

Estimating Air Pollution Related Solar Insolation Reduction in the Assessment of the Commercial and Industrial Rooftop Solar PV Potential

G. Fattoruso[1(✉)], M. Nocerino[2], G. Sorrentino[2], V. Manna[2], M. Fabbricino[2], and G. Di Francia[1]

[1] DTE/FSD/SAFS Lab, ENEA RC Portici, P.Le E. Fermi 1, 80055 Portici, Italy
grazia.fattoruso@enea.it

[2] Civil Construction and Environmental Engineering Department, University of Naples Federico II, Via Claudio, 21, Naples, Italy

Abstract. Air pollution is a serious issue and it has been becoming increasingly urgent over last year, mainly as a result of its effects on human health. Recently, however, a number of scientific papers has appeared reporting on air pollution effects in other fields such as the photovoltaic energy generation and, notably, on the relation between the reduction of the solar insolation reaching the PV systems and $PM_{2.5}$ concentrations in the air. In this study, the rooftop solar PV potential of commercial and industrial (C&I) buildings at regional scale has been estimated tacking into account the spatially distributed solar insolation reduction factor, due to the $PM_{2.5}$ in the air. High resolution LiDAR data and advanced digital surface modeling techniques have been used for determining the available suitable rooftop area and estimating the technical solar PV potential of the C&I rooftops. For the C&I study area of Aversa Nord (South Italy), we find that the suitable rooftops have annually a total electric power potential of 50.75 GWh/*year*. For this area, an annual average $PM_{2.5}$ concentrations of about 13 $\mu g/m^3$ results in a nearly 5% annual solar insolation reduction. Thus, if properly located, the large scale rooftop PV systems could significantly decrease primary energy consumption and contribute to reduce the CO2 emissions.

Keywords: $PM_{2.5}$ concentration · Solar PV potential · LiDAR data and DSM

1 Introduction

Air pollution is a serious issue and it has been becoming increasingly urgent over last years, especially in the cities. While we have much learned about the effects of the air pollution on human health, only very recently its effects in other sectors have begun to be considered and investigated.

In this paper, we investigate such the impact of the haze on solar PV energy potential. As a matter of facts, recent major haze events affecting several cities around the world (e.g. Singapore, Delhi, among others) induced some researchers [1] to investigate the impact such haze events might cause on the energy output of solar PV

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12250, pp. 665–677, 2020.
https://doi.org/10.1007/978-3-030-58802-1_48

installations. In particular, they investigated and quantified the effects of fine air particulate matter on the effective solar irradiance reaching a PV module, being these particles the main contributor to haze events. Correlating measured particulate concentrations and solar insolation in Delhi, it was estimated that the insolation received by silicon PV panels was reduced by about 12% or 200 kWh/m^2 per year due to air pollution. The analysis was extended to 16 more cities around the world and insolation reductions were estimated ranging from 2.0% (Singapore) to 9.1% (Beijing) [1, 2].

According to the EU's re-cast renewable energy directive [3], by 2030, EU countries have to reach the target of the 32% in the energy production by renewable technologies. To achieve that, they need to increase their use of renewables including the solar PV systems whose contribution is evaluated as significant [4].

Until a few years ago, the major contribution to the renewable energy production came from the ground large scale PV plants [5]. In spite of the environmental benefits and advantages, the diffusion of large scale solar PV farms has caused undesirable impacts on land use, landscape, and biodiversity. In order to mitigate the adverse effects, over recent years, the new country regulations have foreseen specific exceptions for installations of ground large size PV systems and promoted measures addressing towards the use of suitable building surfaces - rooftops and facades, for distributed solar PV systems deployments.

These developments have taken advantage of the EU orientation to promote the decentralized electricity generation with renewable technologies including the rooftop PV systems as well as the continuously decreasing costs of the distributed PV installations. Moreover, several studies (see [4, 6, 7] among others) have shown that the existing buildings' rooftops across the EU countries can provide the room for significantly increasing the PV electricity production and often at lower costs.

