Mapping onshore wind turbine generators in Italy from Sentinel-2 data

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Prompted by public investments, sustainability issues and climate change awareness, recent years have seen rapid technological advancements for renewable energy collection and exploitation. In line with the most recent European energy policy (Energy policy: general principles, 2021) which provides to reach at least a 32% Renewable Energy Sources (RES) share of final energy consumption by 2030, wind energy is going to play an important role in the decarbonisation process and is expected to grow everywhere in Europe, either through the repowering of existing plants and with new constructions. Italy for instance, following its 2019 National Energy and Climate Plan (PNIEC 2019) should double its installed capacity by 2030, reaching about 19.3 GW by 2030 with only 0.9 GW of offshore capacity.

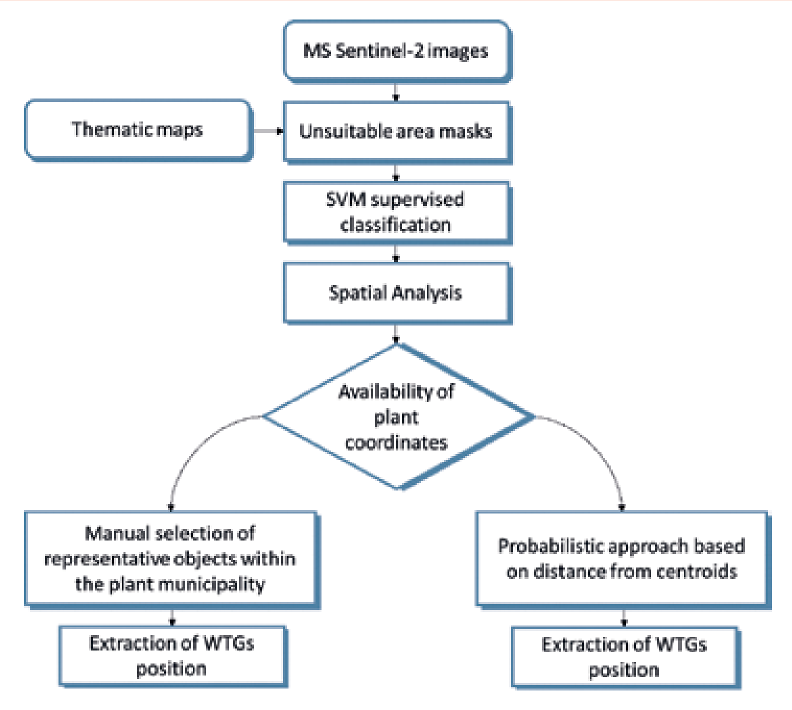

Fig. 1 - Simplified representation of the applied methodology.

Since wind farms installation requires wide areas, a big effort in onshore spatial planning is requested, especially in those countries, like Italy, characterized by complex morphology, high anthropic exploitation and localized concentration of good wind resource.

Effective and conscious spatial planning cannot be separated by an accurate and up-to-date spatial information about wind turbines generators (WTGs). WTGs technical and spatial information can allow performing geospatial analyses on installed wind capacity and wind power densities (Miller & Keith 2018), land requirement for future installations and impacts on ecosystems (Diffendorfer et al. 2015) or for planning new wind capacity, comparing future scenarios, evaluating renewable energy penetration in the electric grid (Johlas, Witherby & Doyle J.R. 2020) and leading to a wider public acceptance (Firestone et al. 2020).

The importance of an accurate WTGs database is testified by the virtuous efforts carried out in many countries to develop RES atlas that, together with resources mapping, try to spatially represent the actual installed capacity.

A significant example is the freely accessible and complete United States Wind Turbine Database (USWTDB) (Rand et al. 2020), which provides location and attributes of more

