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Site selection of large ground-mounted photovoltaic plants: a GIS decision support system and an application to Italy

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Abstract

Latterly, central governments and local authorities have been establishing various constraints on the construction of new large ground-mounted photovoltaic plants, because of the soil consumption, landscape impact and also competitiveness with the crop production. This is particularly important in contexts where the agricultural sector is closely linked to the territory. With the aim of providing a decision support tool based on quantitative indicators for the site selection of large ground-mounted PV plants, in this paper the criteria for the identification of areas suitable for the installation of ground-mounted photovoltaic systems, recently emerged by regional government or in the technical and scientific literature, are applied to the entire territory of the Piedmont region (25,000 km^2). Both qualitative criteria for inclusion/exclusion (e.g. exclusion from areas of great value) and criteria for quantification (e.g. solar resource availability) were considered. The aggregation of the quantitative criteria into the final indicator is done by means of an ANN trained with values corresponding to sites of existing PV plants in the Region. It emerges that the available areas are very limited, concentrated and strongly influenced by the criteria of exclusion/inclusion. Some considerations on the significance of the results for the region of analysis are finally made.

Keywords: ground-mounted PV, decision support systems, GIS, land use.

1 Introduction

Solar photovoltaic is seen to be one of the leading clean energy sources of the future. Nearly 40 countries around the world have implemented a net pricing law to fund photovoltaic and this caused a grown of the PV market, a significant cost reduction and an increase in manufacture capacity for the leading countries (Germany, Japan) (Dinçer, 2011). New PV technologies are emerging and are environmentally assessed by means of the life cycle analysis methodologies (Bayod-Rujula et al., 2011; Battisti and Corrado, 2005; Beylot et al., in press). The environmental impact of a ground-mounted PV plant involves however various aspects: many studies are based on LCA, other treats the visual aspects, others are multidisciplinary. Also the scale of analysis is different. Given this picture, in this paper we concentrated on the land selection, on a territorial scale.

Since 2006 Italy launched five feed-in tariff programs to promote the production of electricity from solar photovoltaic (DM 05/05/2011), which gradually reduced the incentive tariffs for large grid-connected ground-mounted photovoltaic plants. The installation of large ground-mounted PV (up to several MW of installed peak power) is increasingly seen by local communities as variously impacting on the landscape. In the direction of regulating the construction of new plants, the long awaited Italian national guidelines (DM 10/9/2010) that implement the Legislative Decree 387/2003, have been issued. These guidelines contain the criteria for the landscape and territorial integration of the plants. Similarly, some Italian regions, including the Piedmont Region, have issued detailed guidelines.

On the basis of other works done by the same authors with respect to the territorial impacts (Chiabrando et al., 2009) and landscape impacts evaluation

(Chiabrando et al., 2011) of large photovoltaic plants, and on the assessment of the bioenergy potential of a territory (Fabrizio and Branciforti, 2011), in this work some of the criteria for the identification of areas suitable for the installation of large ground-mounted photovoltaic plants, that emerged in the Italian legislation and in the technical and scientific literature, are applied and processed by means of a GIS tool to a large territory such as the one of entire Piedmont region (25,388 km²).

In the energy sector, spatial tools as GIS have been widely used both as a tool to appreciate the spatial distribution of bioresources in terms of availability and demand (Sørensen and Meibom, 1999; Sørensen, 2001), and as decision-support systems for the site selection of energy production plants (Gorsevski et al., 2013).

In the first case, the use of GIS is appropriate because renewable energy resources are spatially distributed. GIS can manage georeferenced information concerning energy resources (such as biomass, wind and solar) and is used to create inventories of resources (Ramachandra and Shruthi, 2005; Ramachandra and Shruthi, 2007; Ramachandra, 2010; Singh et al., 2008; Bosch et al., 2010; Arnette and Zobel, 2011; Gormally et al. 2012) or assess the technical and economical feasibility of the source exploitation (Voivontas et al., 1998; Voivontas et al., 2001; Yu and Wang, 2006; Beccali et al., 2009; Vardimon, 2011; Mari et al., 2011; Hossain et al., 2011; Sliz-Szkliniarz and Vogt, 2011; Ruiz-Ariasa et al., 2012). This is done by linking the available resource with other types of georeferenced information (e.g. distance, population, electricity network, cost) through the computational capabilities of GIS. A critical review on the many applications of geomatics in the renewable energy field, addressing the issues of modelling methods, acquisition, resolution of data and yield calculations, and containing future perspectives can be found on Calvert (2011).

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In the second case, GIS is typically used as a site selection support system, as it is performed in many other fields (Hernandez et al., 2004; Rogge et al., 2008; Domingo-Santos et al., 2011). In the energy sector, applications to wind (Baban and Parry, 2001; Hurtado et al., 2004; Aydin et al., 2010; Janke, 2010; Grassi et al., 2012; Ouammi et al., 2012), biomass plants (Ramachandra et al., 2005; Shi et al., 2008; Zhang et al., 2011) and solar energy plants (Charabi and Gastili, 2010; Clifton and Boruff, 2010; Gastili et al., 2010; Charabi and Gastili, 2011; La Gennusa et al., 2011; Ramirez-Rosado et al., 2011) were particularly investigated. Later also the smart grid modelling was investigated by means of GIS (Tegou et al., 2012).

In this paper, GIS was used according to the second case. The paper is intended to give a contribution on how sites for ground-mounted PV plants should be selected, as a function of spatial information and GIS thematic maps that are already available at a general level and at a territorial scale, or that can be easily determined. This is done on a particular area of analysis which is one of the largest Regions in Ialy. The topics of interest and the original contributions can be identified in:

- the elaboration of a decision-support tool that takes into account both quantitative and qualitative criteria;
- the use of GIS thematic maps that are available at regional level (no direct surveys are requested);
- the estimation of the weights of the criteria for the objective function, in particular for the quantitative indicators by means of an ANN (see paragraph 3.4);
- the extent of the study area, which is more than 25,000 km^2, and the details of investigation of the various criteria adopted (for example the cell size of the digital terrain model was 100 m).

Given the extent of the study area (25,000 km^2) landscape integration criteria based on visual intrusion or visual exposure were not considered in this study, because this assessment has to be done for extremely smaller study areas. Landscape integration criteria are for example treated in other publications where the study areas are small.

2 The identification of the areas suitable to large ground-mounted photovoltaic

Despite the diversity of the authorization procedures that should be followed for the realization of ground-mounted photovoltaic plants, that vary depending on the characteristics of the plant and its insertion, the technical documents that are required to express a judgment about the correct location and that are required in different authorization procedures, can be summarized into four different types:

a) documents that demonstrate the exclusion from zones under all the applicable planning instruments at all levels and scopes;

b) documents regarding the type of crop and land use capability (agronomy report);

c) documents regarding the geological, geomorphological, hydrogeological and seismic surveying of the site (geological report);

d) documents regarding the impact on the landscape of the plant (landscape report).

The evaluation of the site carrying capacity of PV plants, and of any necessary environmental mitigation measure, is made within the applicable authorization procedure (single authorization, verification or evaluation of environmental impact environmental impact) by the competent local Authority, that in the Piedmont region is the Province. However, with the aim of providing criteria for the assessment of the market of sites for PV plants, and before the issuing of the national guidelines, the Piedmont Region introduced into the last Energy Planning Report (DGR 30-12221 of

09.28.2009, Regione Piemonte, 2009) a set of criteria (called ERA) aimed at guiding and facilitating the identification of the sites that are most suitable for the location of ground-mounted photovoltaic plants. Areas of exclusion (E), repulsion (R), neutrality and attraction (A) are identified. In repulsion areas is not a priori precluded the installation of photovoltaic plants, but it is likely that the site conditions require environmental mitigation and compensation measures related to the degree of repulsion expressed by the R criterion. Those ERA criteria were later adopted as a formal regional rule (December 14, 2010, No 3-1183, Regione Piemonte, 2010) and become normative.

With the aim of this work, which is to assess the ground-mounted PV plants carrying capability of a given territory, and based on technical and scientific literature on this subject (Dominguez-Bravo et al., 2007; Aran Carrion et al., 2008a; Aran Carrion et al., 2008b), only the criteria that are contained in the type a), b) and c) documents were considered. As said before, the landscape integration, as for example reported in (Torres Sibille et al., 2009; Rodrigues et al., 2010; Chiabrando et al., 2011), was not considered in this study. In addition to the reasons previously reported in paragraph 1, it should be noted that the landscape assessment of a new installation of a PV plant is made not only by means of GIS spatial analyses, but also by means of other software tools and techniques (e.g. picture analysis).