However, the roof area covers a wide range of PV installations sizes, from residential rooftops characterized by PV systems of even just a few kWp to large commercial and industrial (C&I) roofs with PV systems reaching even hundreds KWp. While in literature several geospatial methodologies were developed for addressing the question on how to estimate to a high level of accuracy the solar PV potential of urban buildings' rooftops (see [4, 8, 10, 11] among others), there is little understanding on the assessment of the rooftop solar PV potential of the C&I areas.

This study has addressed the use of large scale rooftop PV systems and focused on rooftop solar PV potential assessment of the C&I buildings at regional scale tacking into account the spatially distributed solar insolation reduction factor, due to the $PM_{2.5}$ concentration in the air. High resolution LiDAR data and advanced digital surface modeling techniques have been used to determine the available suitable rooftop area and estimating the technical solar PV potential of the C&I rooftops.

The solar insolation reduction factor has been calculated through the empirical relation between $PM_{2.5}$ concentration and reduction in insolation, developed by the authors in a previous work [9] by using high resolution in field data gathered in the city of Naples (South Italy). The case study is the industrial area of Aversa Nord, one of the greatest regional C&I zones of Campania (South Italy).

2 Background and Previous Works

The photovoltaics potential analysis for a site or area is generally carried out taking into account resource, technical and economic levels. In particular, the resource potential is evaluated through the annual incident solar radiation. It can be affected by environmental parameters to be eventually considered such as ambient temperature, wind speed as well as the fine particulate matter in the air which is the main cause of haze reducing the visibility. The technical potential is given by the available suitable surface area and PV system technical performance while the economic potential depends on technology costs.

This study specifically addresses large scale rooftop PV systems and focuses on resource and technical potential assessment of the C&I building rooftops using a high-resolution light detection and ranging (LiDAR) data and digital surface modeling techniques.

For assessing rooftop solar PV potential, there are different spatial methodologies mainly characterized by the specific scale, ranging from local to regional or continental level. Basically, all these methodologies include two main steps: (1) the estimation of available suitable rooftop area and (2) the estimation of solar energy potential.

The literature methodology reviews (see [4, 8], among others) show that the main difference is the method used to determine the available roof area. These methods are based on spatial analysis and distinguished in low-level, medium-level and high-level depending on detail level of data models and solar radiation algorithms. [4, 8, 10].

At large scale, the first high-level methodology has been developed by Bodis et al. [4] to assess rooftops solar PV potential across the EU building stock as a whole. A previous work on EU-wide assessment had been previously developed by Defaix et al. [12] using a medium-level technique.

It is to be noted that the high-level methodologies addressing large areas are generally demanding in terms of data collection and computing power. To overcome this complexity, in literature, the assessment process is performed for a pilot area at local scale, eventually to be extended at a wider scale. In this regard, Rodriguez et al. (2018) [8] developed a high resolution spatial assessment of the PV potential at urban and regional scale, by using 3D city models and a novel procedure based on the state-of-the-art available roof area reduction coefficients. An extensive literature review, that shows the great variety of reduction coefficients used for calculating the available building rooftop area, is available in [8].

Applying a high resolution approach, the potential roof area is derived by the 3D model of the built area that identifies the geometry of the buildings that shape it. However, many circumstances may lead to the reduction of the initial roof area. For determining the suitable roof area, it occurs to perform an architectural and a solar suitability analysis. At this scope, a set of architectural (such as *construction restriction, shading effects, service area*, among others) and solar reduction factors (such as *orientation losses, slopes of roof, separation of the PV panels*, among others) is applied. On the basis of them, an utilization factor is defined which identifies the available roof area suitable to the PV installations. So, the technical solar PV potential is estimated through the available roof area and the incoming solar energy radiation

converted in electrical potential on the basis of the PV modules efficiency as well as the performance ratio.

In this study, the authors intended to estimate the rooftop solar PV potential for C&I built areas at regional scale through a spatial analysis based on high resolution LiDAR data and an insolation reduction factor, ad hoc defined, due to the air pollution. LiDAR data are processed to estimate the available C&I rooftop area and the air pollution related solar radiation reduction and to provide the spatial information needed to apply the architectural and solar suitability criteria.

It is to be noted that the C&I rooftop solar PV potential has been rarely specifically addressed in the literature. In [13], a preliminary study was carried out in Minneapolis, aimed at being extended at the entire Minnesota, analyzing the solar insolation to assess the PV potential capacity of the C&I rooftops for large scale solar PV installations using LiDAR data and GIS methods.

