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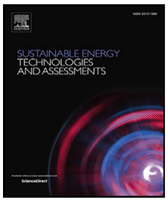

Highway PV capacity potential: A GIS-Driven approach for assessment and prioritization

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ABSTRACT

The increasing electricity demand, driven by electric mobility, has opened up opportunities to use highway areas for photovoltaic systems. Due to the vastness of this infrastructure, identifying suitable areas and estimating the production potential cannot be done manually. In response to this need, this paper presents a methodology for automatically assessing the photovoltaic potential of areas near highways using GIS data. The assessment considers different installation options, taking into account the morphology of the area and the costs of installation and maintenance. Tested on about 3000 km of Italian highways, the analysis shows that 85% of the available areas could be used, giving an estimated total capacity of 926 MWp and a production of 830 GWh per year.

Introduction

Renewable energy sources (RES) are essential for reducing greenhouse gas emissions and mitigating climate change [1,2]. Among RES, photovoltaic (PV) systems are particularly advantageous due to lower installation and maintenance costs compared to wind energy systems [3]. Moreover, the presence of PV systems in distribution networks near electrical loads can reduce energy losses and improve voltage stability [4,5].

The importance of renewable energy, especially in highways, is growing as traffic control systems digitize and the demand for electric vehicle charging stations increases [6]. Specific points on highways, such as interchanges and tunnels, require substantial energy for lighting, ventilation, and signaling, making them particularly appropriate for PV system installation. However, profitability assessments for PV installations must consider several factors like solar irradiance, orientation, and possible shading caused by natural or anthropic elements. The choice of the appropriate PV technology and its implementation form is also crucial.

In assessments involving areas that are particularly large and structurally and geographically varied, like the highway network, it becomes essential to be able to automate all these preliminary evaluations that would otherwise require high time and resources.

Some studies, such as [7], examine the integration of PV modules into noise barriers. While this work focuses on a particular case study and a specific installation method, it highlights the considerable potential offered by exploiting areas already occupied by other existing structures. In contrast, [8] conducts an economic analysis of all areas potentially impacted by photovoltaic installations. The study encompasses a range of technologies and proposes corrective parameters to estimate potential capacity for each. However, these parameters do not match the characteristics of the installation sites under consideration, and the paper does not propose a specific methodology for identifying these areas.

In [9] the authors analyze installations directly integrated into the pavements, the so-called *PV road*, proposing a precise methodology to assess the production potential. This methodology relies on digital surface models (DSMs) obtained through the light detecting and ranging (LiDAR) technique. However, the work itself points out that making such models presents relevant difficulties and consequently their availability is often limited. Differently, [10] combines information derived from toll station layouts to estimate the width and length of highway sections with digital elevation models. However, also in this case the estimation does not consider any particular technology or installation mode and only provides an estimation of solar energy potential.

Recent research has focused on geographic information systems (GIS) as a tool for identifying suitable areas for PV installation. GIS data can provide crucial information on topography, shading, and land

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use, which can be integrated with solar radiation data, such as those available in [11], for more accurate assessments.

Various methodologies using GIS have been proposed for different contexts. An example is found in [12] in which optimal locations for green hydrogen production are identified by coupling electrolyzers with PV systems. However, these studies often miss a correlation between the identified site and specific PV technologies and installation methods. In [13,14], georeferenced data on land conformation and infrastructure proximity are combined to assess possible RES installation limitations and evaluate their economic profitability. In [14], installation sites are not identified through automatic procedures but are searched directly among those at the disposal of the power utility. The works [15,16] couple GIS data with power flow analysis to identify areas for PV installation that will not conflict with production activities or natural reserves. In these cases, the data is often provided by local authorities and the size of installations is not derived from the assessment of the available areas, but different sizes of installations already predetermined are considered. In [17], GIS data are combined with fuzzy logic to prioritize locations for maximizing energy production from RES while considering energy policies.

Notably, in [18], GIS data are used to derive decision parameters prioritized through multi-criteria selection methodologies and the size of the plants is estimated by automatic methods. The results highlight how areas adjacent to highways are particularly suitable for PV installations even if the assessment does not consider any specific installation technology. The work [19] uses GIS data made available by local authorities mapping to derive irradiance and shading but only considers slop-side installations. The space is divided into regular grids, and the different feasible points are clustered using a binary approach. The method is applied to a grid portion of a limited extent equal to 69 km.

