Reversing visibility analysis: Towards an accelerated *a priori* assessment of landscape impacts of renewable energy projects

Romanos Ioannidis[1,*], **Nikos Mamassis**[1], **Andreas Efstratiadis**[1], **and Demetris Koutsoyiannis**[1]

1. Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Heroon Polytechniou 5, 157 80 Zografou, Greece

Abstract

Impacts to landscapes have been identified as major drivers of social opposition against renewable energy projects. We investigate how the process of mitigating landscape impacts can be improved and accelerated, through a re-conceptualization of visibility analysis.

In their conventional format, visibility analyses cannot be implemented in early planning phases as they require the finalized locations of projects as input. Thus, visual impacts to landscapes cannot be assessed until late in development, when licensing procedures have already begun and projects' locations have already been finalized. In order to overcome this issue and facilitate the earlier identification of impactful projects we investigate the reversal of visibility analyses. By shifting the focus of the analyses from the infrastructure that generates visual impacts to the areas that have to be protected from these impacts, visibility analyses no longer require projects' locations as input. This methodological shift is initially investigated theoretically and then practically, in the region of Thessaly, Greece, computing Reverse - Zones of Theoretical Visibility (R-ZTVs) for important landscape elements of the region, in order to then project visual impacts to them by planned wind energy projects.

It was demonstrated that reversing visibility analyses (a) enables the creation of R-ZTV-type maps that facilitate the anticipation of landscape impacts of projects from earlier planning stages and (b) discards the requirement for individual visibility analyses for each new project, thus accelerating project development. Furthermore, R-ZTV maps can be utilized in participatory planning processes or be used independently by projects' investors and by stakeholders in landscape protection.

Highlights:

- Reverse visibility analysis enables the early projection of landscape impacts
- R-ZTV maps enable the integration of visibility analysis in multi-criteria planning
- Once computed, R-ZTV maps can be used for multiple projects thus accelerating EIA
- R-ZTV maps can reduce project investment risks associated with public opposition
- R-ZTV maps can be co-produced with local communities through participatory planning

Keywords:

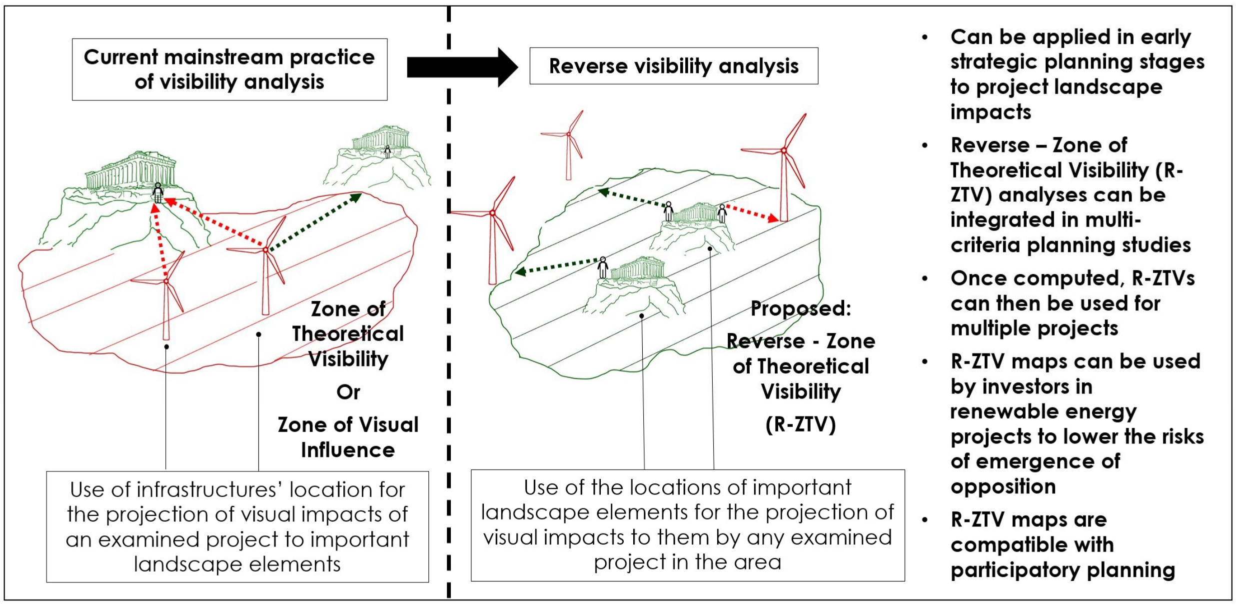
* = Corresponding author details, romanosioannidis@mail.ntua.gr