3 The Methodology

The objective of this study has been to assess the solar PV potential of the C&I buildings for large scale rooftop PV installations, taking into account a new reduction factor, due to $PM_{2.5}$ concentrations in the air, in order to support the diffusion of renewable solar electric energy generation.

To do that, a high resolution digital surface model (DSM) of the C&I built area is generated by processing LIDAR data. On the basis of spatial information derived from DSM, the available rooftop area is identified and a spatially distributed solar radiation model, taking into account air pollution, is generated. Combining these spatial layers and defined reduction factors, the technical solar PV potential for the suitable building rooftops of the C&I study area is estimated.

3.1 The Case Study

The final objective of this study is to generate a high resolution solar radiation cadaster of the C&I building stock referred to the Campania, a region located in South Italy. This region counts 137 C&I areas which cover a ground surface varying from 0.26 Km^2 to 8.16 Km^2. These areas consist in middle and large factories which operate in several sectors – textile, gold, tanning, shoe, food ones. The mayor C&I zones (about 27%) are completely integrated within the residential areas. Thus, the solar PV potential of their rooftops can be considered as integral part of the solar PV potential of the regional building stock.

In this paper, as case study, the rooftop technical PV potential is investigated for the industrial area of Aversa Nord, one of the greatest regional C&I zones. It covers a ground area of 5,82 kmq across the municipalities of Teverola, Carinaro and Gricignano di Aversa, including around 1000 factories of which the major part operates in the textile sector (Fig. 1).

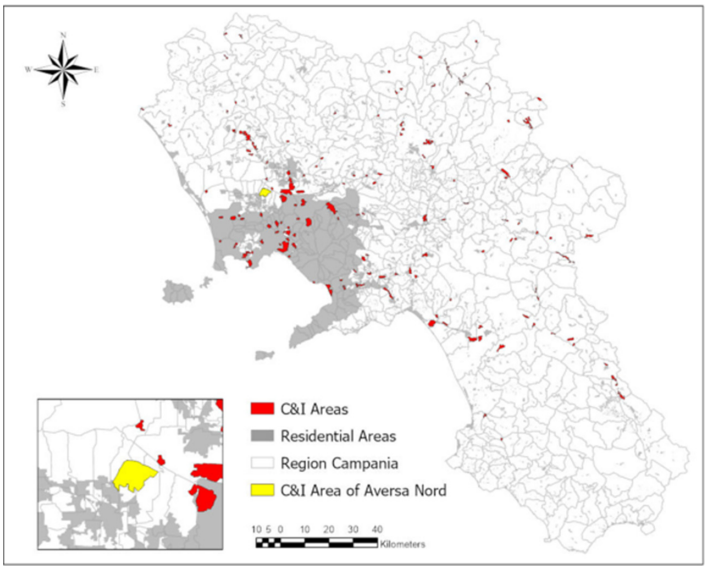

Fig. 1. C&I areas of the Region Campania (South Italy)

3.2 Data

Data sources used as input in the proposed calculation process for estimating the rooftop solar PV potential of the area study are summarized in the Table 1. It includes various GIS databases used to locate the study area (items 1, 2), identify the building footprints (item 3), model the available rooftop area (item 4) and map the air pollution related solar irradiance (items 4, 5).

Table 1. Datasets used in the methodology and their source

Name	Type	Year	Source	Description
The Corine Land Cover	Vector layer (100 m)	2018	Copernicus	Inventory on land cover of EU
Local administrative boundaries	Vector data	2011	ISTAT	National inventory on the regional and local administrative boundaries
LiDAR data	Points cloud - xyz data (2 m)	2013	National PST Project	Point clouds by LiDAR technology covering the national territory
National building stock	Vector layer	2013	National PST Project	National inventory on the building stock including footprint layer with building height attributes
Fine Particulate Matter Measurements	Vector layer	2018	ARPAC database	Annual average $PM_{2.5}$ concentrations dataset by the regional air quality gauge stations network of ARPAC

The GIS software platform used for performing step-by-step the proposed procedure is ESRI-ArcGIS Pro Advanced. Various toolsets have been used including geoprocessing, spatial analysis and 3D analysis tools as well as ad-hoc developed solution tools for extruding the available building rooftops from LiDAR point clouds, processing the elevation surfaces, interpolating air pollution data, and performing solar and shade analysis.