than 60000 wind turbines in the US through an interactive WebGIS interface. Another example is The Wind Power website (www.thewindpower.net) where technical data are available for wind farms worldwide, both in operation or under construction, although in this case coordinates of the single wind turbines are not provided. No examples exist at the whole European scale, but on a national scale, an onshore WTGs database is being developed for the German Wind Energy Association without free access (https://ramboll.com/projects/re/database-with-all-onshore-wind-turbines-in-germany). In Italy RES plants data are recorded by Terna (the Italian Transmission System Operator - TSO) and GSE (Gestore dei Servizi Energetici). In particular GSE publishes the WebGIS Atlaimpianti (https://atla.gse.it/atlaimpianti/project/Atlaimpianti_Internet.html) which at the moment represents the most complete source of geo-referenced data regarding the Italian RES. Alike the examples reported above, Atlaimpianti webGIS shows the central coordinates of the existing power plants and gives the possibility to the user to download some information (mainly the plant capacity and the municipality of installation) but does not provide the number and the position of the wind turbines composing the plant. Although its rich and national-wide information, Atlaimpianti does not thus suffice the need for precise depiction of the WTG localization, which, as above recall, is of great importance for sustainable spatial planning.
With this in mind, we explored the possibility to rapidly and cost-effectively obtain the position of the existing Italian WTGs, by using freely accessible medium-resolution satellite images.
Over the last years, Earth Observation (EO) satellites performances in terms of spatial, spectral and temporal resolutions have been progressively improved, enabling them to effectively operate as reconnaissance and monitoring instruments for a variety of applications.
However, mostly due to the relatively small dimensions of WTGs in relation to the image spatial resolution and the highly variable morphology and land cover of the installation sites, has limited this type of applications to the use of high/very high resolution satellite or aerial images, mainly processed with machine learning algorithms for the automatic identification of objects in series on the Earth's surface (Lee, Goodwin & Biddle 2018). Whilst reliability and accuracy of these applications is out of discussion, costs and working hours can be quite high and would not possibly meet the resources availability of many stakeholders. The methodology presented in this work is instead based on medium resolution Sentinel-2 images. The methodology was first tested within a feasibility study on one region and then extended to the whole Italian territory. The proposed approach assumes that the main wind plants features such as place of installation, total capacity, number or size of wind turbines are known. For this work, technical data were mainly provided by ANEV, the Italian Wind Energy Association.

The feasibility study for wind turbines mapping on Sentinel-2 images

Study area

The experimental region chosen for the feasibility study is Sardinia, where WTGs census was complete and updated (December 2019) and could, thus, be used for calibration and validation of the methodology. The data set accounts for 47 power plants with a total number of 715 WTGs. Each wind turbine is provided with coordinates, manually identified during previous research, and technical attributes related to power, dimensions, type of turbine, constructor and year of construction.

Data

The application has required the use of a combination of satellite images and official thematic maps provided by national or regional agencies.
A selection of 10m cloud-free Sentinel-2A and Sentinel-2B images (level 2A) has been used for WTGs mapping, as, among free satellite data, they offer a good compromise between spatial and spectral resolution. Images have been acquired in clear sky conditions and minimum atmospheric interferences on February 2020. Although any quantification in terms of performances has been computed, empirical comparisons suggest that it is advisable to use images in which the targets are surrounded by a sufficiently spectrally different land cover. Thus, winter images have been selected as they provide higher contrast between cultivated agricultural fields and wind turbine foundation areas.
As the structure of wind turbines cannot be recognized from a medium spatial resolu-

tion image, their positions are uniquely identified by the foundation area, which usually occupies an area comprised between around 1 and 5 pixels. Some foundation areas are very small and are characterized by a high spectral similarity with other land use/land cover features (e.g. bright roofs, unpaved roads and bare rocks). To reduce the risk of false positive detection, we limited image processing to areas where wind turbines are likely to be installed. This can be obtained by masking all the technically unsuitable areas (e.g wetlands, water bodies, urban surfaces and scattered buildings and landslide risk areas) but also areas subjected to environmental constraints. Technical unsuitable areas have been retrieved from Corine Land Cover map (2018), ISTAT inhabited centers maps (2011) and Regional Technical Charts (CTR). As environmental constraint we considered only the altitude threshold set by Italian law to protect mountain areas (law n. 431, 8th august 1985, known as Galasso Law), which, while not completely forbidding the possibility of building wind farms, makes the authorization very unlikely.

Methods

Within the feasibility study, a semi-automatic supervised classification approach has been applied on Sentinel-2 images, after standard pre-processing. Image processing has been performed with the ENVI software version 5.5.3 (Exelis Visual Information Solutions, Boulder, Colorado).

The whole methodology can be roughly divided in two phases: i) wind turbine detection through satellite images processing, and ii) spatial analysis, completed by a visual analysis, to remove false positives and finally confirm WTGs positions. A Support Vector Machine (SVM) (Hsu, Chan & Ling 2003) automatic learning algorithm has been used as the supervised classification method. Although SVM has been widely used in remote sensing applications, no previous experience has been retrieved in literature about applying it to WTGs identification. SVM algorithm is particularly appealing in remote sensing applications due to its ability to generalize well even with limited training samples, whose acquisition is often a critical and time-expensive phase of the supervised classification methods (Mountrakis, Jungho & Ogole 2011). In particular, SVM is a supervised non-parametric statistical learning technique, which, differently from other classification algorithms, makes no assumption on the underlying data distribution, and is thus characterized by high self–adaptability (Chi, Feng & Bruzzone 2008), often providing good results for spectrally complex images and higher classification accuracies than traditional methods (Mantero, Moser & Serpico 2005). A multiclass SVM classifier has been used in this work to classify the study area in foundation areas, roads (mainly unpaved) and vegetated or not vegetated non-urban surfaces from the training samples (nearly 10% of the whole WTGs positions dataset). Since no established heuristics exist for SVM pa-

