems). The characteristic shed inclination angle is assumed to be 30° ($\theta_{ind} = 30°$). The integrated system should again be installed by means of proper supports to achieve the optimal tilt angle. A summary of the parameters used in eq. (1) for the residential and industrial roofing is reported in Tab. (1).
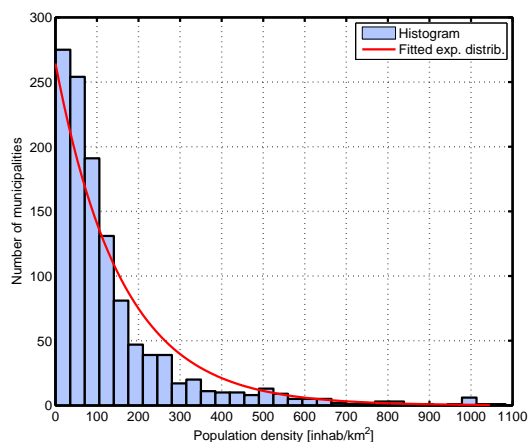
Figure 6: Histogram and fitted exponential distribution of the population density. The mean value is 158 inhab/km^2 ($\mu = 158\ inhab/km^2$), the maximum is Torino with 6982 inhab/km^2 (cut-off point of the x axis at 1100 inhab/km^2). It is noticeable the strong dispersion of the population. This is mostly due to the scarcely populated montain regions.

2.4. Population

All the data concerning the population have been taken on the website of the National Institute for Statistics IS-TAT ([17]. Particularly the list of all the Italian municipalities is freely available on the website [18]. The data-sheet provides informations on each municipality: name, ISTAT code, number of resident population and the province each municipality belongs to. The Piedmont Region (total population of 4432571 inhabitants) is divided into 1206 municipalities, organized in 8 provinces: Torino (TO), Vercelli (VC), Novara (NO), Cuneo (CN), Asti (AT), Alessandria (AL), Verbano-Cusio-Ossola (VB) and Biella (BI). A first interesting consideration on the population distribution can be drawn: 50% ca. of the total number of municipalities

counts less than 1000 inhabitants. The municipalities with more than 50000 inhabitants are only 8, and 1 over 150000 (Torino, with 910000 inhabitants ca.). The mean population density is 158 inhabitants per km^2, the maximux belongs to Torino, with 6982 inhabitants per km^2. It is noticeable that the Piedmont region is characterized by a very high concentration of the population in the main cities (Torino by far over the others). The region presents a strong dispersion of population outside the main cities. This disparity is mostly due to a high number of municipalities located in the mountain region of the Alps which are scarcely populated. Fig. 6 show the histogram and fitted exponential distribution of the population density over the region. For the sake of clarity, we briefly remind the definition of the pdf (probability density function) of an exponential distribution for a sample x (eq. 2):

$$f(x \mid \mu) = \frac{1}{\mu} \cdot e^{-\frac{x}{\mu}} \qquad (2)$$

2.5. Energy conversion

At today, the most employed PV module technologies are essentially three: *mono-crystalline (single-crystalline)*, *poly-crystalline (multi-crystalline)* silicon and *thin film (amorphous silicon)*. The mono-crystalline silicon is the oldest and more expensive production technique, but it is actually the most efficient sunlight conversion technology available. The poly-crystalline has a slightly lower conversion efficiency compared to the mono-crystalline, but the manifacturing costs are also lower. The thin film is obtained by vaporization and deposition of the silicon on glass or stainless steel. The production cost of this last technology is lower than any other method, but the conversion efficiency is also low. Generally the PV module manifacturers provide the *nominal peak power* at *Standard Test Conditions* (STC), which means at $1000W/m^2$ solar irradiance ($H = 1000W/m^2$), a module temperature of $25°C$ ($T_{mod} = 25°C$) and with an air mass 1.5 (AM1.5)[2] spectrum. At today, the PV module market is extremely dynamic, there is a wide range of technologies (continuously changing) and a multiplicity of declared efficiencies by manifacturers for the various module typologies. For the purpose of the present study, it has been decided to assume the following representative values: mono-crystalline $\eta_{MC} = 15\%$, poly-crystalline $\eta_{PC} = 12\%$ and thin film $\eta_{TF} = 6\%$. It is well known that the efficiency

---

Table 2: Summary table of the efficiencies for the various module technologies: MC mono-crystalline, PC poly-crystalline Silicon and TF thin film. Module efficiency η_{mod}, atmospheric efficiency η_{TH}, installation efficiency η_{inst} and total system efficiency η_{TOT}.

η	MC	PC	TF
η_{mod}	0.150	0.120	0.060
η_{TH}	0.900	0.900	0.900
η_{inst}	0.840	0.840	0.840
η_{TOT}	0.113	0.091	0.045

depends on several factors, such as operating temperature and irradiance ($\eta = f(T_{mod}, H)$). The module temperature in turn should be evaluated considering the ambient temperature, eventual cooling effect of the wind, etc. The evaluation of PV module losses (in no STC) is currently subject of great interest by the technical community, several papers are based this (i.e. E. Skoplaki, J.A. Palyvos [19], T. Huld et al. [20]). The performance of the modules, moreover, undergoes a decrease during the operating years (A.J. Carr, T.L. Pryor [21]). In the present paper we assume a generic loss due to temperature variations and irradiance of 10% ($\eta_{TH} = 0.9$) for all the module technologies. Besides the module efficiency (η_{mod}) and losses due to atmospheric variations ($\eta_{TH} = 0.9$), other accessory losses must be taken into account for grid-connected PV systems. Hereby we consider the accessory losses as follows: 3% due to reflection of the sunbeams of the array, 1% due to possible dirt or dust on the PV array, 2% due to the DC electric panel, 10% due to the inverter efficiency, for a total installation loss of 16% ($\eta_{inst} = 0.84\%$). Considering all the above efficiencies, their product leads to the total system efficiency per technology (η_{TOT}) (Tab. 2). The PV potential Π is finally calculated by means of the following equation (3):

$$\Pi = \eta_{mod} \cdot \eta_{TH} \cdot \eta_{inst} \cdot H_m^{mun} \cdot S_{roof}^{avail} \qquad (3)$$