3.3 Determination of the Available Roof Area

For estimating the available rooftop area for large scale PV systems to be installed on C&I buildings, the first step is to derive a rooftops layer

Assuming the building rooftop area equivalent to the related footprints area, the potential rooftops for solar PV installations, in the C&I area of Aversa Nord, were derived through the building footprints layer (item 4) related to this area, identifying 368 potential building rooftops and a potential rooftop area of 1.37 km^2 for PV panels deployments (Fig. 2).

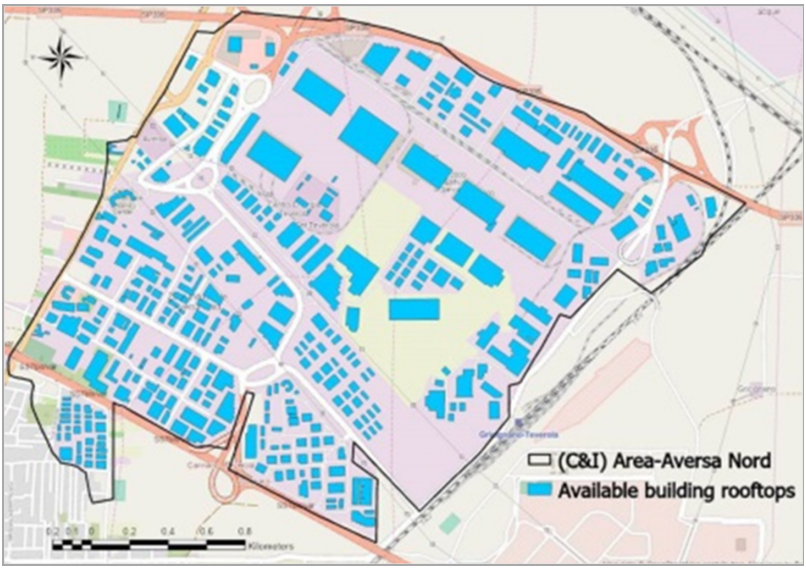

Fig. 2. The C&I built area layer of Aversa Nord

It is known that many factors may lead to the reduction of the potential roof area. These factors, for the present study, were derived from high resolution elevation models of the study area as well as from literature reviews.

At this scope, using a 3D LiDAR point cloud (LAS) dataset (item 3), two elevation models have been derived, one showing elevation of the ground (DTM) and one showing elevation of features and buildings on top of the ground (DSM).

Thus, on the basis of slope and aspect raster layers derived from DSM and the building footprints layer, the suitable rooftops orientation and slopes were derived removing the rooftop areas with a slope steeper than 45° and with an aspect value less than 22.5° or more than 337.5°.

As a matter of facts, the suitable rooftops for large scale PV installations must be flat or have a maximum slope of 45°, as steep slopes tend to receive less sunlight. At the same way, they must be south-facing, as north-facing rooftops in the northern hemisphere receive less sunlight.

For simplicity, in this study, some reduction factors' values were defined after reviewing related publications. In particular, for the factor Construction Restriction (CON), referred to space already occupied by elements located on the roof, we used the value of 0.8 as suggested by [14]. Similarity, for the factor of Separation of PV panels (GCR – Ground Cover Ratio), referred to the distance between the panels to avoid reciprocal shadowing, was chosen the value of 0.42 [15]. Accordingly, being already accounted the available space in GCR, the value of SA, referred as the necessary space for PV maintenance and access, was set to 1 [15].

Applying these reduction factors, the available rooftop area is reduced to 1.07 km^2.

3.4 Determination of Solar Energy Potential

The solar radiation reaching the available rooftops is the main factor for assessing if buildings have technical potential for solar panel installation. The annual insolation $[KWh/m^2 year]$ is here calculated on the ground and on the roofs of the buildings, based on DSM of the area, using the Area Solar Radiation tool. This tool calculates the radiation taking into account the position of the sun throughout the year and at different times of the day, taking into account obstacles that may block sunlight such as nearby trees or buildings and the slope and orientation of the surface. In this way, also the shading effects which affect the incoming solar energy are calculated.