In addition to these, more criteria to evaluate the technical feasibility and the quantity of electricity produced by the plant were considered in this work, as reported in paragraph 3.

3 Materials and methods

3.1 The study area

The study area is the Piedmont Region that extends for 25,388 km^2 in the North-

West of Italy (Figure 1). It is an area mainly mountainous (43% of the territory) with hills (30%) and plains (27%). It is surrounded by the Alps and Apennines to north, west and south, and by the Po plain to est. The territory is characterized by both flat land and mountains, up to 4500 m above the sea level and by various types of landscape and land use. It is therefore particularly interesting for the application of a procedure of selection of a site carrying capability, because various land characteristics are found.

Figure 1. Piedmont Region in Italy.

3.2 Method

In the following section, the criteria for the land carrying capacity of a ground-mounted PV plant are defined. Each criterion is assumed to be represented by a digital map, intended as a regular sampling over the territory of its value. It is believed that, for this function, the most suitable digital map format is the raster one. The pixel of the raster is hereinafter mentioned as land unit (LU).

The criteria that were taken into account can be divided into two types:

- Exclusion/Inclusion criteria: they are formalized by means of Boolean operators applied to each pixel of the raster representation, *B* (x,y). An opportunely designed query checks for the satisfaction, or not, of the considered condition assigning value 0 to the excluded LU (areas where PV plants cannot be placed) and value 1 to the included ones (areas where PV plants are admitted). For example, all the criteria for the compatibility with the planning instruments are exclusion/inclusion criteria.

- Quantification criteria: they are formalized by means of spatially distributed indices, C_i (x,y), varying in the interval [0,1], that define the degree of PV carrying capacity of each pixel according to the considered criterion.

In order to map a synthetic index of the ground-mounted PV plants land carrying capability, the criteria described above were combined into an appropriate objective function that reads

$$f = \left(\sum_{i=1}^{n} \alpha_i \cdot C_i \right) \cdot \prod_{j=1}^{m} B_j \qquad (1)$$

where n is the number of quantification criteria $C(x,y)$, m is the number of exclusion/inclusion criteria $B(x,y)$ and α_i are weights assigned to the quantification criteria. The determination of the weights of the objective function is carried out in paragraph 3.4.

3.2.1 Exclusion/Inclusion criteria

The following criteria of Exclusion/Inclusion were identified and represented by digital maps:

- *Restricted Areas*. All built-up areas, airports, lakes, rivers, mountain areas (defined as the art. 142 of D.Lgs.42/04) and the compliance zones A, B and C

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of the hydrogeological planning are excluded (A, B and C zones are areas where a river can overflow following the national Italian legislation).

- *Protected Areas.* All national and regional parks areas, SPA, SCI, SIR zones, areas subject to constraints of law 1497/1939, areas called "Galassini" (national laws on the cultural environment) and river and lake sides compliance zones are excluded.
- *Land Use Capacity*. For the evaluation of the productive potential of the soil the usual classification into 9 classes of land use capacity was adopted. The classification is done according to the land use capacity system elaborated since 1961 by the Soil Conservation Service of the Department of Agriculture of the United States and adopted by the FAO in 1974 . The definition considers eight classes, of which the first four are suitable for agriculture, pastures and woods. From the fifth to the seventh classes, the capacity is limited to woods and/or pastures. In the eighth class any human intervention is possible. For the purpose of this study, it is considered that the excluding categories are the first, second and third.

$$B_{lu}(x,y)=\begin{cases}1 \ \ if \ \ lu(x,y)=4^{\wedge},5^{\wedge},\ldots 9^{\wedge}\\0 \ \ if \ \ lu(x,y)=1^{\wedge},2^{\wedge},3^{\wedge}\end{cases}$$

- *LU Slope:*. the terrain slope *s(x,y)* influences both the optimality conditions for orientation and inclination of the PV modules and the technical feasibility of the plant. From a survey on various manufacturer and professionals, it is believed that the maximum slope that makes the plant installation technically feasible is 15%. Above this slope, it is necessary that the construction works are done on dry land and in a period of time when rainfall is not expected, that together with the plant, suitable works for control the waters, to avoid phenomena of subsidence due to leaching, are done. Obviously, in this case an higher cost for the maintenance should be estimated.This criterion can be therefore formalized as

$$B_s(x,y) = \begin{cases} 1 & if \quad s(x,y) \le 15\% \\ 0 & if \quad s(x,y) > 15\% \end{cases}$$

- *LU geographical orientation (azimuth):* the effect of the land surface orientation $\alpha(x,y)$ is combined with the slope $s(x,y)$ and affects the technical feasibility of the plant; for low slopes the orientation is irrelevant because it can be easily compensated by the support structures of the PV panels; instead, over steeper slopes, the orientation of the ground is a constraint imposing that only in south-oriented terrains the plant can be built. On the basis of previous experiences (Dominguez Bravo et al., 2007), the following conditions were fixed

$$B_\alpha(x,y) = \begin{cases} 1 & if \quad s(x,y) \le 3\%\,,\ \forall\ \alpha(x,y) \\ 1 & if \quad 3\% < s(x,y) \le 15\%\,, 135 < \alpha(x,y) < 225 \\ 0 & for\ all\ other\ cases \end{cases}$$

where the azimuth α is expressed in degrees from north in a clockwise direction.

Both slope and orientation criteria affect the specific peak power (peak power per unit area of the ground) that can be installed.

For the definition of B_α and B_s, the LU geographical orientation takes into account also LU slope criterion; only the B_α criterion will therefore be taken into account hereinafter.

3.2.2 Quantification criteria

- *Total annual solar radiation (direct, diffuse and back-reflected from the ground) on horizontal plane*. This quantity was selected in order to provide a quantitative evaluation of the electricity production of a PV plant. It was mapped using the specific procedures available inside the ESRI ArcMap 9.3 GIS commercial software, customizing the input data in order to obtain values consistent with the ones of the PV-GIS database (Súri et al., 2005) for the selected location. In particular, the diffuse/total radiation parameter was derived from the PV-GIS database for each of the four subset of DTM. The morphological features of the areas were determined on the basis of the available DTM (see paragraph 3.3). The DTM was partitioned into 4 different smaller DTM in order to allow a more refined calculation of the Sun position, that is based on the mean latitude. As the evaluation of the real total annual solar radiation on a south-oriented surface, tilted at optimal inclination thanks to the solar panels structures, would be complex and suffering from some uncertainties on the input data (e.g. the ratio between direct irradiance and total irradiance), the amount of collected solar radiation at the LU, *E(x,y)*, calculated by the sofware according to the input DTM, was adopted in this work. The quantification criterion for this parameter, assigned to the baricenter of the cell (criterion of maximum) is expressed as

$$C_E(x,y) = \frac{\overline{C}_E(x,y) - \overline{C}_{E\,\min}}{\overline{C}_{E\,\max} - \overline{C}_{E\,\min}} \quad \text{where} \quad \overline{C}_E(x,y) = \frac{E(x,y) - \mu_E}{\sigma_E}$$

The value of $\overline{C}_{E\max}$ was assumed equal to 2.461, and the value of $\overline{C}_{E\min}$ equal to 2.268, while the values of the mean (μ_E) and standard deviation (σ_E) resulting from the solar radiation map produced were respectively equal to 1584 kWh (mean value) and 185 kWh (standard deviation value). The two in cascade normalizations are intended to constrain the index in the range [0,1], as needed to homogenize all of the criteria, and at the same time to avoid the negative effect of the outliers of the solar radiation map.

- *Annual average air temperature*. This parameter takes into account the effect that the cooling of the module has on the improvement of the energy efficiency (criterion of minimum)

$$C_t(x,y) = 1 - \frac{t(x,y) - t_{\min}}{t_{\max} - t_{\min}}$$

where the minimum temperature *t* equals ï 3 °C and the maximum temperature equals 14.4 °C, and *t(x,y)* is the annual average air temperature (see paragraph 3.3)

Annual average rainfall cumulative height. With the intent of allocating to the PV electricity production portions of territory that do not conflict with agricultural production, also in low land use capability areas, an indicator on the aridity of the soil (criterion of minimum) was also included

$$C_h(x,y) = \frac{h_{min}}{h(x,y)}$$

where the minimum height *h* is equal to 461 mm and *h(x,y)* is the annual average rainfall cumulative height (see paragraph 3.3).