Different scenarios of energy exploitation are presented in this work. The distribution of the PV module typologies over the Region has been evaluated on the basis of the statistical data of 2009 ([10]). The first possible scenario is to consider that in 2010, the total number of available roof surface area would be exploited by different module technology according to the statistical trend of 2009 (Fig. 1(b)). Two alternative scenarios are presented: the cases in which the energy would be exploited by means of the modules with the highest and lowest efficiency.

---

[2]The air mass coefficient characterizes the solar spectrum after the solar radiation has traveled through the atmosphere.
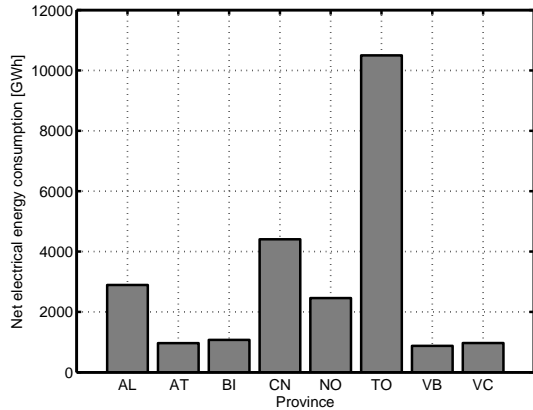
Figure 7: Net electrical energy consumption [GWh] for province in 2009: Alessandria (AL), Asti (AT), Biella (BI), Cuneo (CN), Novara (NO), Torino (TO), Verbano-Cusio-Ossola (VB), Vercelli (VC)

Table 3: Subdivision of the municipalities in classes according to the number of inhabitants. Seven quantiles have been used and it has been decided to report in Appendix (Tab. 5) the numerical results for class 4, describing 70% ca. of the whole population.

Class	range	N_{mun}	$\%_{mun}$	Pop	$\%_{pop}$
1	≥1000	606	50	4145756	93.5
2	≥2000	353	29	3786720	85.4
3	≥3000	239	20	3516313	79.3
4	≥5000	134	11	3113066	70.2
5	≥10000	67	5.5	2631635	59.3
6	≥20000	32	2.5	2141437	48.3
7	≥50000	8	0.5	1394477	31.5

- scenario A, different module technologies;

- scenario B, mono-crystalline only;

- scenario C, thin-film only.

2.6. Electrical energy demand

The electrical energy demand has been evaluated basing on the public statistical data of 2009 available on the distributor website [9]. The maximum level of resolution of the available data is the provincial detail. In 2009 the total net electrical energy comnsumption of the whole region has been of 24560.3 GWh (5532 kWh per inhabitant ca.), at the net of the energy for the railways. The losses have been of 1293 GWh increasing the total energy demand to 25853.3 GWh. Torino (TO) is by far the province with the highest consumption (10500 GWh), it required more than twice the energy needed by the second province with the highest consumption, which is Cuneo (CN) with 4403.5 GWh (7). In 2009, the total net production of the entire region has been 24399.7 GWh, of which 66 % ca. from thermoelectric sources, 33.7 % ca. from hydroelectric and a negligible part from photovoltaic (0.2 % ca.) and eolic (0.07 % ca.) sources.

3. Results

The analysis has been carried out according to a hierarchical procedure, proceeding from the smallest unity (municipality) towards the regional scale. The presentation of the results follows the same order in the paper.

3.1. Municipal level

The large amount of data of the municipal detail, does not allow the presentation of the results achieved for the whole 1206 municipalities. The population has been thus divided into classes, according to seven quantiles (Tab. 3). It has been decided to report the numerical results for class 4 (number of inhabitants greater than 5000), which include 134 municipalities and describes 70% ca. of the population. Attached to the present work, the table in Appendix (Tab. 5) reports the numerical results achieved for the municipalities of this last class. The analysis has been nevertheless carried out on all 1206 municipalities. The total number of industrial and residential buildings per municipality has been calculated, together with the relative available roof surface area (eq. 1). An example of the residential and industrial roof surface distribution achieved is reported for the municipality of Torino in Fig. 8(a) and 8(b) respectively. At this level, the results achieved on the PV potential are reported only for the exploitation scenario A (roof surface available divided in each municipality as follows: 35% mono-crystalline, 57% poly-crystalline and 8% thin film modules). The PV potential has been calculated for the residential only and industrial roofing only (eq. 1, 3), the total potential has then been achieved (Tab. 5 for municipalities of class 4, Fig. 9 for an overview of the whole region). The yearly sum of the global solar radiation over the region ranges between 1796 and 1434 kWh/m^2year, with a mean value of 1560 kWh/m^2year. It should be reminded that these values have been calculated assuming all the PV modules installed at the optimal inclination angle. For Piedmont, the mean optimal installation angle is 37° ca. (ranging between 35 and 40°). Despite the highest values of ir-