Once obtained the solar radiation map, the insolation reduction due to the fine particulate particles in the air has been evaluated using the empirical method developed in [9].

Solar Insolation Reduction. Recent studies have discussed how the fine particulate matter in the air may affect energy yield of PV installations [1, 2].

A similar study has been carried out by the authors with the scope of quantifying the effects of the fine particulate concentrations in the air on the solar insolation in the city of Naples. An empirical relation between the $PM_{2.5}$ concentrations and the reduction in solar insolation has been developed using local high-frequency insolation and pollution data [9]. The functional relation is given by:

$$\frac{I(PM_{2.5})}{I_0} = exp\left(\frac{-PM_{2.5}}{250}\right) \tag{1}$$

where I_0 is the isolation at 0 $\mu g/m^3$ and I is the insolation affected by $PM_{2.5}$ concentrations.

For Naples, we found that solar insolation reaching a potential PV installation site was reduced by 5% or 66,20 kWh/m^{-}, per year between May 2018 and May 2019 due to air pollution.

On the basis of the findings of this research, it is evident that the insolation reduction related to the air pollution is a factor to be considered because in some cases it could result in a substantial difference in the assessment of solar PV potential.

The functional relation (1) enables a way to estimate the solar insolation reduction in the generation of the solar radiation distribution model of the C&I built area.

At this step of the calculation process, a continuous map of $PM_{2.5}$ distribution on the C&I built area (Fig. 3) was generated based on the dataset of the $PM_{2.5}$ measured points (item 5) and averaged over the year, by the regional air quality gauge stations network, using a geo-statistical interpolation technique - Ordinary Kriging.

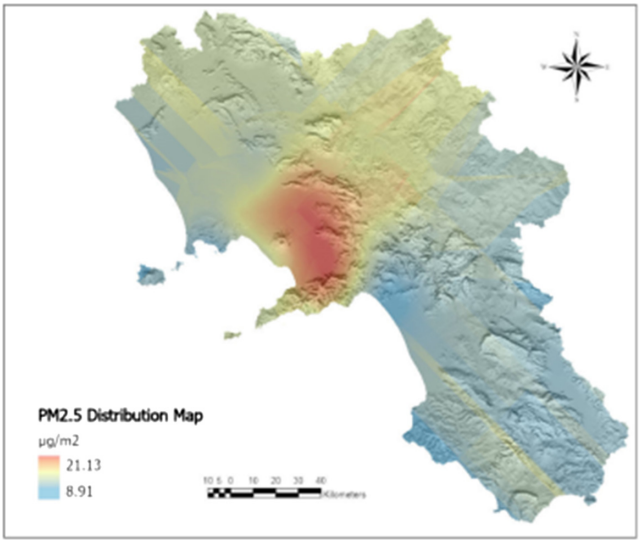

Fig. 3. $PM_{2.5}$ distribution map of the region Campania (South Italy)

Combining the $PM_{2.5}$ distribution and solar radiation raster layers in the map-algebra statement based on the Eq. (1), a high resolution (2 m) solar isolation distribution model affected by the fine particulate was derived for the C&I built area (Fig. 4).

The derived insolation reduction map (value %) in Fig. 5 shows that the solar insolation reaching the C&I rooftops is reduced by about 5%, due to annual average $PM_{2.5}$ concentrations of about 13.38 µg/m3 on the study area.

Finally, only buildings with solar insolation on their roof above a threshold value which indicates a minimum amount of radiation that is required for the installation, were considered. Assuming the threshold value of 800 kWh/m^2 [15], the rooftops with lower solar radiation were removed from available rooftop area on the basis of the derived solar radiation distributed model.