3.3 Data sources

The digital geographical data adopted for this study come from different sources, with different scales and reference systems. Thus a first important step was their homogenization, especially concerning the reference system. The one selected for this work was the UTM 32N WGS84.

The *Restricted Areas*, *Protected Areas* and *Land Use Capacity* criteria,were generated by converting to the raster format the original vector data obtained from the Environmental Geographical Information System Database of the Piedmont Region (www.sistemapiemonte.it /sitad).

The rasterization cell size was posed equal to 100 m; this size was considered reasonable with respect to both the nominal scale of the original vector data (declared equal to 1:100.000) and the specific application of this work.

The slope, orientation and solar radiation criteria were calculated from a raster DTM corresponding to a down-sampled release (100 m resolution) of the DTM of the Piedmont Region whose original cell size was 50 m.

The *Annual average air temperature* and the *Annual rainfall cumulative height* criteria were provided in raster format, with a cell size of 250 m, by the Hydraulics research group of the Faculty of Agriculture, University of Turin. The meteorological data that were used to derive the above mentioned maps refer to a period of 17 years, from 1991 to 2007, and consist of daily series of rainfall and temperature provided by a network of 400 weather stations spread around the Piemonte region. For the spatial interpolation of precipitation, the spline method was adopted, while for the temperature map a multivariate linear regression method (Borgogno Mondino et al., 2009) was used.

3.4 Estimation of weights for the quantification criteria

It is well known that one of the main issues in decision making tools which aggregate many judgments in a final indicator is the selection of the weights to be assigned to each sub-parameter. In this work, weights α of Eq. (1) that are assigned to each quantitative indicator C were determined using an MLP (Multi Layer Perceptron) Artificial Neural Network (ANN), as shown, for example, in (Lee et al., 2004; Ermini et al., 2005; Melchiorre et al., 2008). In order to train the ANN, 20 sites of PV plants in the Piedmont Region were selected by photointerpretation; the relative C_E, C_t and C_h parameters were derived from the correspondent raster maps by the GIS tool and were used as positive references. Not necessarily these parameters may assume high values, but they were considered as representative of good locations. Furthermore, 20 sites representative of the worst conditions were selected minimizing the parameters C_E, C_t and C_h by a Boolean query on the digital maps.

The C_E, C_t and C_h parameters were selected as inputs of the ANN while an arbitrary value varying in the range [0,1] was assigned to each element of the training set as expected output, according the following criteria. Values around 1 were assigned to the positive observations, while values around 0 were assigned to the negative ones. The variability around 1 (Figure 2) was determined for each position by subtracting to 1 the Euclidean distance in the parameter space between the i-th input and the optimal reference defined by the three maximum C_E, C_t and C_h (1,1,1); the variability around 0 was determined for each position by adding to 0 the Euclidean distance in the parameter space between the i-th input and the worst reference defined by the three minimum C_E, C_t and C_h (0,0,0). It is therefore:

$$1-\sqrt{(C_{E,i}-1)^2+(C_{h,i}-1)^2+(C_{t,i}-1)^2} \quad \text{for each positive observation}$$

$$0+\sqrt{(C_{E,i})^2+(C_{h,i})^2+(C_{t,i})^2} \quad \text{for each negative observation}$$

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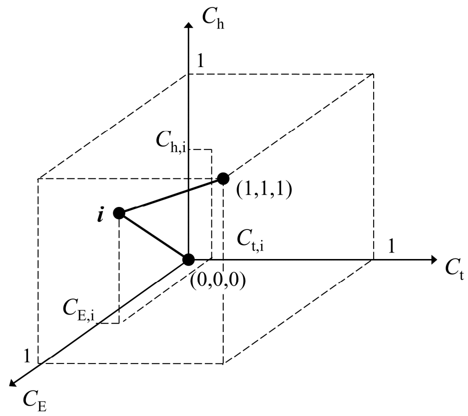

Figure 2. The parameter space and the Euclidean distances of each input i

The ANN architecture was determined by an iterative self-developed Matlab© routine (Lessio et al., 2011) able to stop the trials when a selected training score threshold (Root Mean Square Error of the residuals) is satisfied. The training was performed according to the Back Propagation algorithm using the Levenberg-Marquardt (1944) approach testing 1200 epochs for each trial. The solution that was found is represented in Figure 3 showing a single hidden layer of 4 nodes. The adopted transfer functions are the *symmetric sigmoid* for the hidden layer and the *pure linear* for the output layer. The RMSE threshold was set to 0.001.

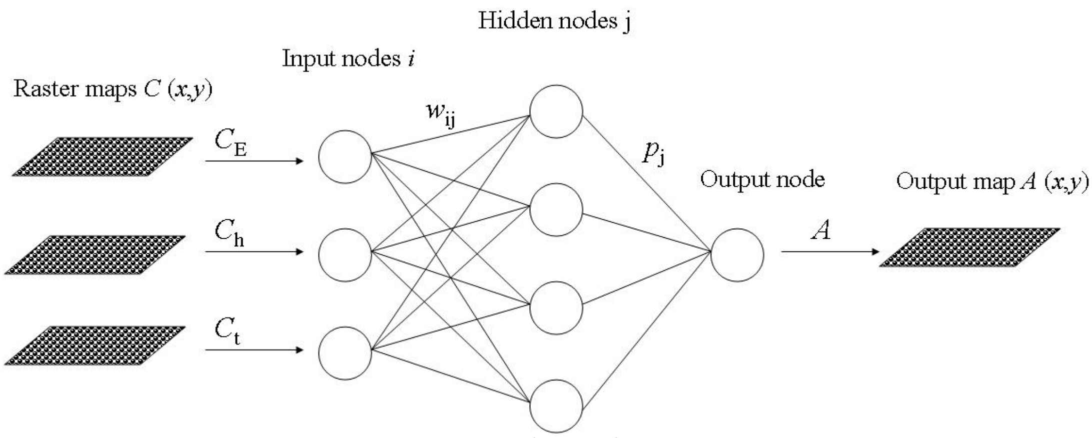

Figure 3. Architecture of the artificial neural network

As a result of the training, the weights for each criterion at each hidden node w_{ij} are reported in Table 1 and the relative weights of each hidden node in the output layer p_j are reported in Table 2. From the two quantities, the weight α of each sub-parameter

C can be derived as

$$\alpha_i = \sum_{j=1}^{4} w_{i,j} \cdot \frac{p_j}{100} \qquad \forall\ i = \{1,2,3\}$$

where j is the number of hidden nodes. The weights are equal to 62.47 % for C_E (solar radiation parameter), 6.96 % for C_t (temperature parameter) and 30.57 % for C_h (rain parameter).

Table 1. Percentage weights for the hidden layer of the trained ANN

Hidden Layer	Weight C_E (*i=1*) (% at the node)	Weight C_t (*i=2*) (% at the node)	Weight C_h (*i=3*) (% at the node)	Total
Node j=1	88.71	3.61	7.68	100
Node j=2	43.74	12.90	43.36	100
Node j=3	41.85	5.19	52.96	100
Node j=4	60.51	8.55	30.94	100

Table 2. Percentage weights for the output layer of the trained ANN

Output layer	Node 1	Node 1	Node3	Node 4	Total
Weight (% at the node)	30.33	14.85	22.00	32.82	100

The authors also used the trained ANN as a feed-forward structure to produce the *A*(*x*,*y*) output map, instead of calculating the weighted sum of Eq. (1) by means of the GIS raster calculator. The objective function of Eq. (1) becomes therefore

$$f = A(x,y) \cdot \prod_{j=1}^{m} B_j(x,y) \qquad (2)$$

4 Results and discussion

In figures 4 to 6 some of the Inclusion/Exclusion criteria are mapped where the green pixels are representative of the positive observations (value equal to 1) and viceversa for the brown pixels. It can be noted that Restricted areas (Fig. 4),

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Protected areas (Fig. 5) and Land use capacity (Fig. 6) criteria are not particularly stringent (69%, 64% and 64% of the surface has a value of 1). However the land use capacity criterion tends to exclude all the flat areas that are placed on the center of the region (Padana Plain), while most of the restricted and protected area falls in the mountain territory.