radiance are located on the mountain regions (Fig. 3), the low building density and thus the paucity of available roof surface area for installations, do not allow a full exploitation of the highest solar potential as shown in the next paragraph, *Provincial level*.
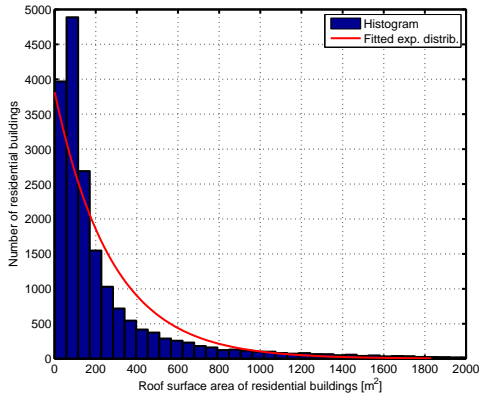
(a)
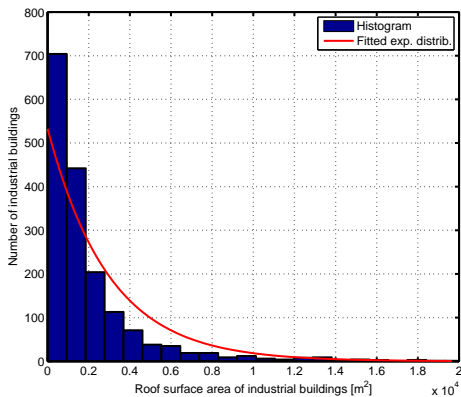
(b)

Figure 8: Histogram and fitted exponential distribution of the residential (a) and industrial (b) roof surface area in the municipality of Turin. For a better visualization, the cut-off points of the x axes are respectively 2000 and 20000 m^2. $\mu_{res} = 277\ m^2$ and $\mu_{ind} = 2974\ m^2$.

3.2. Provincial level

The results reported in this section are the aggregated of the municipal detail. The results achieved at the provincial level are reported in table 4. The table is organized in sections and reports: general results for each province (population and number of municipalities), the results on the available residential and industrial roofing and the numerical results achieved for exploitation scenario A. The provinces with the highest mean solar radiation
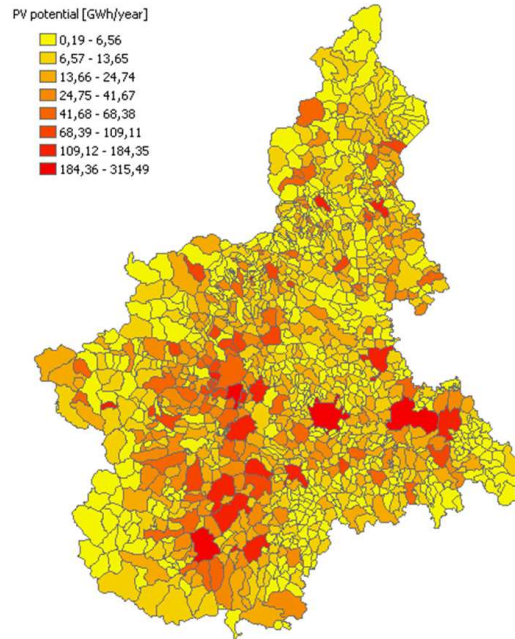
Figure 9: PV potential for each of the 1206 municipalities of the Piedmont Region (exploitation scenario A) [GWh/year].

are Cuneo (CN) with 1696 $kWh/m^2 year$, Torino (TO) 1610 $kWh/m^2 year$ and Asti (AT) 1588 $kWh/m^2 year$. Despite Cuneo is the province with the highest mean solar radiation, the highest PV potential belongs to Torino (TO) (followed by Cuneo (CN) and Alessandria (AL)), because of the larger roof surface available. The employment of the industrial roof surface area accounts respectively for 42% (TO), 28% (CN) and 29% (AL) ca. of the total PV potential of the province. The exploitation scenario A is then compared with scenario B and C for each province (Fig. 10). Scenario B corresponds to energy exploitation by means of mono-crystalline modules only (highest efficiency, most expensive technology), an thus to the highest PV potential. Scenario C for thin film modules only (cheapest technology but lowest efficiency), and thus to the lowest PV potential. Comparing the electrical potential of the three scenarios with the yearly electrical energy consumption shows that despite Torino (TO) is the province with the highest potential, its demand is not locally satisfied in any case (negative balance). On the other hand Cuneo (CN) and Asti (AT) for instance, would be able to self-sustain their local demand according to perspective scenarios A and B (Fig. 11).

Table 4: Summary table for provinces: Population (P_{pro}), number of municipalities (N_{pro}^{mun}), population density (D_{pro}^{pop}) [$inhab/km^2$], number of residential buildings (N_{res}^{bui}), residential building density (D_{res}^{bui}) [bui/km^2], residential roof surface available (S_{res}^{avail}) [km^2], number of industrial buildings (N_{ind}^{bui}), industrial building density (D_{ind}^{bui}) [bui/km^2], industrial roof surface available (S_{ind}^{avail}) [km^2], mean solar radiation (H_m) [kWh/m^2year], PV potential for scenario A (res, ind, tot), (Π_A) [$GWh/year$].