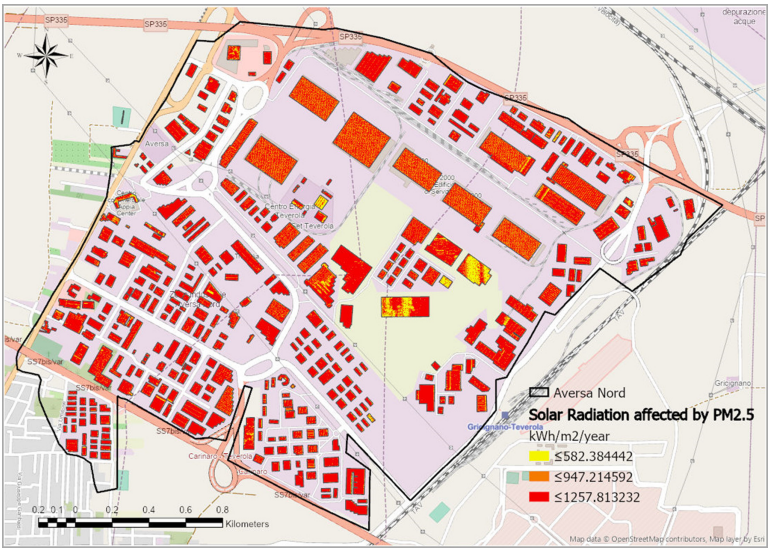

Fig. 4. Map of solar insolation affected by $PM_{2.5}$ in the air

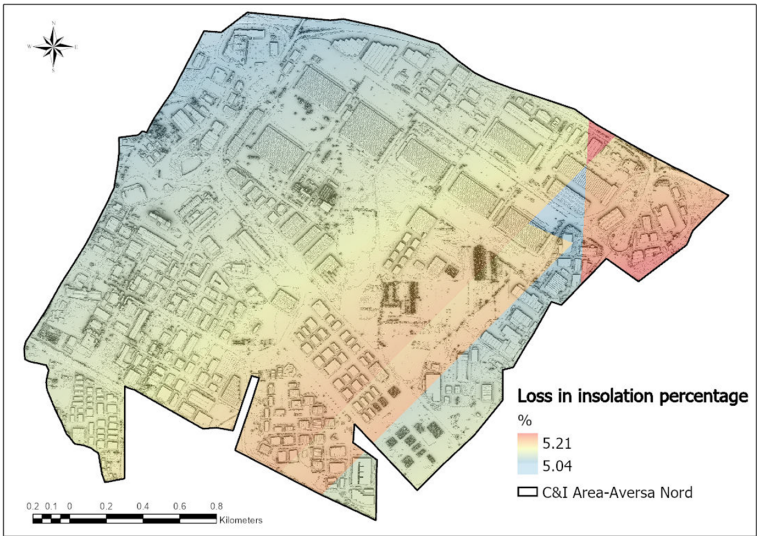

Fig. 5. PM2.5 related solar insolation reduction map

In addition, a minimum roof area was considered, so buildings whose roof areas were below that minimum value were not taken into account. We chose a minimum roof area of 140 m^2 which is that required for the installation of a PV systems with minimum nominal power of 20 kWp, considering a minimum area of 7 m^2 for one kWp [15].

As result, a solar energy potential map was calculated for each suitable rooftop of the C&I study area, taking into account the air pollution effects (Fig. 6)

Aggregating the solar energy potential data, for our study area, we found a total amount of solar radiation received per year by usable rooftop area, including 134 suitable rooftops, of 393.45 GWh/*year*.

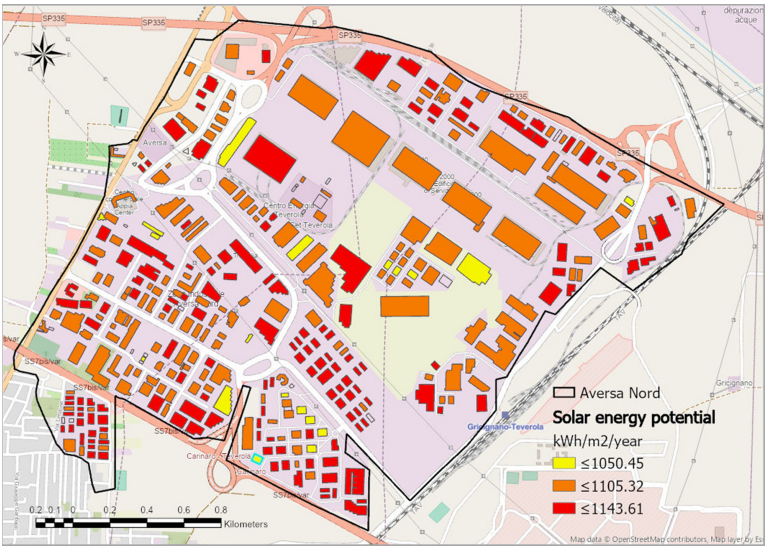

Fig. 6. Solar energy potential map for usable rooftop area of Aversa Nord

3.5 Technical PV Potential

The technical potential is defined by implementing PV panels on all suitable rooftop surface.