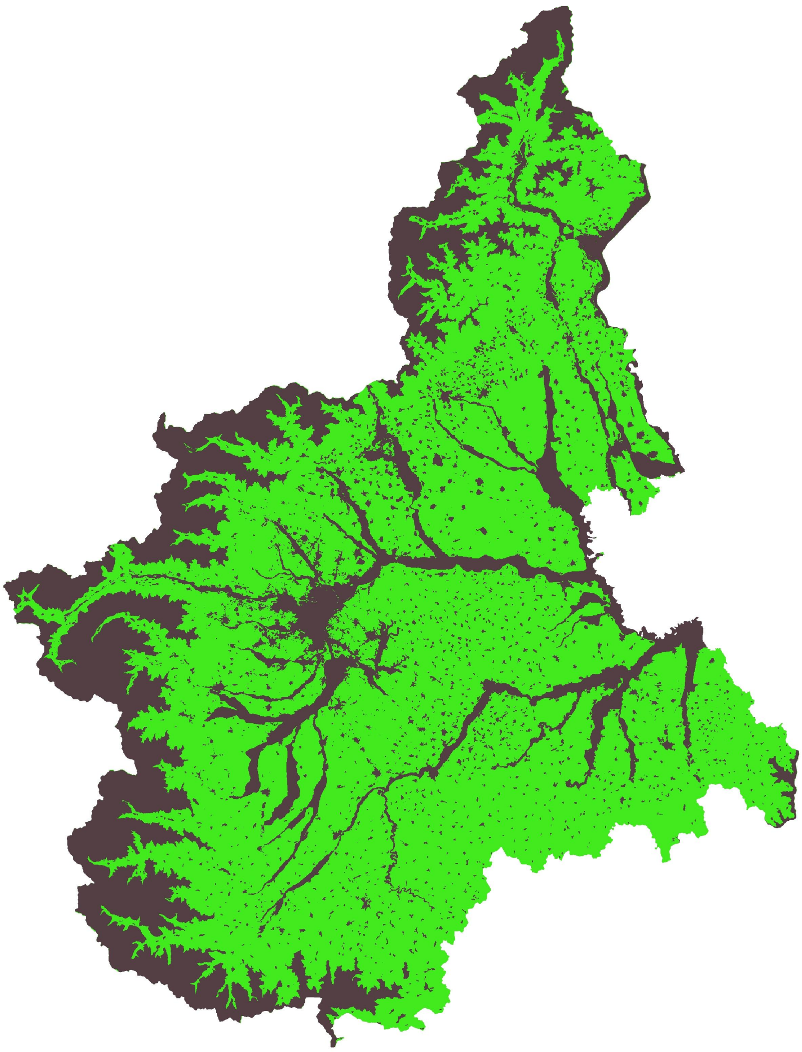

Figure 4. Map of the *Restricted Areas* exclusion criterion (value 1 is green*)*.

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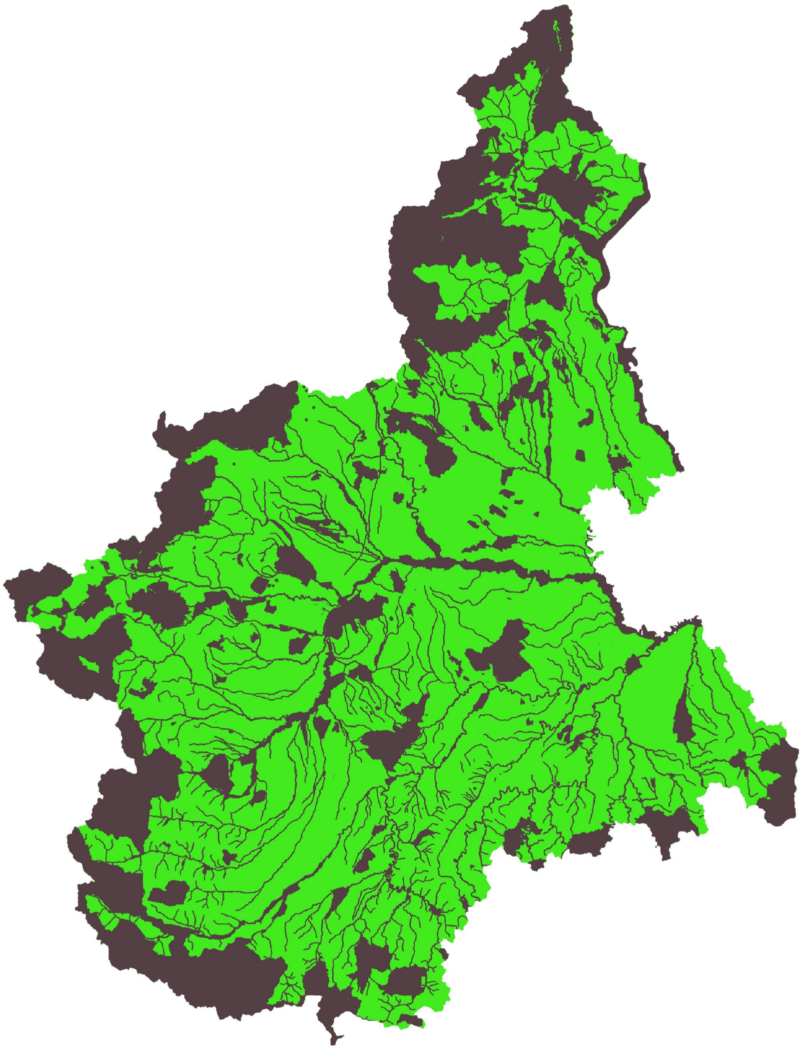

Figure 5. Map of the *Protected Areas* exclusion criterion (value 1 is green).

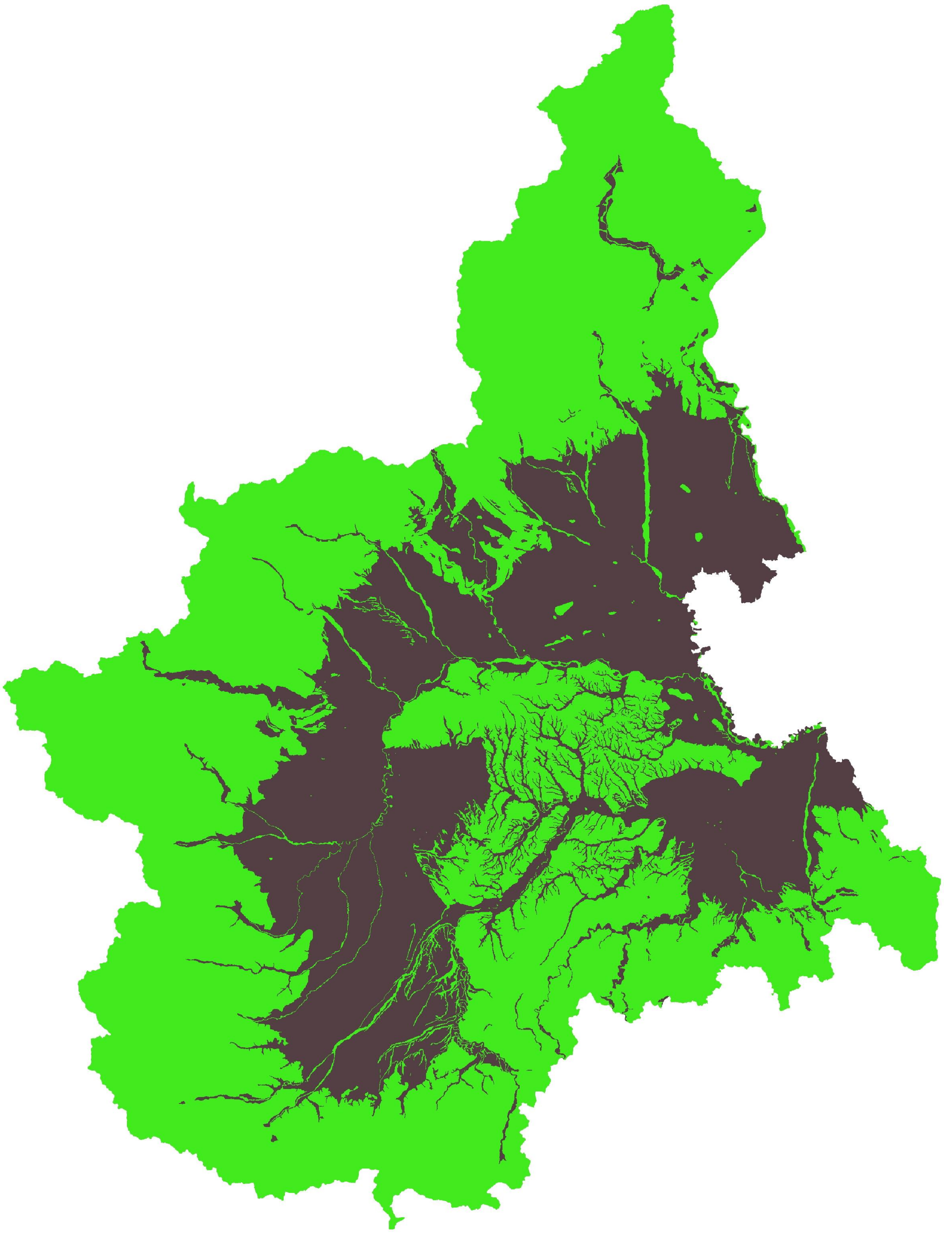

Figure 6. Map of the *Land use capacity* exclusion criterion (value 1 is green).