Building on the discussed approaches, this paper develops a completely automated methodology for assessing the PV capacity of highway infrastructure. This method correlates environmental and spatial GIS data with highway-specific characteristics. This infrastructure is characterized by a high degree of fragmentation, with stretches where one dimension is dominant over the other, and usually, the width of the areas is limited to a few meters. The characteristics of the territory can vary considerably, which in turn affects the most profitable applicable PV technology. Additionally, the proximity of these areas to private property or public lands necessitates integrating cadastral topography for accurate identification.

All this information is analyzed, manipulated, and used for the identification of areas that can be affected by PV installations. The different areas are clustered and associated with the most suitable PV module technology and installation. Lastly, the most promising plants are selected through a ranking method based on specific prioritization rules.

Finally, the entire process provides an indication of the most significant installation interventions, as well as a very accurate estimate of the potential production capacity over the entire highway network. The method is based on GIS data normally available to infrastructure managers and its application is therefore generalizable. To demonstrate its effectiveness, the method is applied to the portion of the Italian highway network managed by the company Autostrade per l'Italia (ASPI).

Proposed methodology

A direct overview of the structure of the proposed methodology is provided through Fig. 1. The yellow section represents the inputs to the procedure, all of which are GIS data in the form of lines, points, or raster maps. Most of these data are provided by the highway manager's GIS. This system is based on the Google Earth platform and implements some specific layers related to the highway infrastructure. However, for the sake of generality, the implemented methodology uses only georeferenced points or lines and does not make use of metadata. Therefore, what is described in this work can be implemented using any GIS. The corresponding code was developed in Python without using any additional software.

The other colors in Fig. 1 correspond to the three main phases of the procedure. In the first phase (in blue) all available data are organized and matched. In the second phase (in green) the database of candidate PV installations is generated. In the third phase (in purple) the prioritization parameters are calculated.

The details of the procedure are described in the remainder of this Section.

Data matching and organization

This part of the procedure aims to organize all data to enable easy further processing. The selected primary reference elements are the roadway centerlines, which represent the center of each highway lane (both right and left carriageways). These lines are sampled at variable intervals, with closer points on curves and wider spacing on straight sections. The sampling distance ranges from a few meters to one kilometer. An example of the roadway centerline can be found in the Supporting Information. All other available information will be linked to the roadway centerlines as described below.

Three different types of data are considered here, each requiring distinct processing: line data that overlap the roadway centerline, point data that also overlap the centerline, and lines that do not overlap the centerline. These data are associated with obstacles (such as tunnels, bridges, and overpasses) or with elements that define the boundaries of the available surfaces (such as guardrails and barriers). Some examples of these data are shown in Fig. 2.

The procedure for matching overlapping linear data is described in the corresponding blue box in Fig. 1. For each linear element (such as tunnels and bridges in the analyzed dataset), the endpoints are projected onto the roadway centerline. If the centerline does not already have points corresponding to the projections, they are added. The segment of the centerline between the projected endpoints is then marked with information about the presence of the obstacle.

To accurately match point data (i.e., overpasses), each point is projected onto the roadway centerline, and a buffer is created to account for object size, safety clearances, and shadowing. This buffer is used to generate new points along the centerline, allowing for accurate classification of all segments in the buffer.

The third group consists of data that does not overlap the roadway centerline. This group is critical as it includes barriers and guardrails that define the boundaries of the available surfaces. These data should also be associated with the centerline to enable an easy integration of this information with the classification.

To correctly associate the segments of guardrails and barriers with the roadway centerline, the procedure (described in the right side of the blue box of Fig. 1) projects the points that characterize the centerline onto the lines of the elements to be associated; thus, new sampling points can be added to these latter elements. This operation must also take into account curvature, when present, to avoid having unassociated parts or multiple associations. Fig. 3(a) shows an example of the procedure of the projection of the roadway centerline points on the barriers and on the guardrail. The points added during the association procedure are marked with a red cross.