Visibility analysis, reverse viewshed, landscape impacts, zone of theoretical visibility (ZTV), multi-criteria planning, renewable energy, wind turbines, opposition, cultural heritage

Abbreviations:

RE – Renewable Energy, Zone of Theoretical Visibility (ZTV), R-ZTV – Reverse Zone of Theoretical Visibility, DEM – Digital Elevation Model, EIA – Environmental Impact Assessment and GIS – Geographic Information System

Graphical Abstract:



1 Introduction

In the last two decades, the expansion of renewable energy (RE) has imposed extensive land use requirements [1–4] and resulted to major transformations of the visual character of landscapes [5–8]. Since the design of the RE equipment is mostly predefined by industrial specifications and cannot be adapted to architectural traditions and local landscape features, these projects have been strongly criticized for industrializing landscapes [9]. This is primarily the case for wind turbines, but also applies to photovoltaic solar panels, and to a lesser extent to hydroelectric projects [10–12]. Following the definition of landscape by the European Landscape Convention [13], i.e. "landscape is part of the land, as perceived by local people or visitors, which evolves through time as a result of being acted upon by natural forces and human beings", the industrialization of landscapes by infrastructure can be the cause of negative perception due to unwanted cultural, environmental and aesthetic transformations to landscapes. In the case of RE, landscape impacts have been identified as one of the major motivators for opposition against new projects [6,9,14]. Indicatively, In Europe, the conflict between RE development and landscape quality is demonstrated in the following two ways:

A) Public opposition against RE on landscape-protection grounds has significantly delayed their desirable penetration into the energy mix. Even though RE has been associated with significant impacts to the natural [14], cultural [15,16] and aesthetic [17,18] character of landscapes, so far spatial planning of RE systems for the mitigation of landscape impacts has been given a secondary role [19]. Thus, landscape impacts have become a major cause of public opposition and, consequently, of delays in the pan-European effort to make renewables the key player in energy production and moving beyond the goal of a minimum 32% share for RE in the energy mix, under the so-called "2030 Climate and Energy Framework". In Greece, for example, there has been significant opposition to wind energy projects from activist initiatives [20] and local communities [9] that has even escalated to clashes between police and opposing groups. The installed capacity of the major projects that have been challenged, using various arguments – including landscape impacts – adds up to more than 1200 MW [9]. For comparison, in 2020 Greece was 3512 MW below [21] its target for 7050 MW for wind power capacity in 2030 [22]. Similarly, in the rest of Europe, landscape quality degradation due to RE has been identified as a major issue [6,8] that has arguably contributed to opposition and that is eventually associated with the failure of more than half of the member states in meeting RE development targets based on the EU directives.

B) While the penetration of RE is a broadly desirable goal, a non-controllable expansion of such projects is expected to cause significant transformations to European landscapes. Arguably, Europe has a very high density of scenic landscapes that are associated with architectural and cultural monuments and historical settlements. The protection of this heritage is of high priority not only for its preservation and its connection to the sense of place, cultural identity and quality of life of European citizens, but also due to its direct link with touristic and, consequently, economic development. Using one of the most informative quantifications for the extents of visual intrusion of RE projects to landscapes, viewshed analysis, it was estimated that the portion of the land area from which wind turbines were clearly visible was 18% in Spain, 21% in the Netherlands and even 96% in Denmark (Jutland region) [23–25]. Such extensive impacts require specific mitigation strategies, especially when they are carried out in the vicinity of protected cultural [26] or natural landscapes [27], and also given that suitable locations for siting RE projects are currently diminishing.