	General			Residential			Industrial				Potential		
	P_{pro}	N_{pro}^{mun}	D_{pro}^{pop}	N_{res}^{bui}	D_{res}^{bui}	S_{res}^{avail}	N_{ind}^{bui}	D_{ind}^{bui}	S_{ind}^{avail}	H_m	Π_A^{res}	Π_A^{ind}	Π_A^{tot}
TO	2290990	315	335	311908	45	30.14	14435	2.10	21.84	1610	4575.12	3285.83	7860.95
VC	180111	86	86	45138	22	4.67	1988	0.95	2.65	1519	675.38	381.84	1057.22
NO	366479	88	274	66878	50	6.57	3294	2.46	4.17	1493	932.73	592.61	1525.34
CN	586020	250	85	176291	26	16.99	5265	0.76	6.73	1696	2734.31	1076.21	3810.52
AT	220156	118	146	66965	44	6.06	3448	2.28	3.10	1588	914.21	468.29	1382.50
AL	438726	190	123	115187	32	11.18	3328	0.93	4.56	1563	1654.95	672.19	2327.13
VB	162775	77	72	65085	29	3.53	1027	0.45	1.18	1499	499.87	165.20	665.07
BI	187314	82	206	45107	49	3.61	2357	2.57	3.38	1508	516.43	482.80	999.23
REG.	4432571	1206	174	892559	35	82.75	35142	1.38	47.61	1560	12502.99	7124.97	19627.96
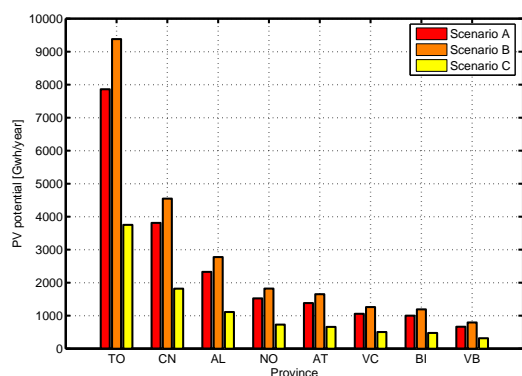
Figure 10: Comparison of the yearly PV potential for the different exploitation scenarios (A, B, C) for the 8 provinces of Piedmont: Alessandria (AL), Asti (AT), Biella (BI), Cuneo (CN), Novara (NO), Torino (TO), Verbano-Cusio-Ossola (VB), Vercelli (VC).

3.3. Regional level

In this paragraph the aggregated results of the previous levels are reported. Over the entire region, the residential roof surface available for installations is 83 km^2 ca. and the industrial 47 km^2 ca., for a total of 130 km^2 ca. of roof top surface area suitable for BIPV installations. It is interesting to highlight that the industrial roofing accounts for a 36% of the total roof surface available. Considering the total roof surface, the total PV potential achieved for scenario A is 19.6 TWh/year (12.5 TWh/year from residential and 7.1 TWh/year from industrial installations). On the other hand, according to scenario B, the total PV po-

tential is 23.4 TWh/year (14.9 TWh/year from residential and 8.5 TWh/year from industrial installations), and 9.4 TWh/year for scenario C (6 TWh/year from residential and 3.4 TWh/year from industrial installations). According to the methodology proposed in the present paper, the yearly PV potential over the region for the proposed exploitation scenarios ranges between 9.4 and 23.4 TWh/year, which yields a total mean PV potential pro capite ranging between 2.1 and 5.2 MWh/year. Considering the only residential buildings, the mean roof surface available pro capite is 18.5 m^2, for a PV potential ranging between 1.3 and 3.3 MWh/year. The yearly PV energy yield per square meter of installation is 150, 180 and 70 kWh/m^2year ca. for scenarios A, B, C respectively. Considering the yearly energy yield range per square meter, one may easily estimate his own PV production range simply multiplying these values for his meters of installation. In conlusion, it is interesting to make a comparison between the results obtained for Piedmont and the whole Italian energy production from PV resources in 2009 [9]: the total national production has been of about 676 GWh, the only Piedmont accounted for 50.2 GWh (7.5% ca.). The estimated total PV potentials for Piedmont range in three orders of magnitude above.

4. Confidence level

A systematical analysis over large-scale territories like this, is always affected by a certain level of uncertainty. Particularly, the accuracy of the final results strongly
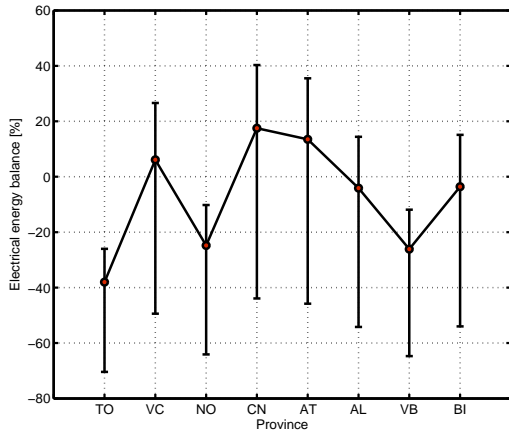
Figure 11: Electrical energy balance for the 8 provinces. The central red-dotted-line refers to the comparison demand/supply for scenario A. The error bars show the comparison of demand with scenario B (upper bound) and C (lower bound).

depends on the quality of the input data. The first uncertainty to consider is that the CTRN of the Piedmont region consists of various differently updated sections. The newest version presents updates from 1991 to 2005. The newly-built buildings, for instance, are not present. The actual version of the CTRN is nevertheless the most precise document available and suitable for a large scale analysis. Despite this, it should be noticed that the roof surface computation is not based on samples, but on the whole cartographic database of the region. The extrapolated roof surface can be thus assumed to be errorless. The error due to the association building/municipality discussed in paragraph 2.2 *Territorial analysis* instead, has been estimated considering the municipality with the highest and lowest number of total buildings (respectively Torino and Claviere). Excluding the ambiguous buildings (falling on the administrative limit), thus associating to the relative municipality only the buildings falling completely within the administrative limits, gives a maximum relative error of 1.7%. The evaluation of the roof surface available, directly depends on the values assumed for the corrective coefficients (eq. 1), thus the variation of the coefficients affects directly the resulting PV potential.