Generation of candidate PV installations

Once all the information has been matched to the centerline segments, the second phase of processing focuses on creating a database of potential PV installation areas. This process involves three key steps. First, infeasible sites, such as tunnels, overpasses, and bridges, are excluded, leveraging the exclusion criteria already accurately linked to the roadway centerline in the previous step. Second, the available areas for potential installations are calculated based on the geometric

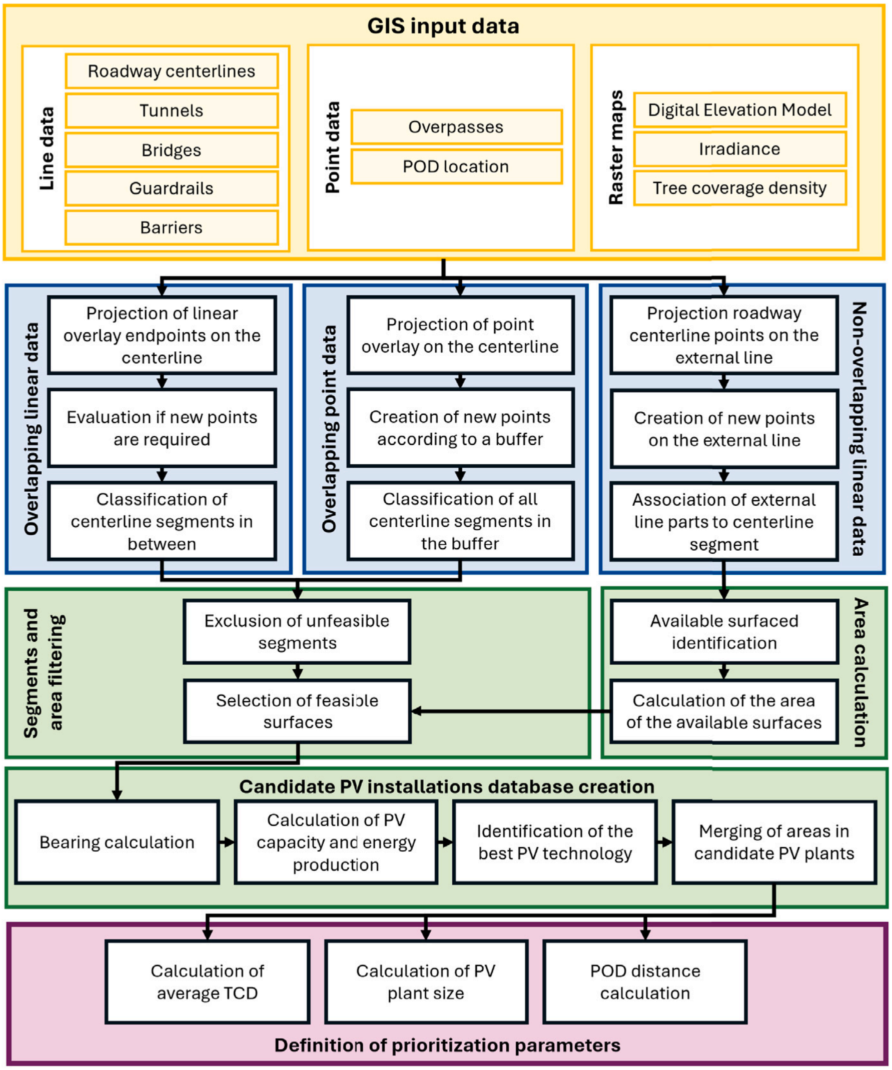


Fig. 1. Methodology flow chart. The required inputs are listed in the yellow box, while the other colors represent the three phases of the procedure: blue for data matching and organization, green for generating candidate PV installations, and purple for calculating prioritization parameters.

characteristics of the identified sites. Third, a database of candidate PV installations is created.

To calculate the available areas in the second step, the polygons that delineate the surfaces are generated using guardrails and barriers as boundary references. Their areas are computed using the shoelace formula, ensuring that a minimum distance from the guardrails is maintained to allow adequate access, ensure safety criteria, and facilitate maintenance operations. An exemplification is shown in Fig. 3(b) .

Then, to create candidate PV installations, it is required to estimate the most suitable type of photovoltaic installation. This work considers two types of installations, chosen for their technical and economic characteristics. The first type consists of monofacial modules installed parallel to the highway slope. Although the typical highway slope of 54° exceeds Italy's optimal PV tilt (i.e., approximately 30° [20]), installing modules directly on the slope simplifies structures and lowers investment costs. The second installation type consists of vertical bifacial modules, which are particularly advantageous in configurations where the area has a predominant north-south orientation or a limited width. Additionally, this type of installation is attractive due to its reduced cleaning costs and maintenance efforts [21].