This is why when all the three criteria are taken into consideration together, only 29% of the surface is available: the corresponding map is reported in Figure 7 where the product of the Restricted areas, Protected areas and the Land use capacity criteria was made by means of a raster calculator. The consideration of those 3 criteria together is also of considerable interest because they are the normative ones established by the regional legislative requirements (Regione Piemonte, 2010)0. It results that only 29% of the regional territory can potentially be used for a PV plant development, and that the sites are placed mainly in the piedmont area, between mountains and flats, and in hillsides.

The map of the LU geographical orientation criterion is reported in Figure 8, where it can be noted that the vast majority of the available areas are the plains one that are located in the region centre. When the B_{α} and the B_{lu} criteria are multiplied (Figure 9) it can be seen that the available areas represent only 9.7% of the total area.

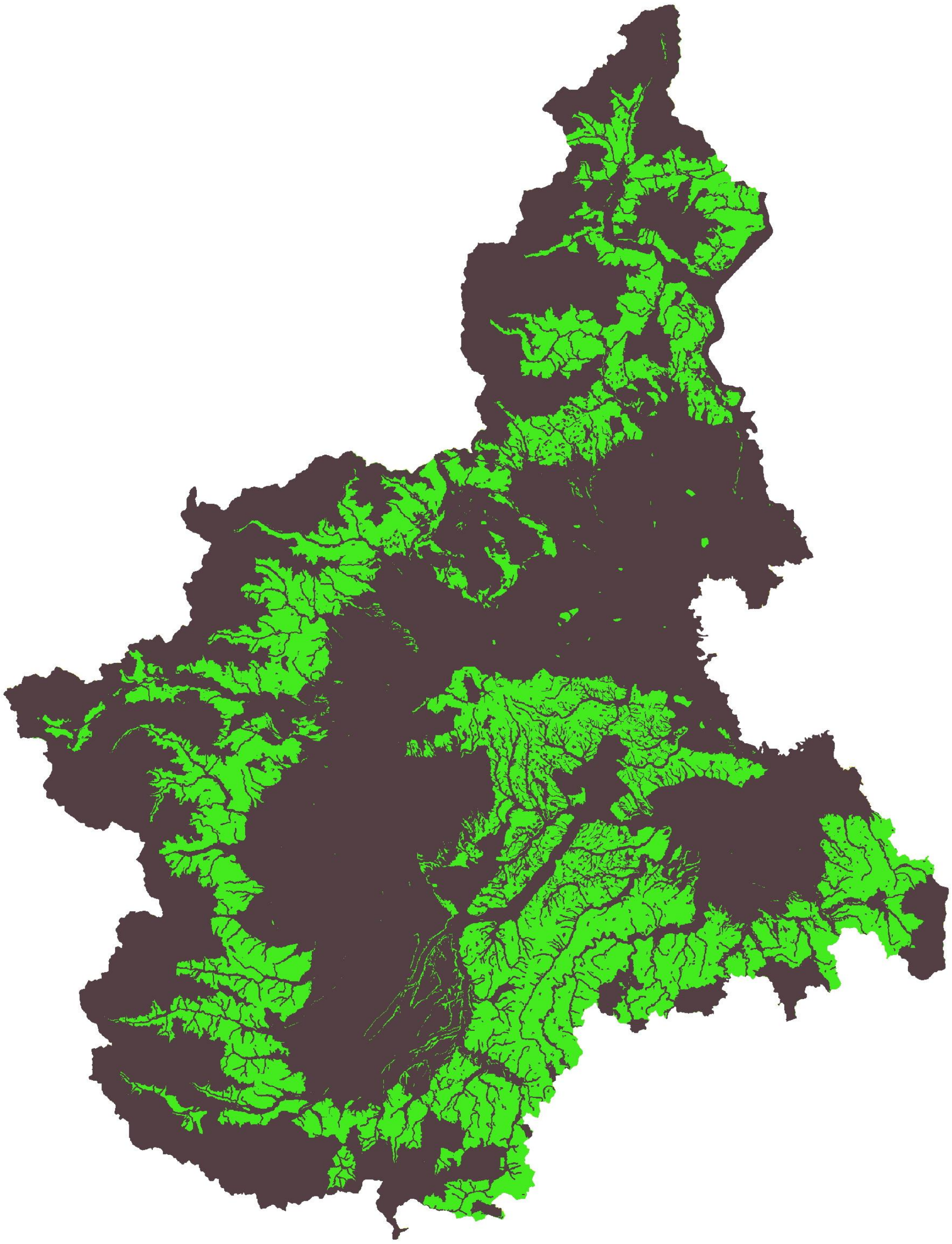

Figure 7. Map of the product of the 3 normative criteria (value 1 is green).

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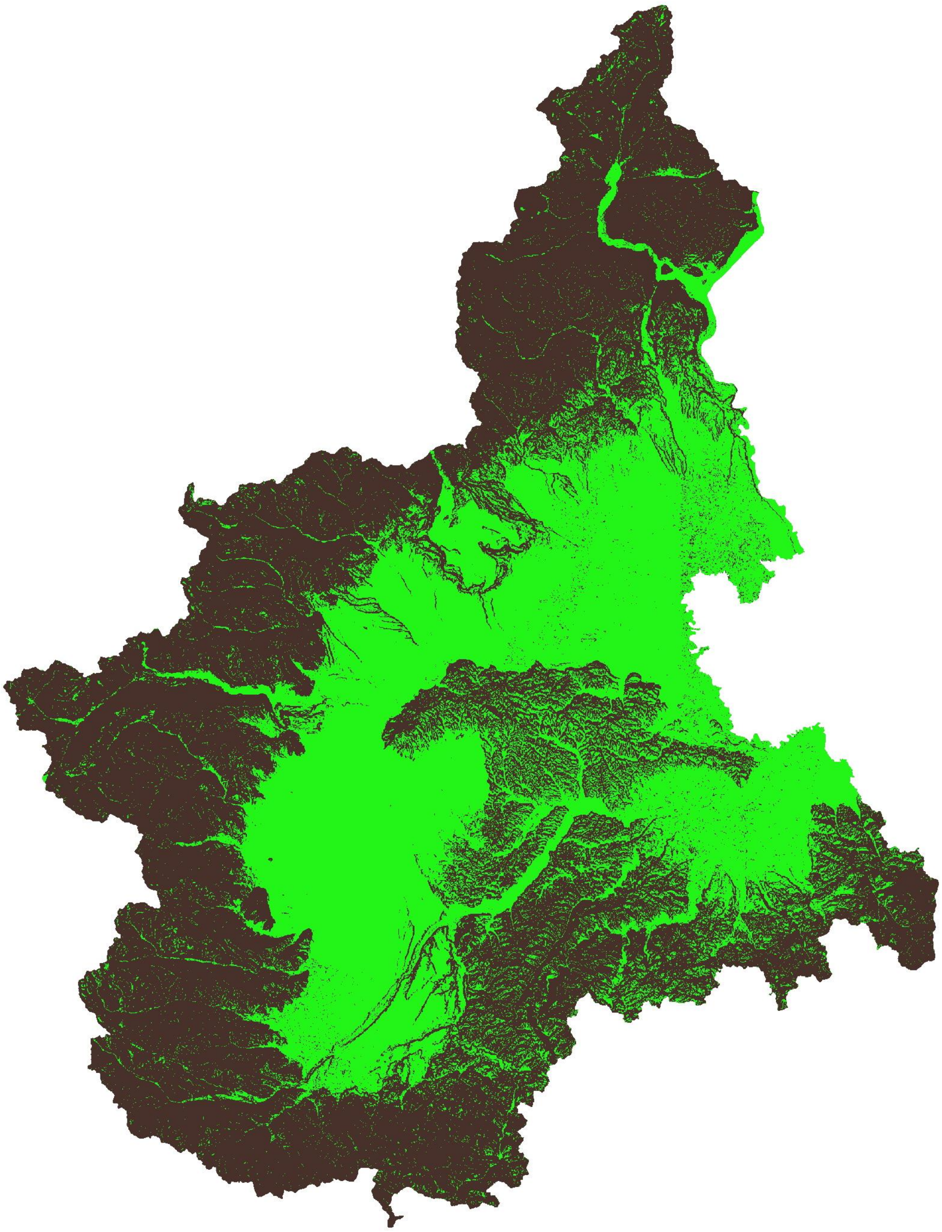

Figure 8. Map of the *LU geographical orientation* exclusion criterion (value 1 is green).