In the PV potential calculation, the reciprocal shadowing of buildings has not been taken into account (i.e. block of flats in the cities). The eventual computation of this parameter supposes the knowledge of the height of each building. Actually there exist no data at this detail. The PV potential has been calculated assuming

a mean irradiance value in each municipality. Considering to assume the maximum and minimum value instead, yields a confidence level of ± 1% on the PV potential. The yearly PV energy yield per square meter of installation obtained (ranging between 70 and 180 $kWh/m^2 year$) is consistent with the results obtained by a similar work for Spain (Izquierdo et al., [6]).

5. Conclusions and developments

In the present paper, a methodology for the PV solar energy potential assessment has been presented. The hierarchical procedure proposed is accomplished through the evaluation of the useful global solar radiation, the roof surface available for roof-top integrated PV systems and their relative performances. Basically the procedure requires easy and freely accessible data, as solar radiation maps (database for Europe, [16]), statistical data on population and energy consumption and GIS data of the area object of study. It is indeed reproducible for other regions or countries at different scale (obviously depending on the computational resources available).

In the present work the methodology has been applied to the Piedmont Region (North-Western Italy). Different exploitation scenarios have been presented and it has been shown that, by means of roof-top integrated PV systems, the solar energy potential over the region may reach 23.4 TWh/year (according to the best exploitation scenario). It is interesting to denote that in 2009 the total net electrical energy consumption of the region has been of 24.5 TWh ca. (national net consumption of 300 TWh ca.) [9].

The presented methodology has been here applied for the PV solar energy potential assessment, but it can be easily applied for the solar-thermal potential assessment. Furthermore, a similar procedure could be accomplished to evaluate the possibility of installations along highways, railways or other marginal areas.

phase of the territorial analysis has been really appreciated. Thanks to Thomas Huld, of the Joint Research Centre of the European Commission, for his hints on the solar radiation data. We are also thankful to our friend Salvador Izquierdo, who first applied a similar methodology to Spain ([6]), for our enlightening discussions and comparisons.

References

[1] Conto Energia 2010. GSE S.p.a., Gestore Servizi Energetici. Publicly-owned company promoting and supporting renewable energy sources (RES) in Italy. 2010, (www.gse.it).

[2] Regional Council of Piedmont. 2010, (www.regione.piemonte.it).

[3] Castro, M., Delgado, A., Argul, F., Colmenar, A., Yeves, F., Peire, J., *Grid-connected PV buildings: analysis of future scenarios with an example of southern Spain*, Solar Energy 79 (2005) 8695.

[4] Sorensen, B., *GIS management of solar resource data*, Solar Energy Materials and Solar Cells, 67 (2001)(14), 503509.

[5] EEA, 2010. European Environment Agency (http://www.eea.europa.eu/data-and-maps/).

[6] Izquierdo S, Rodrigues M, Fueyo N., *A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations*, Solar Energy 82 (2008) 92939.

[7] Kabir, Md.H., Endlicher, W., Jgermeyr, J., *Calculation of bright roof-tops for solar PV applications in Dhaka Megacity, Bangladesh*, Renewable Energy 35 (8) (2010), pp. 1760-1764.

[8] Wiginton, L.K., Nguyen, H.T., Pearce, J.M., *Quantifying rooftop solar photovoltaic potential for regional renewable energy policy*, Computers, Environment and Urban Systems 34 (4) (2010), pp. 345-357.

[9] Terna S.p.a., 2010. Energy Transmission Grid Operator. *Statistical Data on electricity in Italy (for 2009)*, (www.terna.it).

[10] GSE S.p.a., 2010. Gestore Servizi Energetici. Publicly-owned company promoting and supporting renewable energy sources (RES) in Italy. *Statistical Data on photovoltaic solar energy in Italy for 2009*, (www.gse.it).

[11] Marcel Šúri, Thomas Huld, Tomáš Cebecauer, Ewan D. Dunlop, *Geographic Aspects of Photovoltaics in Europe: Contribution of the PVGIS Website*, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, v 1, n 1, p 34-41, 2008.

[12] Šúri M., Hofierka J., *A new GIS-based solar radiation model and its application to photovoltaic assessments*, Transactions in GIS 8, 175190, 2004.

[13] Šúri M., Dunlop E. D., Huld T. A., 2005. *PV-GIS: A web based solar radiation database for the calculation of PV potential in Europe*, International Journal of Sustainable Energy 24 (2), 5567.

[14] Marcel Šúri, Thomas Huld, Tomáš Cebecauer, Ewan D. Dunlop, Heinz A. Ossenbrink, *Potential of solar electricity generation in the European Union member states and candidate countries*, Solar Energy 81 (2007) 12951305.

[15] ESRA, 2010. European Solar Radiation Atlas (http://www.helioclim.org/esra/).

[16] JRC, 2010. Joint Research Centre of the European Commission, IE Institute for Energy. *PVGIS*, (http://re.jrc.ec.europa.eu/pvgis/).

[17] ISTAT 2010. National Institute for Statistics, (www.istat.it).

[18] ISTAT 2010. National Institute for Statistics, (www.istat.it/strumenti/definizioni/comuni/).

[19] E. Skoplaki, J.A. Palyvos, *On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations*, Solar Energy 83 (2009) 614624.

[20] Thomas Huld, Ralph Gottschalg, Hans Georg Beyer, Marko Topic, *Mapping the performance of PV modules, effects of module type and data averaging*, Solar Energy 84 (2010) 324338.

[21] A.J. Carr, T.L. Pryor, *A comparison of the performance of different PV module types in temperate climates*, Solar Energy 76 (2004) 285294.