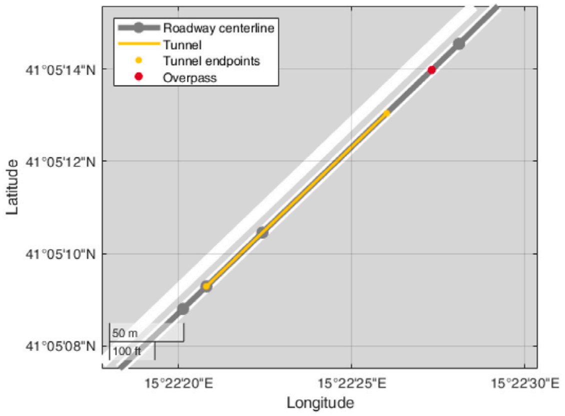
The procedure for estimating the energy capacity potential of the calculated areas takes into account the geometric characteristics of the surfaces, particularly orientation and width. Orientation is a key factor as it determines surface exposure, guides the selection of the optimal installation type, and enables energy production estimation. Consistent with the typical configuration of Italian highways, the study assumes the carriageway plane is elevated, with orientation assessed outward from the carriageway.

The PV capacity is determined using geometric considerations for both installation types, accounting for the space required for PV module maintenance and compliance with highway safety regulations, including a minimum distance of 0.5 m from the guardrail. In both configurations, the PV arrays are assumed to be aligned parallel to the highway, allowing the azimuth to be derived directly from the bearing.

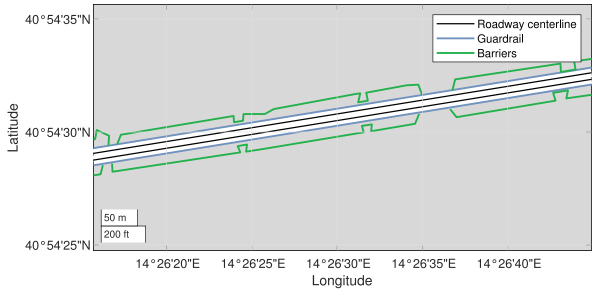
For monofacial installations, shading does not affect production as the modules are mounted parallel to the ground. The considered arrays in this configuration consist of two rows of modules spaced 2 m apart to facilitate inspection and maintenance. Conversely, vertical installations must account for shading effects. Hence, assuming an installation height of 5 m, a spacing of 4 m between rows is considered.

In the direction parallel to the highway, spacing constraints are addressed by assuming that only 80% of the available length can be used for PV array installation.

To select the optimal configuration, the estimated energy production of the two PV installation types is compared including heuristic factors that account for differences in installation and maintenance costs.

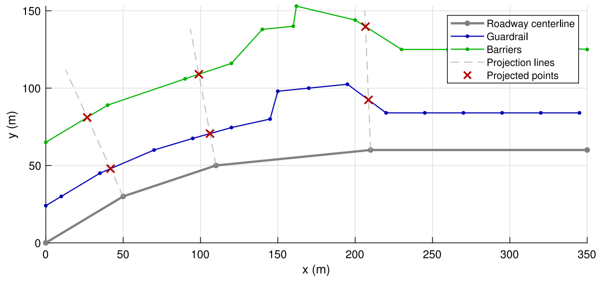


(a) Overlapping data

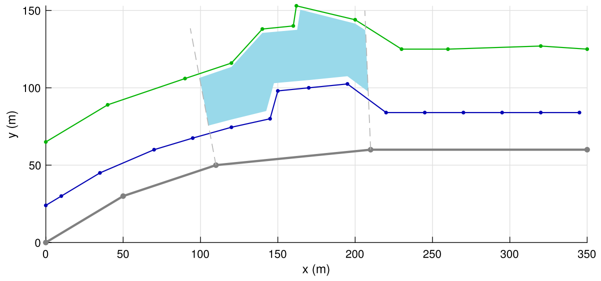


(b) Non overlapping data

Fig. 2. Example of input data. (a) shows overlapping line data (a tunnel) over the roadway centerline and point data (an overpass), while (b) shows non-overlapping data (guardrails and barriers).