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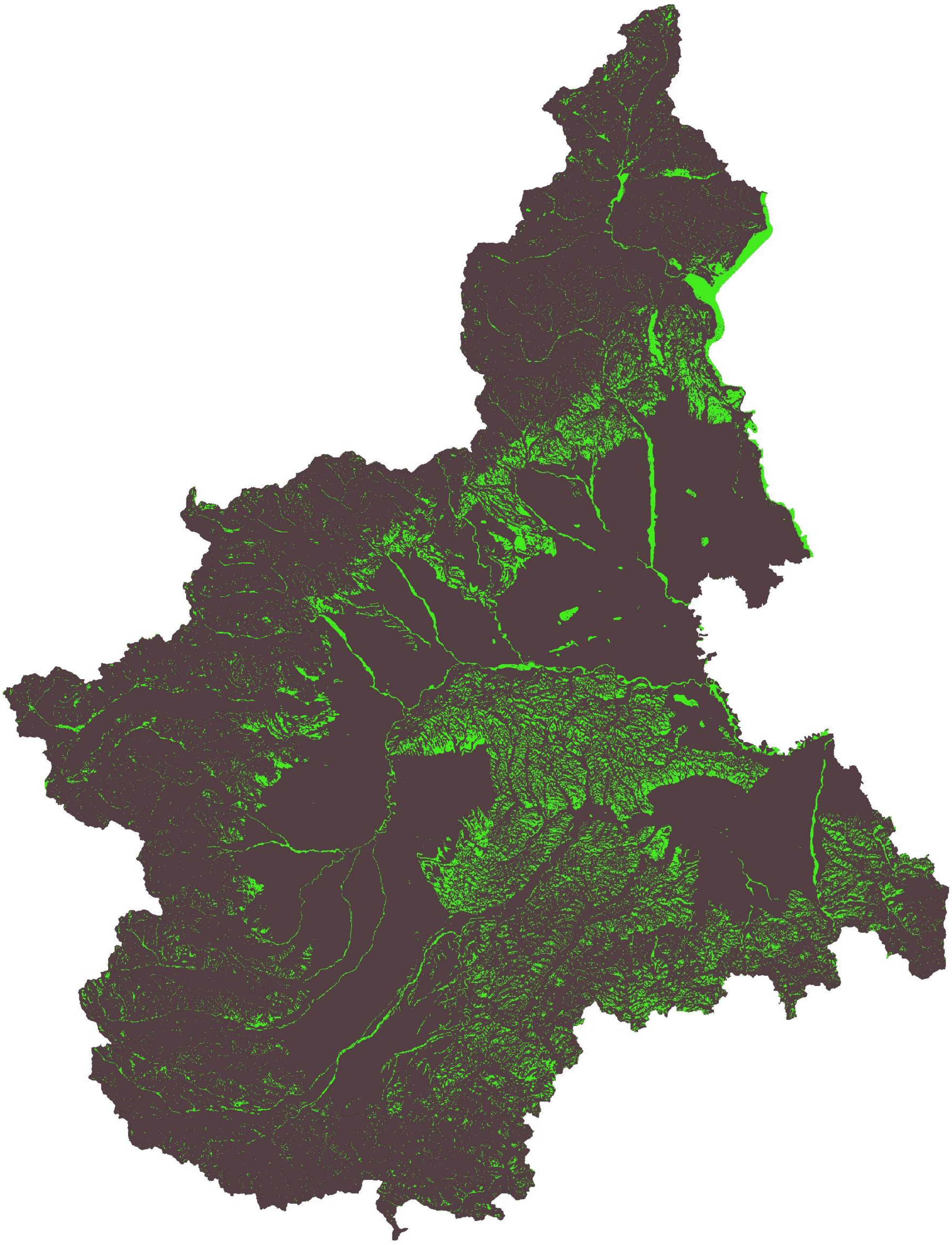

Figure 9. Map of the product of B_{lu} and B_{α} criteria (value 1 is green).

The application of all the Inclusion/Exclusion criteria (Figure 10) leads to a total available area which is only the 3.4% of the total area

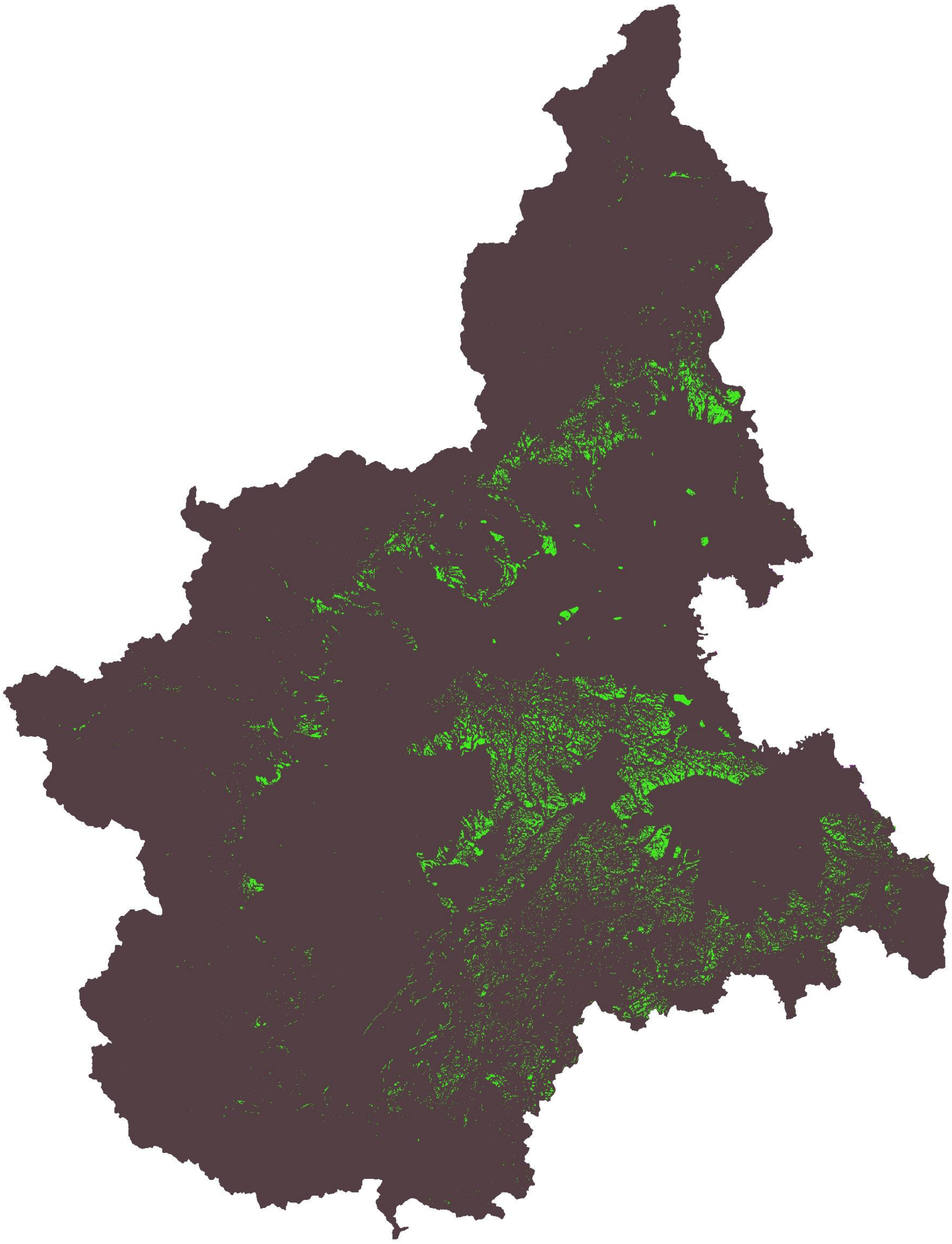

Figure 10. Map of the product of all the exclusion criteria (value 1 is green).