Table 5: Summary table for municipalities: Surface (S_{mun}), Population (P_{mun}), population density (D_{pop}^{mun}) [$inhab/km^2$], number of residential buildings (N_{res}^{bui}), residential roof surface available (S_{res}^{avail}) [m^2], number of industrial buildings (N_{ind}^{bui}), industrial roof surface available (S_{ind}^{avail}) [m^2], total roof surface available (S_{tot}^{avail}) [m^2], mean solar radiation (H_m) [$kWh/m^2 year$], PV potential for scenario A (res, ind, tot), (Π_A) [$GWh/year$].

Municipality	Prov.	S_{mun}	P_{mun}	D_{pop}^{mun}	N_{res}^{bui}	S_{res}^{avail}	N_{ind}^{bui}	S_{ind}^{avail}	S_{tot}^{avail}	H_m	Π_A^{res}	Π_A^{ind}	Π_A^{tot}
Almese	TO	17.9	6292	351	1849	112179	63	46178	158357	1622	17.3	7.1	24.4
Alpignano	TO	12.0	17246	1443	2330	175881	168	157505	333386	1587	26.5	23.8	50.3
Avigliana	TO	23.3	12183	524	2548	161688	93	54410	216098	1631	25.1	8.4	33.5
Beinasco	TO	6.8	18142	2684	1140	135141	154	368724	503865	1582	20.3	55.4	75.8
Borgaro Torinese	TO	14.4	13552	944	979	123204	150	228257	351461	1557	18.2	33.8	52.0
Brandizzo	TO	6.4	8141	1270	1272	106561	44	65907	172468	1563	15.8	9.8	25.6
Bruino	TO	5.6	8437	1509	1141	97906	105	124613	222519	1618	15.1	19.2	34.2
Bussoleno	TO	37.4	6597	176	2598	108654	106	44691	153345	1729	17.9	7.3	25.2
Buttigliera Alta	TO	8.3	6574	797	1157	81404	30	57802	139206	1611	12.5	8.8	21.3
Caluso	TO	39.5	7549	191	1418	225683	108	116185	341868	1547	33.2	17.1	50.2
Cambiano	TO	14.2	6318	444	889	80271	119	140636	220907	1595	12.2	21.3	33.5
Candiolo	TO	11.9	5646	474	741	83563	21	68008	151571	1591	12.6	10.3	22.9
Carignano	TO	50.2	9129	182	1645	226543	74	72228	298771	1591	34.3	10.9	45.2
Carmagnola	TO	96.4	27927	290	4777	412178	273	387684	799862	1611	63.1	59.4	122.5
Caselle Torinese	TO	28.7	17949	626	1937	228849	155	292581	521467	1554	33.8	43.2	77.0
Castellamonte	TO	38.5	9935	258	4346	319076	109	105751	424827	1565	47.5	15.7	63.2
Castiglione Torinese	TO	14.2	6261	442	1427	93112	41	24550	117662	1569	13.9	3.7	17.5
Cavour	TO	49.1	5592	114	2157	189014	93	65504	254518	1655	29.7	10.3	40.0
Chieri	TO	54.3	35849	660	4008	480715	300	338040	818755	1599	73.0	51.3	124.4
Chivasso	TO	51.3	25378	495	3233	349453	227	212523	561976	1547	51.4	31.2	82.6
Cirié	TO	17.8	18827	1058	2944	366732	129	220182	586914	1559	54.3	32.6	86.9
Collegno	TO	18.1	50072	2763	2977	270983	277	444969	715952	1573	40.5	66.5	107.0
Cumiana	TO	60.8	7858	129	2543	193111	61	52900	246011	1679	30.8	8.4	39.2
Cuorgné	TO	19.4	10175	525	2198	178598	67	66292	244890	1580	26.8	10.0	36.8
Druento	TO	27.7	8429	305	1196	105918	111	117928	223846	1562	15.7	17.5	33.2
Favria	TO	14.9	5148	347	1080	101969	99	73924	175893	1545	15.0	10.9	25.8
Gassino Torinese	TO	20.5	9578	468	1384	120578	25	21835	142413	1583	18.1	3.3	21.4
Giaveno	TO	72.0	16425	228	5146	299249	175	96574	395823	1714	48.7	15.7	64.5
Grugliasco	TO	13.1	37691	2873	2903	293381	332	633504	926885	1581	44.1	95.1	139.2