(a) Example of projection of roadway centerline on guardrails and barriers.



(b) Example of surface associated to a segment.

Fig. 3. Details of the association procedure and surface definition. (a) illustrates the projection of the roadway centerline points (in gray) on guardrails (in blue) and barriers (in green). The red crosses are the points added in the procedure. (b) shows the resulting surface associated with a segment (in light blue). The required distances are considered from guardrails and barriers.

The estimated energy production is computed using irradiance data from the Global Solar Atlas Solargis database [22], which provides raster maps of global horizontal irradiation (GHI) and direct normal irradiation (DNI) at a spatial resolution of 10 m. These data, generated by combining meteorological information, environmental variables, and satellite imagery, inherently account for terrain elevation and shading effects. The GHI map for Italy is provided in the Supporting Information.

The irradiance on the inclined surfaces of the PV modules is calculated using the model described in [23], which integrates meteorological and geometric factors to simulate solar exposure on tilted surfaces. The power output of the PV modules is then estimated by applying conversion efficiency parameters for both the modules and the inverters, as described in [24]. This methodology provides a detailed evaluation of PV system performance incorporating real-world operational efficiencies and losses.

In order to select the best PV installation for each surface, several aspects have been considered. The first one is obviously the energy production, which is affected by the chosen technology. In addition, three cost parameters were considered: the different costs of the modules, the costs of the structures that bear the modules, and the maintenance costs.

The final step in creating a comprehensive PV database is the identification of the adjacent surfaces, i.e. sets of adjacent surfaces with the same type of installation. All the adjacent surfaces are combined into single PV installations.

With all these steps, a comprehensive PV dataset is generated by estimating the solar irradiation and power potential for each candidate site, providing a basis for further analysis and prioritization.

Calculation of prioritization parameters

Unlike the studies presented in [9,10], which focus solely on energy production assessment, the methodology developed in this paper extends the analysis by introducing an additional prioritization step. This step involves selecting the most promising PV installations through a ranking method based on a defined set of prioritization criteria. Once the individual adjacent installations are identified, different prioritization parameters are considered. The first one is the installation's nominal capacity and its energy production. The second prioritization parameter is the distance between the PV installation and the existing point-of-delivery (POD) in the electrical network, serving as a proxy for the potential connection cost. This factor is particularly relevant in the highway context, where long stretches often lie far from urban centers and are less served by a dense power grid infrastructure. The third, and last, prioritization parameter is the tree coverage density (TCD) around the PV plant. The TCD is an estimate of the percentage of an area covered by trees. These data can be obtained from the website of the European Commission program Copernicus [25]. The data are based on a grid of 10 m × 10 m cells, created considering only the high vegetation. Thus, it can be used to have a first estimation of possible shadings on the PV plants. The TCD map for Italy can be seen in the Supporting Information.

Case study

The whole Italian highway network extends for about 6600 km [26] mainly in the peninsular territory and for about 300 km in the island of Sicily (see Fig. 4). It is divided into 36 main branches indicated by the letter A and a sequential number from 1 to 36.

The management of the network is entrusted to 26 different companies and, among these, the company Autostrade per l'Italia is the one that manages the most extensive portion of about 2855 km, which is among the largest in Europe. Within the network, there are 320 service interchanges (connections between highways and low-order

Fig. 4. Overview of the highways network in Italy. The one managed by Autostrade per l'Italia (ASPI) is in blue.

facilities), 51 system interchanges (connections between highways), and 204 service stations placed at an average distance of 29 km.

Along the entire network, there are 2264 grid connection points from which the necessary power supplies are derived for all traffic management and maintenance services such as light signals, variable message signs, security, control systems, etc.

In linear sections, areas near the roadway are part of the highway appurtenances. Their distance is variable and depends on many factors, mainly geographical. For example, in mountainous stretches linking east to west, such areas have a reduced extent since most of the routes pass over bridges and viaducts and in some cases have escarpments. In many other sections, however, such areas are free of forest vegetation and have uneven ground contours. For several sections, especially those near rural settlements, such appurtenances are affected by the installation of noise barriers.

It is evident that such a multifaceted context necessitates an automated method for analyzing the available locations for the installation of photovoltaic systems, particularly to obtain a reliable estimate of the actual production capacity.