To estimate its annual value on the study area, the usable solar radiation values were converted to electric power production potential. The amount of power that solar PV panels can produce depends not only on solar radiation, but also the solar PV panels' efficiency and the installation's performance ratio. In this study, we assumed that the solar PV panels were capable of converting 15% of incoming solar energy into electricity, and 86% of that electricity was maintained throughout the installation. Combining these reduction factors with the solar radiation layer, the rooftop technical PV potential for each suitable rooftop of the our C&I area was calculated as shown in Fig. 7.

Aggregating the technical PV potential, we found that the whole C&I built area generated a total annual electric power amount by rooftop PV systems of 50.75 GWh/*year* which might cover partially or totally the electricity demand of the C&I buildings as well as provide the electricity surplus produced to the electricity grid.

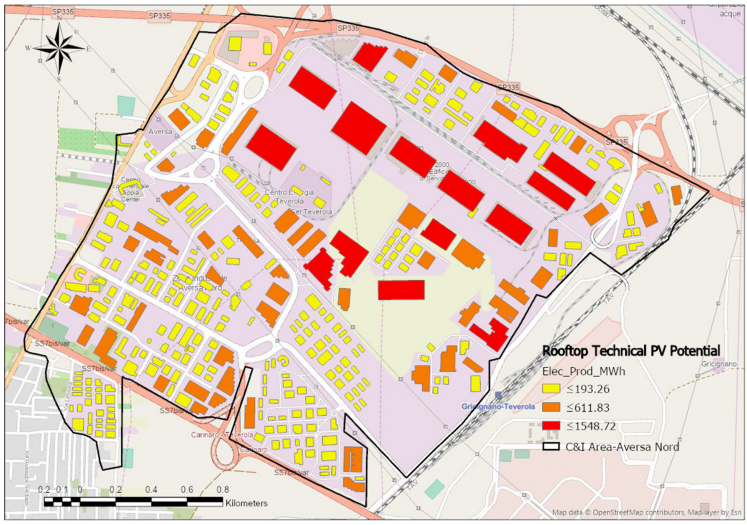

Fig. 7. Rooftop technical PV potential map for the C&I built area of Aversa Nord

4 Conclusions

Locating suitable building surfaces as facades or rooftops for solar PV installations can contribute to increase the use of renewable technologies in the energy production.

To address that, concerning large scale PV systems, through a high resolution spatial analysis, we have identified the suitable rooftops and estimated the rooftop solar PV potential of a C&I built area. The applied methodology is based on available rooftop surface analysis, irradiance simulation and reduction coefficients estimation. Specifying properly the architectural and solar reduction factors is fundamental for determining accurately the rooftop solar PV potential. At this scope, the effects of the air pollution by fine particulate matter on the solar PV energy potential of the C&I rooftops have been investigated, including in the calculation process the related reduction factor, calculated by an empirical relation previously developed. This reduction factor can result in a substantial difference in the assessment of solar PV potential.

A realistic scenario for distributed large scale PV implementations has been developed in the case study of Aversa Nord, to be extended at all regional C&I built areas. From the results obtained, using the entire suitable rooftop space, the pilot C&I area can generate a total electricity power amount of 50.75 GWh/year which might cover partially or totally the electricity demand of the C&I buildings and provide the electricity surplus produced to the electricity grid. Then, for the investigated area, an annual average $PM_{2.5}$ concentration of about 30 μg/m^3 results in a nearly 5% annual solar insolation reduction.

In conclusion, if properly located, the large scale rooftop PV systems could significantly decrease primary energy consumption and contribute to reduce the CO_2 emissions.