Ivrea	TO	30.2	24409	809	3303	338690	151	285213	623903	1517	48.8	41.1	89.9
La Loggia	TO	12.8	7666	599	1017	112016	57	198906	310922	1587	16.9	30.0	46.9
Lanzo Torinese	TO	10.4	5377	519	2047	140701	71	56142	196843	1597	21.4	8.5	29.9
Leiní	TO	32.5	14624	451	1910	250068	285	488319	738387	1555	37.0	72.2	109.1
Luserna San Giovanni	TO	17.7	7748	437	1721	146357	33	79916	226273	1724	24.0	13.1	37.1
Moncalieri	TO	47.6	57788	1213	5452	698403	300	649763	1348166	1588	105.4	98.1	203.5
Montanaro	TO	20.8	5456	262	1092	108208	40	38547	146755	1548	15.9	5.7	21.6
Nichelino	TO	20.6	49060	2377	2904	361623	175	337658	699281	1585	54.5	50.9	105.3
Nole	TO	11.3	6828	604	1378	119714	34	48931	168645	1563	17.8	7.3	25.1
None	TO	24.7	7927	321	1186	151399	77	229521	380920	1597	23.0	34.8	57.8
Orbassano	TO	22.1	22254	1009	1909	232477	231	352601	585078	1586	35.0	53.1	88.2
Pianezza	TO	16.5	13590	824	1741	150658	205	198756	349414	1565	22.4	29.5	51.9
Pinerolo	TO	50.3	35491	706	3833	459943	127	182597	642540	1687	73.7	29.3	103.0
Pino Torinese	TO	21.9	8663	396	1656	174677	13	7341	182018	1594	26.5	1.1	27.6
Piossasco	TO	40.0	18032	451	2070	203974	70	106277	310251	1632	31.6	16.5	48.1
Novara	NO	103.0	103602	1006	7324	1047223	464	806853	1854076	1501	149.3	115.1	264.4
Oleggio	NO	37.8	13222	350	2861	230982	162	146938	377920	1489	32.7	20.8	53.5
Poirino	TO	75.7	10149	134	2037	287639	161	247025	534664	1604	43.8	37.6	81.5
Rivalta di Torino	TO	25.3	19001	753	2391	241829	181	337010	578839	1605	36.9	51.4	88.3
Rivarolo Canavese	TO	32.3	12372	383	2152	230456	215	235266	465722	1545	33.8	34.5	68.4
Rivoli	TO	29.5	50015	1694	5626	457470	581	637397	1094867	1595	69.3	96.6	165.9
San Benigno Canavese	TO	22.2	5577	251	1239	122315	65	59184	181499	1547	18.0	8.7	26.7
San Maurizio Canavese	TO	17.5	9123	521	1818	203181	71	101804	304985	1550	29.9	15.0	44.9
San Mauro Torinese	TO	12.6	19333	1540	1985	158463	167	351700	510163	1576	23.7	52.7	76.4
Santena	TO	16.2	10548	651	1733	162199	98	129587	291786	1595	24.6	19.6	44.2
Settimo Torinese	TO	32.4	47539	1469	3463	338514	419	907145	1245659	1557	50.1	134.3	184.3
Strambino	TO	22.8	6381	280	1397	150535	62	64453	214988	1522	21.8	9.3	31.1
Susa	TO	11.3	6806	604	1997	103436	129	43563	146999	1668	16.4	6.9	23.3
Torino	TO	130.2	908825	6982	18843	5219410	1730	5145144	10364554	1576	781.7	770.6	1552.3
Trofarello	TO	12.3	11125	903	1380	129362	114	146003	275365	1593	19.6	22.1	41.7
Venaria Reale	TO	20.3	34682	1709	1324	197582	169	358117	555699	1555	29.2	52.9	82.1
Vigone	TO	41.1	5300	129	1579	150164	156	104082	254246	1628	23.2	16.1	39.3
Vinovo	TO	17.7	13860	785	1817	219553	86	201190	420743	1586	33.1	30.3	63.4
Volpiano	TO	32.4	14771	456	3012	265973	188	260907	526880	1554	39.3	38.5	77.8
Volvera	TO	20.9	8643	413	1050	111529	67	168724	280253	1608	17.0	25.8	42.8
Borgosesia	VC	40.6	13447	332	2624	221075	96	185397	406472	1518	31.9	26.7	58.6