Fig. 2 - a) actual positions (black points) of the wind turbines of a wind field and b) detection results in an example location of the study area (Villaurbana – OR).

rameters selection (Chi, Feng & Bruzzone 2008), their values have been set through a trial and error approach.
Objects classified as WTGs have been then processed through a GIS spatial analysis. Only polygons having an area smaller than 4000 m2, considered as a maximum extension representative of WTGs foundation areas, have been retained for further processing. Due to the high spectral similarity of the foundation areas with other land cover elements, only a portion of the polygons derived from classification is actually representative of WTGs positions, despite they are dimensionally filtered out.
Under the hypothesis that wind field coordinates are available (e.g. wind turbine centroid or connection cabin), through a probabilistic approach polygons nearer to the centroid can be retained more representative of WTGs respect to more distant polygons, thus reducing the number of polygons to be subjected to manual check. The research area could be further limited within a buffer centered on the centroid and having radius varying with the declared plant nominal power. Otherwise WTGs research should be manually performed by scanning all polygons belonging to the municipality where the wind field is installed.
The whole applied methodology is summarized in DIDA: Fig. 1.

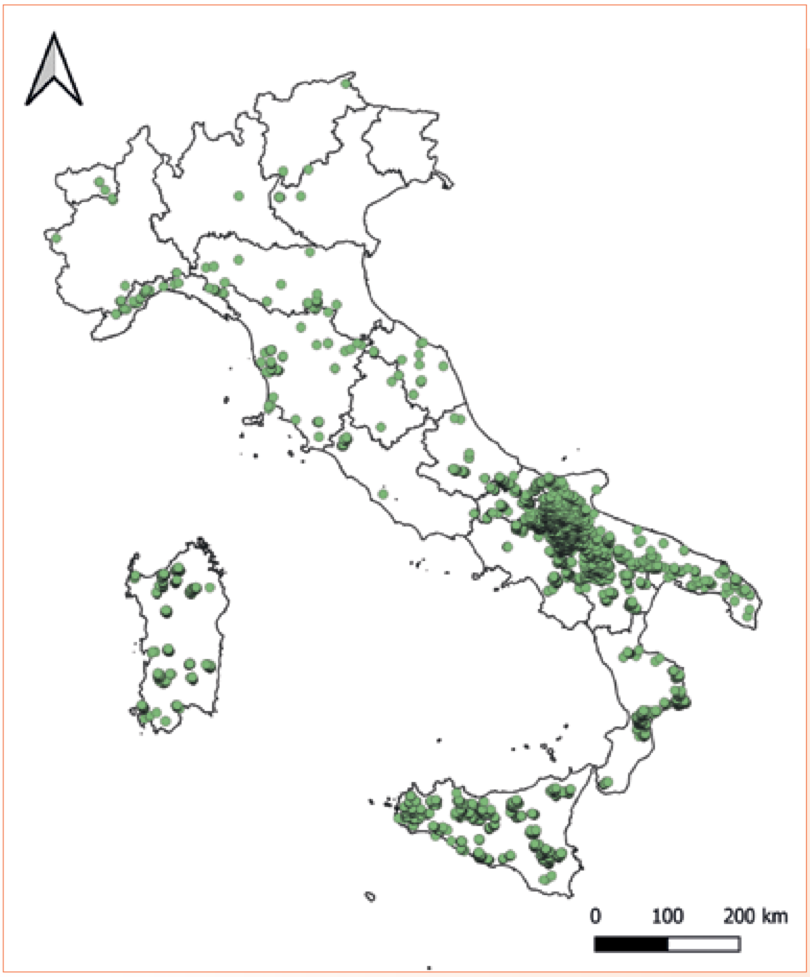

Fig. 3 - National distribution of database WTGs.

Main outcomes

The applied methodology over the case study area has shown positive results, with a probability of detection on the validation sample of 86%. a shows a detail of the actual position of the wind turbines for the Villaurbana (OR) wind field, while b shows a detail of detection results.

Missed detections (14% probability) mainly include wind turbines located in masked and cloud shaded areas. Despite the above described spatial analysis, the methodology produces a considerable number of false positives, which should be removed by the operator's manual intervention by comparison with high resolution images. This phase is not particularly demanding as false detections are mainly clustered and located in areas with a prevalence of uncultivated agricultural areas, exposed bare rocks, unpaved roads or small bright roofs.