5 Future Work

During this study, some future developments have been identified which could result in more precise rooftop technical PV potential calculations. First of all, the developments of a 3D building model of the C&I built area from LiDAR data that could return a more detailed available rooftop surface, including the rooftops' forms – tiled and flat. Thus, some reduction factors, which have taken from the literature review, could be properly calculated on the basis of the precise buildings geometry.

Then, a more precise insolation reduction factor could be obtained by using high resolution $PM_{2.5}$ distribution simulation models.

Regarding the aggregated data of the technical PV potential, analysing the electricity demand of the C&I built areas, the coverage percentage depending on several PV efficiency scenarios could be estimated. Similarity, the potential CO_2 emission savings due to the implementation of PV modules could be quantified as well as an economic analysis could be developed.

Developing a high resolution spatial analysis methodology for estimating the C&I rooftop energy power potential for large scale PV installations taking into account a comprehensive set of reduction factors is clearly the main challenge in a future research work in order to extend this analysis at regional scale.

Acknowledgements. We thank the Regional Agency for Environmental Protection (ARPAC) operating in Campania (South Italy) in the person of Eng. Paolo D'Auria, for providing solar radiation and $PM_{2.5}$ measurements by the regional air quality monitoring network.

References

1. Peters, I.M., Karthik, S., Liu, H., Buonassisi, T., Nobre, A.: Urban haze and photovoltaics. Energy Environ. Sci. **11**, 3043–3054 (2018)
2. Liu, H., et al.: The impact of haze on performance ratio and short-circuit current of PV systems in Singapore. IEEE J. Photovolt. **4**, 1585–1592 (2014)
3. Council of European Union: Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (2018)
4. Bódis, K., Kougias, I., Jäger-Waldau, A., Taylor, N., Szabó, S.: A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renew. Sustain. Energy Rev. **114**, 109309 (2019)
5. Castillo, C.P., e Silva, F.B., Lavalle, C.: An assessment of the regional potential for solar power generation in EU-28. Energy Policy **88**, 86–99 (2016)
6. Weiss, W., Biermayr, P: Potential of Solar Thermal in Europe, Report of the EU-funded project RESTMAC (2010)
7. Defaix, P., Van Sark, W., Worrell, E., de Visser, E.: Technical potential for photovoltaics on buildings in the EU-27. Sol. Energy **86**, 2644–2653 (2012)
8. Rodríguez, L.R., Duminil, E., Ramos, J.S., Eicker, U.: Assessment of the photovoltaic potential at urban level based on 3D city models: a case study and new methodological approach. Solar Energy **146**, 264–275 (2017)

9. Nocerino M., et al.: Assessing the impact of Haze on solar energy potential using long term of $PM_{2.5}$ concentration and solar insolation field data in Naples, Italy. In: Workshop AISEM 2020, LCNS in Electrical Engineering, Springer, (under review)
10. Freitas, S., Catita, C., Redweik, P., Brito, M.C.: Modelling solar potential in the urban environment: state-of-the-art review. Renew. Sustain. Energy Rev. **41**, 915–931 (2015)
11. Byrne, J., Taminiau, J., Kurdgelashvili, L., Kim, K.N.: A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renew. Sustain. Energy Rev. **41**, 830–844 (2015)
12. Borfecchia, F., et al.: Remote sensing and GIS in planning photovoltaic potential of urban areas. Eur. J. Remote Sensing **47**, 195–216 (2014). https://doi.org/10.5721/eujrs20144713
13. Online report: A map showing potential solar energy production of commercial, industrial, and mixed used buildings in Minneapolis (2014). https://www.arcgis.com/home/item.html?id=b5d60dabc48b47828bc1dc4111ad253c
14. Schallenberg-Rodríguez, J.: Photovoltaic techno-economical potential on roofs in regions and islands: the case of the Canary Islands. Methodological review and methodology proposal. Renew. Sustain. Energy Rev. **20**, 219–239 (2013)
15. Moser, D.: Rapporto sull'importanza dell'energia solare su scala regionale e sul potenziale di sviluppo dell'energia solare a livello locale. Technical report (2015). https://doi.org/10.13140/RG2.1.4794.9284