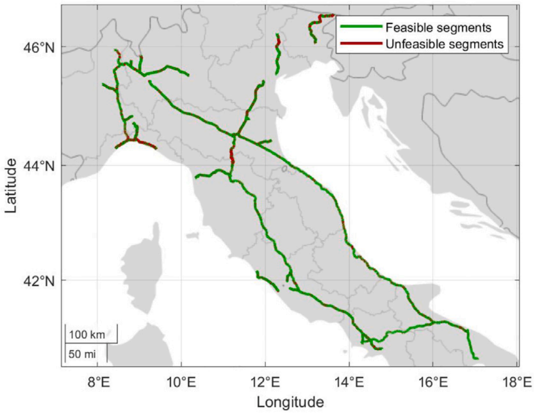
Results and discussion

The proposed methodology has been tested on the described Autostrade per l'Italia network. The results of the different phases are separately discussed in the following sections.

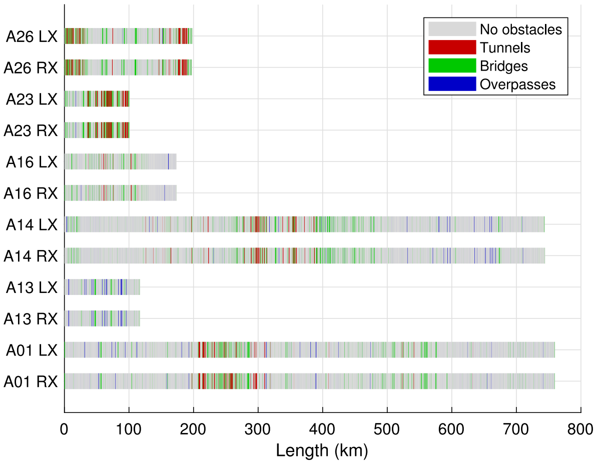
Data matching and classification

The first step of the procedure is the classification to identify the segments that are unfeasible for PV installations.

An overview of the results of the segment classification is provided through Fig. 5. In green are shown the feasible segments, while in red are shown the portions associated with categories not feasible for installations. In general, the unfeasible areas are concentrated in specific points that correspond to the portions of the network that develop through mountain regions. The feasible segments give a total length of 4950.78 km (i.e., 85.63% of the total network extension). The most common obstacle is the presence of bridges (7.24% of the length), followed by tunnels (5.97%) and overpasses (1.16%). A detail of the classification is provided in Fig. 5(b) which refers to the six longest main branches analyzed, split into left and right carriageway.



(a) Overview of feasible and unfeasible segments.



(b) Details of the classification.

Fig. 5. Results of the classification procedure. (a) Overview of all the analyzed highways: red segments correspond to unfeasible locations for PV installations. (b) Details of the classification on the 6 longest highway network main branches indicated with the letter A and a number (LX: left carriage and RX: right carriage). A more detailed result of the classification is reported in the Supporting Information to provide additional details.

Generation of candidate PV plants

The second step of the procedure involves calculating the available area for PV installations. Fig. 6 presents the outcomes for the entire highway network, where the color data were post-processed to compute the area available per unit length, ensuring that the segment length does not distort the results. Highways in southern Italy generally exhibit a higher area availability per unit length, a notable finding given their theoretically greater solar potential.

The width distribution of the surfaces shows a high occurrence in the range from 5 m to 10 m, with a median value of 6.5 m and an average value of 8.5 m. On the other hand, the length distribution has a median value of 95 m and an average value of 400 m. This last value is highly biased by the numerous surfaces with a high length: 30% of the surfaces have a length greater than 500 m and 8.2% greater than 1000 m.