Municipality	Prov.	S_{mun}	P	D_{pop}	N_{res}^{bui}	S_{res}^{avail}	N_{res}^{bui}	S_{res}^{avail}	S_{tot}^{avail}	H_m	Π_A^{res}	Π_A^{ind}	Π_A^{tot}
Crescentino	VC	48.3	8124	168	1368	193698	54	147535	341233	1542	28.4	21.6	50.0
Gattinara	VC	33.5	8399	250	1314	154618	84	179578	334196	1496	22.0	25.5	47.5
Santhiá	VC	53.3	9078	170	1616	155587	155	153152	308739	1507	22.3	21.9	44.2
Serravalle Sesia	VC	20.4	5129	252	1066	105213	77	121909	227122	1505	15.0	17.4	32.5
Trino	VC	70.6	7711	109	1140	204591	87	156020	360611	1530	29.8	22.7	52.4
Varallo	VC	88.7	7586	86	2277	166819	40	47475	214294	1530	24.3	6.9	31.2
Vercelli	VC	79.8	47080	590	3774	593541	344	563197	1156738	1513	85.3	81.0	166.3
Arona	NO	14.9	14588	980	2117	206784	54	61282	268066	1480	29.1	8.6	37.7
Bellinzago Novarese	NO	39.3	9120	232	1614	156741	52	55520	212261	1493	22.2	7.9	30.1
Borgomanero	NO	32.3	21305	660	4177	334680	182	184812	519492	1495	47.5	26.3	73.8
Cameri	NO	39.6	10792	272	1619	135606	91	146726	282332	1496	19.3	20.9	40.1
Castelletto sopra Ticino	NO	14.6	10000	686	2109	179899	66	69042	248941	1476	25.2	9.7	34.9
Cerano	NO	32.1	6879	214	944	139622	84	134522	274144	1499	19.9	19.2	39.0
Galliate	NO	29.5	15062	510	2052	234834	135	171591	406425	1496	33.4	24.4	57.8
Gozzano	NO	12.5	5808	464	1510	120645	109	141286	261931	1503	17.2	20.2	37.4
Romentino	NO	17.7	5133	290	675	86121	40	47640	133761	1496	12.2	6.8	19.0
Trecate	NO	38.4	19602	511	1804	209088	147	169414	378502	1499	29.8	24.1	53.9
Alba	CN	54.0	30994	574	3505	440578	118	335054	775632	1632	68.3	51.9	120.3
Bagnolo Piemonte	CN	62.9	5969	95	3008	208624	11	15229	223853	1713	34.0	2.5	36.4
Barge	CN	82.4	7757	94	3874	272359	74	53727	326086	1692	43.8	8.6	52.4
Borgo San Dalmazzo	CN	22.3	12212	549	1856	186592	93	137989	324581	1781	31.6	23.4	54.9
Boves	CN	51.1	9889	194	2305	204930	38	65893	270823	1777	34.6	11.1	45.7
Bra	CN	59.6	29608	497	4462	462027	201	320640	782667	1633	71.7	49.7	121.4
Busca	CN	65.8	9941	151	2748	281810	86	87346	369156	1743	46.7	14.5	61.1
Canale	CN	18.0	5747	319	1200	130378	59	84437	214815	1615	20.0	13.0	33.0
Caraglio	CN	41.5	6780	163	1933	184004	59	59136	243140	1776	31.1	10.0	41.0
Cavallermaggiore	CN	51.6	5418	105	1340	176560	70	85692	262252	1634	27.4	13.3	40.7
Centallo	CN	42.8	6681	156	1607	175104	38	38027	213131	1713	28.5	6.2	34.7
Ceva	CN	43.0	5884	137	1373	143660	31	42128	185788	1691	23.1	6.8	29.9
Cherasco	CN	81.2	8287	102	2132	245796	128	215913	461709	1639	38.3	33.6	71.9
Cuneo	CN	119.9	55201	460	5955	902254	240	502878	1405132	1752	150.1	83.7	234.0
Dronero	CN	58.9	7313	124	2108	209664	37	60261	269925	1772	35.3	10.1	45.5
Fossano	CN	130.7	24595	188	4568	542343	236	363774	906117	1685	86.8	58.2	145.1
Mondoví	CN	87.3	22473	258	3562	426777	180	293284	720061	1707	69.2	47.6	116.8
Peveragno	CN	68.4	5448	80	2214	215624	31	44730	260354	1775	36.4	7.5	43.9
Racconigi	CN	48.0	10068	210	1746	212461	87	126288	338749	1621	32.7	19.4	52.2
Saluzzo	CN	75.8	16797	222	2575	363809	95	140472	504281	1657	57.3	22.1	79.4
Savigliano	CN	110.7	20845	188	3215	484061	211	261574	745635	1664	76.5	41.4	117.9
Sommariva del Bosco	CN	35.6	6326	178	1294	145738	43	67596	213334	1625	22.5	10.4	32.9
Verzuolo	CN	26.2	6406	245	1312	148807	34	115930	264737	1701	24.1	18.7	42.8
Villanova Mondoví	CN	28.4	5771	203	1405	141096	51	52997	194093	1742	23.4	8.8	32.1
Asti	AT	151.8	75298	496	10530	848252	816	757248	1605500	1580	127.3	113.7	241.0
Canelli	AT	23.6	10628	451	2213	249182	178	262653	511780	1595	37.8	39.8	77.5
Costigliole d'Asti	AT	36.9	6061	164	2404	199445	102	61260	260705	1595	30.2	9.3	39.5
Nizza Monferrato	AT	30.4	10388	342	2173	250304	119	108435	358739	1587	37.8	16.4	54.1
San Damiano d'Asti	AT	48.0	8445	176	2602	214255	132	87216	301471	1597	32.5	13.2	45.8
Villanova d'Asti	AT	42.1	5600	133	1448	161067	140	265999	427066	1607	24.6	40.6	65.2
Acqui Terme	AL	33.4	20426	611	3059	326825	108	125444	452269	1589	49.4	18.9	68.3
Alessandria	AL	204.0	93676	459	10617	1305765	643	853865	2159630	1537	190.8	124.7	315.5
Arquata Scrivia	AL	23.4	6127	262	1538	95159	38	92390	187549	1588	14.4	13.9	28.3
Casale Monferrato	AL	86.3	36039	418	4429	711225	188	345238	1056463	1532	103.5	50.2	153.8
Castelnuovo Scrivia	AL	45.4	5513	121	1023	166815	65	87353	254168	1517	24.0	12.6	36.6
Novi Ligure	AL	54.2	28581	527	3476	370147	123	220593	590740	1562	55.0	32.7	87.7
Ovada	AL	35.3	11912	337	2047	211828	76	149280	361108	1607	32.3	22.8	55.1
Serravalle Scrivia	AL	16.0	6272	392	1113	94415	60	138998	233413	1566	14.1	20.7	34.7
Tortona	AL	99.3	27476	277	4004	420451	390	525666	946117	1534	61.3	76.6	137.9
Valenza	AL	50.1	20282	405	2247	300280	55	61323	361603	1531	43.7	8.9	52.6
Domodossola	VB	36.9	18452	501	3357	274670	51	67842	342512	1489	38.9	9.6	48.5
Biella	BI	46.7	45842	982	4605	469523	366	560857	1030380	1503	67.1	80.1	147.2
Candelo	BI	15.1	8041	534	1445	142086	45	71943	214029	1489	20.1	10.2	30.3
Cossato	BI	27.8	15050	542	3146	223115	163	223305	446420	1496	31.7	31.8	63.5
Trivero	BI	29.9	6326	212	1475	121724	69	202637	324361	1515	17.5	29.2	46.7
Vigliano Biellese	BI	8.4	8482	1012	1532	105563	116	186798	292361	1489	14.9	26.4	41.4
Cannobio	VB	51.2	5132	100	1465	122635	12	3569	126204	1453	16.9	0.5	17.4
Gravellona Toce	VB	14.7	7781	529	1255	94628	95	133995	228623	1469	13.2	18.7	31.9
Omegna	VB	30.8	16074	522	2802	228477	166	219626	448103	1500	32.6	31.3	63.9
Stresa	VB	33.2	5179	156	2060	143657	7	5560	149217	1453	19.8	0.8	20.6
Verbania	VB	37.7	31134	827	4283	356034	177	229213	585247	1441	48.7	31.4	80.1
Villadossola	VB	18.0	6909	385	1665	98462	77	121673	220135	1471	13.8	17.0	30.8

15