Values of the three quantitative indicators (solar radiation, temperature and rain height) were calculated for each land unit but, given the previous result, they are of interest for only the 3.4 % of the land units. The solar radiation map that was calculated following the specifications reported in 3.2.2 is plotted in Figure 11. Greater solar radiation values can be found not only for south oriented slopes, but also where the height above sea increases.

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Final values of the objective function at each LU were calculated by aggregating the criteria as reported in Eq. (2) by means of the Raster Calculator in ArcView 9.3. The result is shown in Figure 12. It is evident that there are very limited areas potentially available, and that they are concentrated in the Asti, Alessandria and Biella provinces. In total, 136 km^2 are available (objective function > 0); the histogram distribution of values of the objective function is shown in Figure 13 and is centered on the classes 0.85 to 0.95

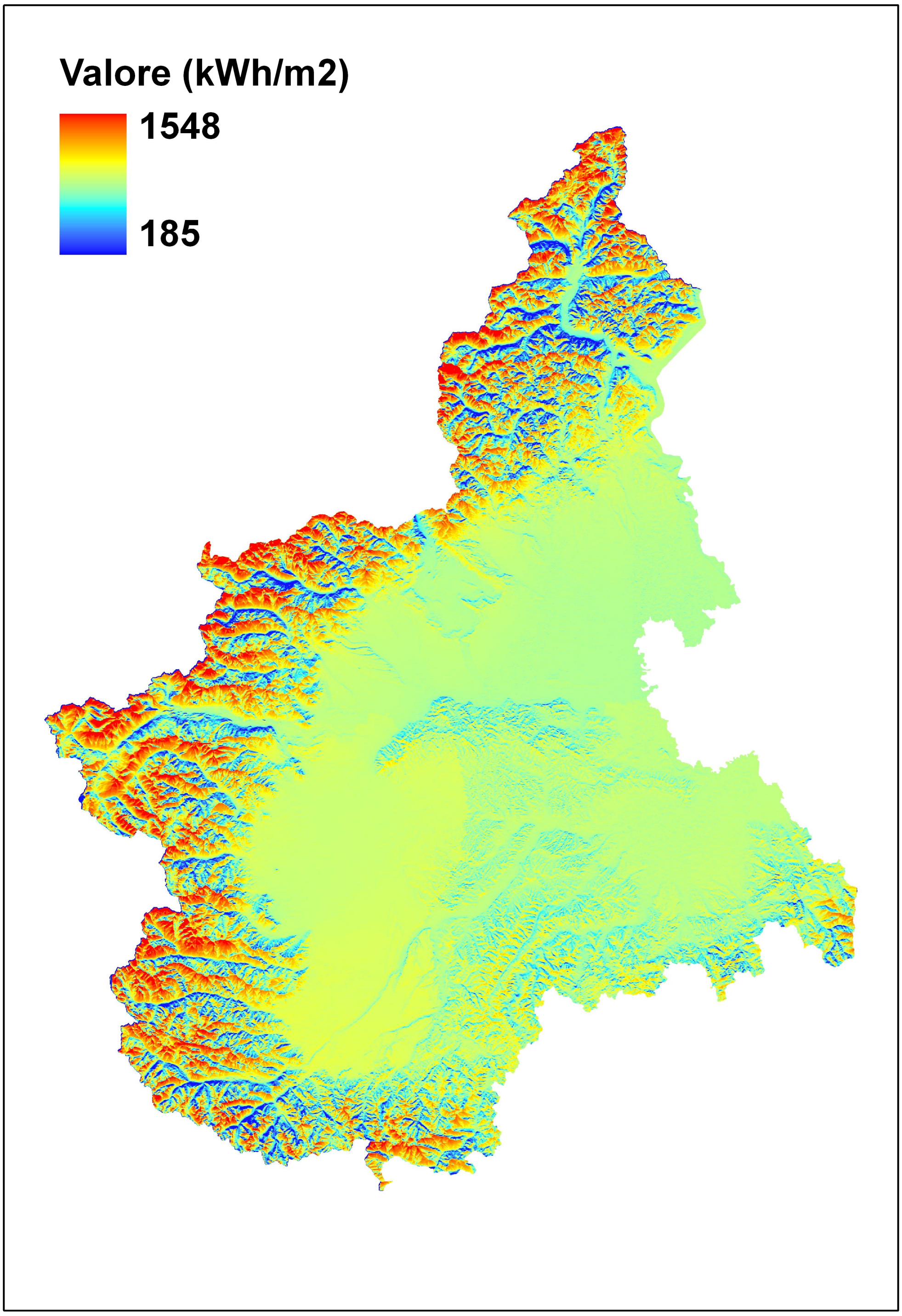

Figure 11. Map of the Total annual solar radiation.

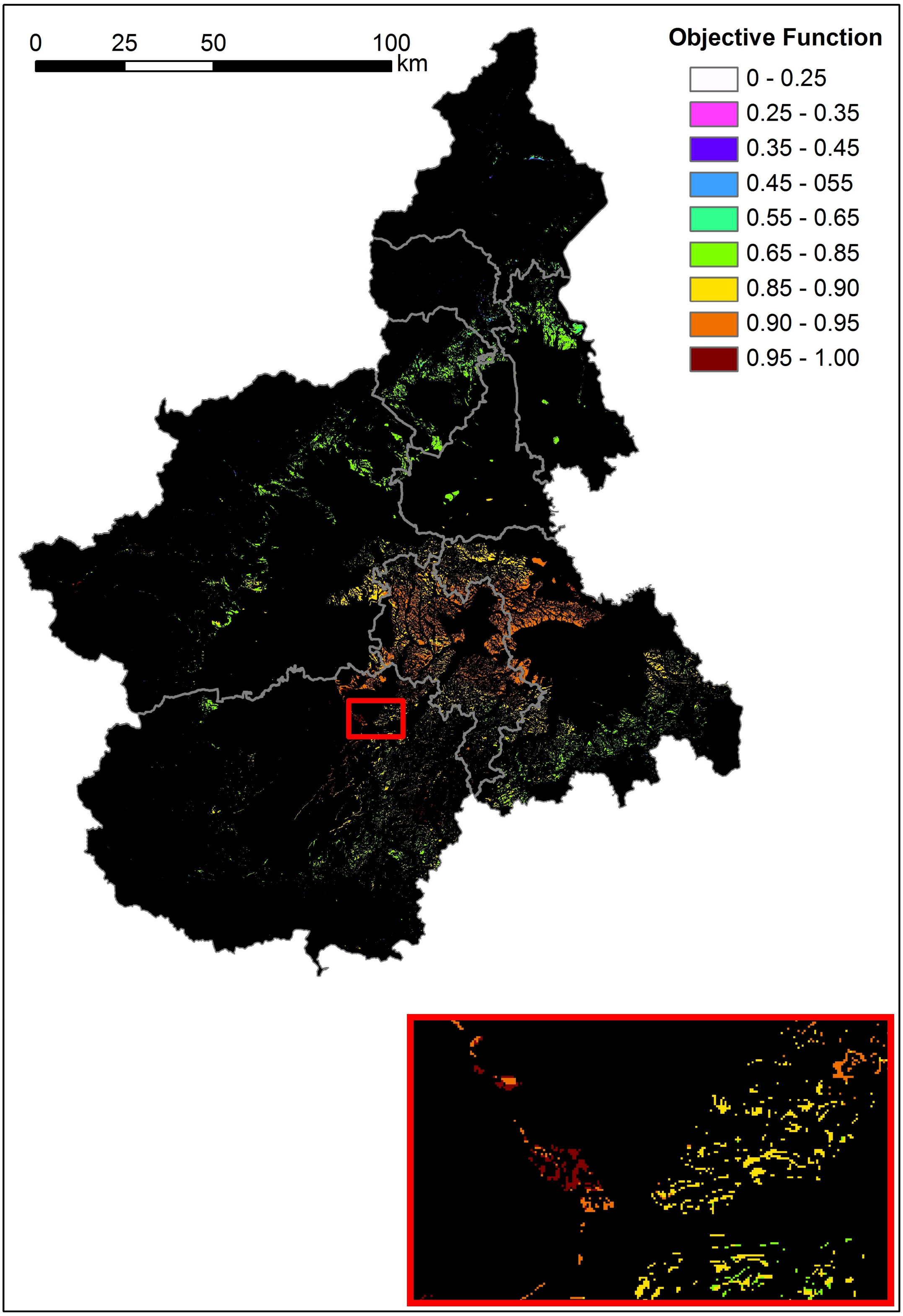

Figure 12. Objective function map.