Another important aspect that is considered for the capacity calculation is the bearing associated with each surface, i.e. the angle between the corresponding carriage and a vector pointing toward the north. The bearing distribution presents two peaks at +120° and at −60°. These values can be expected because most of the analyzed highways develop from north to south with a slight orientation to the east. This aspect impacts the selection of the considered PV technologies. In fact, with these angles, a traditional installation is not as effective as the

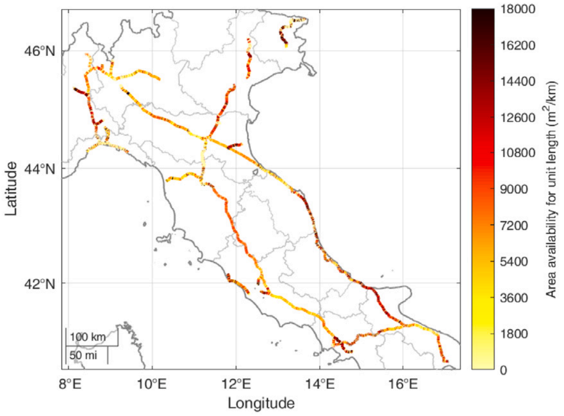


Fig. 6. Overview of the area available per unit of length. The color of the lines represents the associated values, with yellow indicating lower values and red indicating higher values.

Table 1
Area, PV capacity, and energy production for each installation type.

	No installation	Bifacial	Monofacial
Number of surfaces	4902	3387	1171
Area (m^2)	$16.29 \cdot 10^6$	$17.75 \cdot 10^6$	$6.39 \cdot 10^6$
Capacity (MWp)	0	1122.04	522.30
Energy (GWh/y)	0	961.71	502.89

one exploiting vertical bifacial modules. On the other hand, for all the surfaces directed toward the south, it is possible to use traditional monofacial modules. However, in those cases, the opposite carriageway will have no installation because it is oriented to the north.

After determining the appropriate PV technology for each area, the corresponding PV capacity is estimated. This analysis is based on sample module specifications for both installation types:

- Monofacial modules. Dimensions of 1 m × 1.65 m with a rated power of 400 W.
- Bifacial modules. Dimensions of 1 m × 2 m with a rated power of 440 W. It is assumed a rear-side efficiency of 17% and a conservative value of bifaciality factor of 50% to take into account the presence of a necessary supporting mechanical structure [27].

As previously discussed, monofacial modules are assumed to be installed parallel to the highway slope, resulting in a tilt angle of approximately 54°, while bifacial modules are considered for vertical installation.

The number of PV modules for each surface is estimated by adjusting the available area to account for necessary spacing between rows, considering compliance with safety regulations, maintenance accessibility, and shading prevention. Thus, in the direction orthogonal to the roadway, a minimum clearance of 0.5 m from the guardrail is considered. In the direction parallel to the roadway, the effective installation length is assumed to be 80% of the total surface length.

The results of this analysis are shown in Table 1. The first two rows are related to the number of surfaces and their total area. Even if most of the surfaces (51%) are assumed free of installation, they correspond to a smaller percentage of the whole area (40%). The prevalence of the vertical bifacial installation over the monofacial is a consequence of the bearing distribution. Since more than half of the potential installation surfaces are either very small or oriented to the north, rendering them suboptimal for solar energy capture, no installations are associated with these potential surfaces according to the constraints adopted in the methodology.

Monofacial technology is selected on approximately one-third of the available surfaces. Despite occupying only one-third of the total area, these types of modules contribute to nearly half of the installed capacity and account for more than half of the energy production. The outcomes of the case study reveal how bifacial technology has emerged as a crucial alternative, particularly in scenarios where monofacial modules are not feasible due to the too high azimuth of the surfaces.

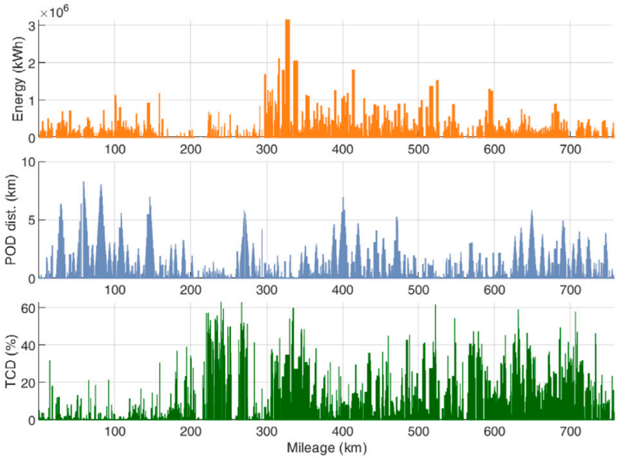


Fig. 7. Details of the prioritization parameters for the A1 main branch, i.e. the longest analyzed highway.