Extension of the methodology to the national territory

Given the positive results provided by the feasibility study, the proposed approach based on satellite image processing has been applied for regions with a relevant development in wind power plants (Abruzzo, Basilicata, Calabria, Campania, Molise, Apulia, Sardinia and Sicily), using the most recent winter/early spring Sentinel-2 images. As the wind field locations (centroid coordinates) were not available for the whole national territory, the spatial analysis phase only included the dimensional filtering of polygons (< 4000 $m^{2)}$, neglecting the probabilistic selection based on distances.

For the remaining regions, those with a very scarce development in wind power plants (i.e. most of Northern and Central Italy), WTGs have been manually retrieved from Google or Bing high spatial resolution images knowing the installation municipality of wind power plants and the occasional support of OSM.
Currently, the wind turbine dataset contains 8638 positions confirmed or newly identified through the satellite-based approach. All the new detected positions have been assigned technical attributes (e.g. wind turbine technical characteristics and power) derived from the wind plants data base provided by ANEV.
A regional detail of wind turbines identification results is shown in DIDA: Fig. 4.
Besides, more than 900 small WTGs (power < 200 kW) have been detected by chance, but a systematic effort to map small and micro wind turbines, which are generally isolated and scattered throughout the territory, went beyond the aims of this work and is left to future research.
Finally, we evaluated the consistency of the obtained WTGs database by comparison with the statistical regional data yearly published by GSE (Rapporto Statistico GSE 2019). This validation has shown a difference of nearly -98,4 MW throughout the whole country, meaning that nearly 98% of the official total installed power is represented. The consistency of the results highlights the effectiveness of the proposed methodology to map wind turbines from medium resolution satellite images. Regional overestimations or underestimations could be respectively due to small WTGs, which are not included in our database, or to missed identification of dismantled or repowered wind turbines.

Conclusions and possible improvements

Resources availability assessment plays an important role in renewable energy management and related development scenarios for the achievement of decarbonization objectives. Together with the more traditional methodologies for the extraction and analysis of territorial data useful for RES management, images acquired by sensors installed on board EO satellites are effectively used as recognition tools and detailed thematic mapping.
Justified by a lack of homogeneous geolocalized information, in this work a methodology to map onshore wind turbine positions over the national territory is described. This aim has been achieved through a semi-automatic approach based on 10m Sentinel-2 satellite images processing for regions with a consistent increase in wind turbines installation, while a manual identification method based on high resolution data for regions with a moderate increase in wind turbines installations has been applied.
To the authors' knowledge at the time of writing, this work constitutes the first attempt to update a geodatabase of all wind turbines in Italy using EO satellite products.
Although the methods could surely benefit from methodological refinements which could limit false positive detections, such as taking into account wind fields installation technical requirements (e.g. terrain morphology, presence of service roads), and a completely automatic approach should be desired for consecutive updates, positive results obtained within the methodology validation phase and the comparison with GSE data confirm that medium resolution satellite images considerably facilitate wind turbines localization on wide areas even starting from few geographic information (e.g. the municipality where wind farms are installed) and help pointing out recent wind turbines repowering operations using old foundation areas for new installations.

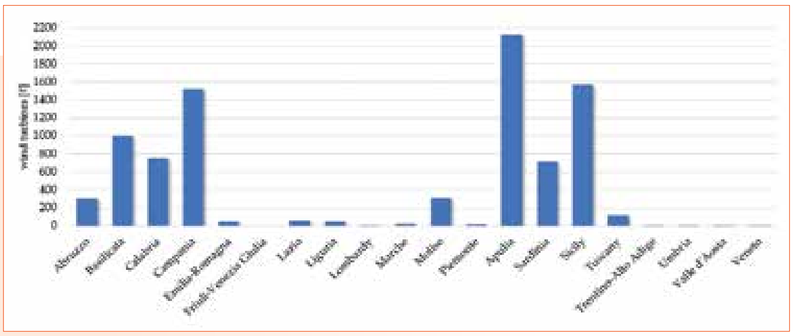

Fig. 4 - Regional distribution of database WTGs.

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Disclosures
The authors declare no conflict of interest.

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KEYWORDS

Wind turbines mapping; optical remote sensing; image classification; renewable energy resources

ABSTRACT

Resources availability assessment is essential for renewable energy planning and related development scenarios for the achievement of decarbonisation objectives. As national information about wind farm projects often lack a geographic connotation, the definition of a rapid and extensive approach for mapping installed wind turbines is a priority. The currently available free medium resolution satellite data considerably facilitate WTGs localization and represent a valid instrument to retrieve input data to models and applications for renewable energy sources spatial planning.

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