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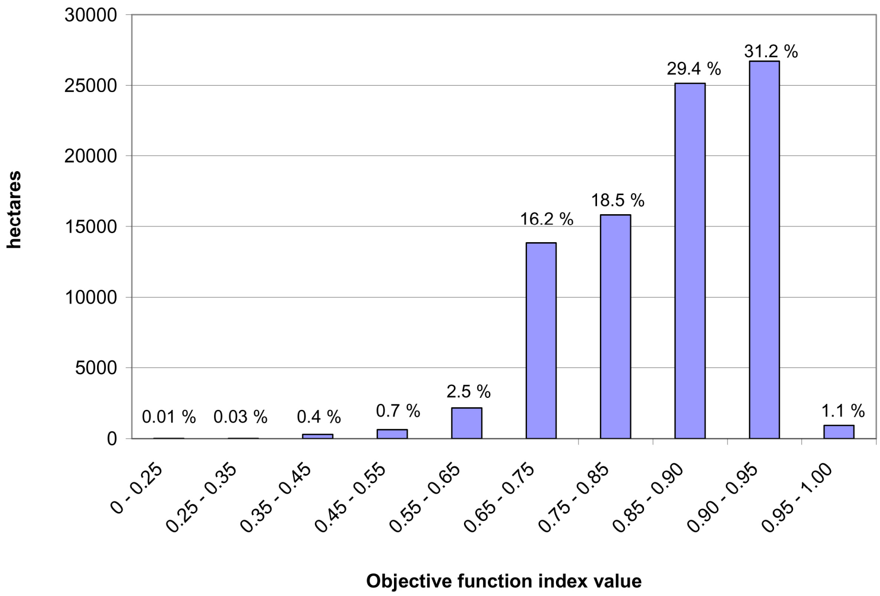

Figure 13. Histogram of the values of the objective function.

It can easily be noticed that the distribution of the suitable areas is mainly determined by the product of the criteria of exclusion/inclusion; on the contrary, the quantification criteria do not affect significantly the result: most of the values of the objective function falls in a narrow range varying between 0.65 and 0.95 (very rare are the cells whose value is lower than 0.55). This is due to the C_E criterion. As the exclusion/inclusion criteria are concerned, it is possible to make a selection between the *Restricted Areas*, *Protected Areas* and *Land Use Capacity* ï that are normative ones ï and the slope and orientation of the terrain ï that is a technological one. Inside the first group the *Restricted Areas* and *Protected Areas* (Figs. 4 and 5) show a behaviour in opposition with the *Land Use Capacity* (Fig. 6). The technological criteria instead are found to be much more stringent; in particular, the combination of the normative criteria and the technological criteria makes the available areas reduced in size and highly fragmented over the territory (as can be seen in Figure 10).

As an example of the results, some sites were selected in order to verify that the

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pixel information was consistent with the information on more detailed cartography. In the example that is reported in Figure 14 the raster objective function map of Figure 12 was superimposed to the Regional cartography of the site of Solonghello (province of Alessandria), where it can be noted that the pixel (LU) dimension is 100 m. Sometimes there are some discrepancies between the objective function and the cartography: for example, cells that have a value near 0.9 but are situated into villages are due to the fact that the built-up area (Restricted areas criterion of paragraph 3.2.1) does not cover farmsteads or small villages, but only large urban areas.

In any case, the use of the objective function information should always be done in association with other cartographic information, and following detailed verifications for each project development.

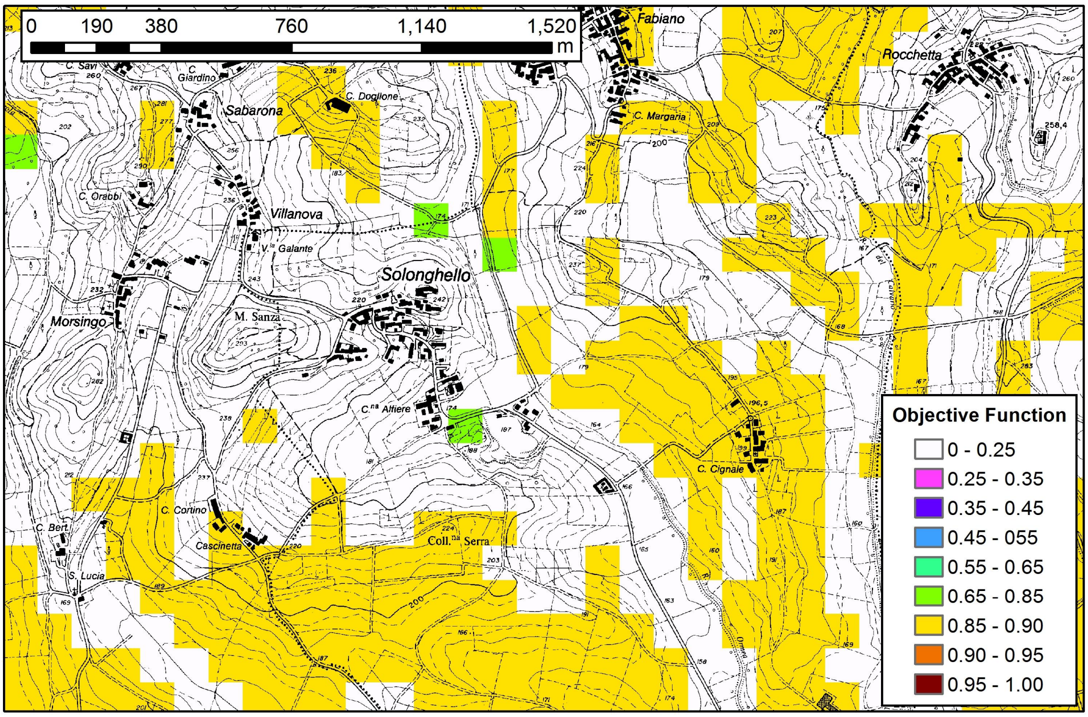

Figure 14. Example of the objective function for a given site

5 Conclusions

Given this picture, it is clear that there are no substantial quantitative differences between the available areas. The possibility of selecting an area is very limited by the various exclusion criteria that were considered in this study. The results are of great interest for planners and energy managers at regional level. For example, regional planners established the ERA criteria that were used in the paper (see paragraph 2), but not a computation of the available areas (or conversely of the excluded areas) was done.

Given a land occupancy ratio of a ground-mountedPV plant of 1,5 ha/MW_p, the 136 km^2 that were found as available areas for the installation give a potential of peak power of about 9000 MWp. Following the Italian atlas of PV plants [http://atlasole.gse.it/atlasole] Piedmont has 2023 installations with a peak power larger than 50 kW_p for a total of 580 MWp. The study presented here shows that, even with the most stringent requirements that were set by the regional government to limit the installations, a considerable amount of available areas still exists and may be used to cover a part (approx 30%) of the Piedmont electricity demand (2500 ktep).

As regards the development of the carrying capabilities evaluation procedures, further investigations may refine the criteria for inclusion/exclusion, in particular those derived from the DTM. For example, a significant aspect surely worth to be investigated is that of the precision in determining the height of the DTM. It is known in fact that uncertainty in the height for the DTM is normally (including the one of the Piedmont Region) of a few meters. This limit is not a important problem in areas highly uneven, but rather in flat areas where such precision may influence the calculation of derived quantities such as the orientation and the slope of the terrain. Therefore, a frenetic succession of slopes and orientations, whose existence is only virtual, is frequently found in plain areas. This phenomenon can be observed, for example, in Figure 8 for the orientation of the land unit, a criterion that strongly influences the final results.

Finally, not all the areas that were identified as suitable for a PV installation as a result of the proposed decision support tool may be actually exploited when the appropriate landscape studies will be made, but this is considered to be a second step of analysis that should be carried out only when other various factors (e.g. an investor, financial income, etc.) combine to make the installation possible.

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