Prioritization procedure

Candidate PV installations are prioritized based on three key parameters: the estimated energy production, the distance to the point of delivery (POD), and the tree coverage density (TCD).

The estimated energy production and tree coverage density (TCD) data are derived from the raster datasets reported in the Supporting Information. On the other hand, the distance to the POD is computed easily by combining the related GIS data.

Fig. 7 shows these three prioritization parameters for the longest highway analyzed (i.e., A01). It is worth noting that all the prioritization parameters are unevenly distributed along the highway, demonstrating the necessity of this detailed GIS-based analysis.

The energy production is indicative of the diverse geometrical configurations of the surfaces across different segments. Indeed, it appears evident that the primary factor influencing energy production is the surface area. In fact, these two parameters demonstrate a Pearson correlation coefficient of 0.94.

In the first third of this highway branch along the northern part of Italy, a considerable number of surfaces are situated at a significant distance from the POD. However, this issue can potentially be mitigated due to the proximity of this part of the highway to production sites and towns. The infrastructure in this part of Italy provides numerous opportunities for establishing connections to the existing grid, thereby reducing the effective connection cost of the PV installations. Conversely, in the other areas, surfaces with high POD distances are often associated with higher TCD. Given the significant energy potential of these surfaces, a comprehensive analysis of connection costs is essential.

An overview of the results for all three prioritization parameters on the entire network can be found in the Supporting Information.

Exploiting these prioritization parameters, some identified PV installations can be excluded and a more conservative estimation of the PV potential along the analyzed highways can be obtained. The results show that:

- Considering all the surfaces, 3216 PV installations are identified, with a total capacity of 1657.96 MWp.

- The energy production associated with all the PV installations is 1478.03 GWh/y.
- In the conservative scenario, the number of installations is 1681, equal to 52.27% of the initial estimation.
- The total capacity in the conservative scenario is 1443.13 MWp (97.64% of the initial estimation), and the estimated production is 1290.91 GWh/y (87%)

The results indicate that, although the number of installations is reduced in the conservative scenario, the total capacity remains almost unchanged. This is because the conservative scenario retains only the most promising PV installations. This effect is reflected in the increase of the average installation width, which rises from 10.3 m in the full scenario to 11.6 m in the conservative one.

Considering that Italy's installed PV capacity is around 30 GWp by the end of 2023, the potential for additional installations on highway slopes is particularly significant. This additional capacity is estimated to be around 3% of the current total, underlining the significant contribution that highway slopes could make to national PV capacity. This highlights the importance of exploring unconventional locations for solar installations. Utilizing highway slopes for PV installations not only makes use of otherwise underutilized land but also supports the diversification and expansion of renewable energy infrastructure.

Conclusions

The work presented the different steps and operational details of the methodology developed to assess the potential offered by areas adjacent to the highway network, i.e., the highway slopes, in terms of PV production. This methodology, based mainly on GIS data, was applied to the portion of the highway network managed by Autostrade per l'Italia and spanning approximately 3000 km. However, the developed methodology is fully generalizable to any highway infrastructure since it is based on data normally used by operators of this type of infrastructure for multiple functional, management, and monitoring purposes.

Although several factors, such as land configuration, orientation, and the presence of tunnels and bridges, prevent the installation of photovoltaic systems, the results of the work emphasize the high potential offered by highway slopes. In fact, in the specific case analyzed in the study, which refers to a geographically highly articulated territory such as Italy, it is possible to concern with photovoltaic system installations an area of about 24.14 km^2. Through an appropriate choice of the technology of the modules installed, it is possible to obtain an annual energy yield that reaches a terawatt-hour.

The presence of PV installations along highways can also support the energy supply for electric vehicle charging stations. These plants can be integrated with more conventional PV systems installed at service stations, creating a complementary energy infrastructure. A deeper study of this integration can be considered as a future development of this work. Other future studies could expand the range of module technologies considered, incorporating more diverse and innovative implementations.

CRediT authorship contribution statement

Alessandro Niccolai: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation. **Vincenzo Cirimele:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Conceptualization. **Diego Franceschini:** Writing – review & editing, Visualization, Validation, Resources, Methodology. **Valerio Apicella:** Writing – review & editing, Visualization, Validation, Resources. **Benedetto Carambia:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Sonia Leva:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.seta.2025.104384.

Data availability

The authors do not have permission to share data.

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