From a social perspective, RE is subject to a major contradiction. On the one hand, there seems to be a general support for renewables [28–30], yet on the other there are strong oppositions movements against numerous projects under development [9]. Given that literature has disapproved of the well-known NIMBY ("not in my back yard") disposition as the primary source of social oppositions against RE [30–34], their root should also be looked for in planning methods and procedures instead of public attitudes. Thus far, large-scale multi-criteria analyses have supported the siting decisions for RE projects based on technical issues, such as resource availability, distance from the electricity grid and the road network, and various socio-environmental restrictions [35–41]. However, these analyses rarely account for landscape protection and when they do so, they have not managed to fully integrate calculations of project visibility and visual impacts in their assessments [42], with very rare exceptions [28]. Of course, the visibility of RE projects is not always perceived negatively. Actually, it is reported that considerable percentages of observers have neutral or even positive perception in the view of RE works, due to aesthetic [43,44], cultural [45,46] or other reasons [47,48]. Indicatively, in the review of relevant literature in 2020, it was found that 34% of articles investigating landscape impacts of wind energy works also included references to positive perception of the examined landscape transformations and that this percentage dropped to 22% for solar energy. Interestingly, in the case of hydroelectric energy, the positive views were actually more than the negative ones [9]. Nevertheless, it is made clear from these percentages that, especially in the case of wind and solar energy, negative opinions seem to be predominant.

For the minimization of this footprint through planning and the mitigation of landscape impacts, visibility analysis has been established as the best practice [19,49,50]. In this vein, it can be generally hypothesized that the lack of utilization of such analyses at the early planning stages of RE projects is a significant limitation to the projection, assessment and mitigation of landscape impacts, and may be responsible for such strong public oppositions [9]. The present study investigates the reversal of visibility analyses as a methodological twist that can enable the earlier identification and mitigation of potential landscape impacts of new projects.

The motivation of this study lies in the facilitation of a more sustainable development of RE through improved methods for the mitigation of landscapes impacts. In this regard, preemptive reverse visibility analysis is proposed, by employing the concept of Reverse - Zones of Theoretical Visibility (R-ZTVs), in order to consult the siting of RE infrastructures, in terms of minimizing their landscape impacts, at early stages of their planning or conception. The method aims at improving the mitigation of impacts to the cultural, natural and aesthetic character of landscapes, as it is perceived by humans, and thus reducing associated impacts and public opposition.

2 Materials and methods

2.1 Visibility analysis in spatial planning of renewable energy – Current practice

With the emergence of landscape impacts as a major cause of opposition to RE, significant effort has been put into their mitigation, through planning policy and targeted guidelines [23,24,51,52]. In this endeavor, various visual impact assessment (VIA) methods [42] have been developed. Among them, visibility analysis has been established as the basis for the quantitative assessment of landscape impacts [53]; e.g. the prominent Scottish SNH guidance [49,51] and the Spanish Method [19,50]. Arguably, the most widely used mapping method for visual impacts of RE projects in the academic literature [9,54], planning practice [49,55] and institutional reports [23,56,57], are the so-called Zones of Theoretical Visibility [58]. A ZTV is defined as the sum of all locations from which particular examined objects are theoretically visible, and is calculated with the use of spatial analysis tools of Geographic Information Systems (GIS). In this respect, the locations of an array of examined objects that generate visual impacts, e.g., wind turbines, are inserted in a digital elevation (or terrain) model, and a line-of-sight test is carried out, producing a binary map of locations from which the objects are visible and the locations from which they are not. In a more in-depth review of terminology and methodology, ZTV mapping has also been recognized as similar [58] or interchangeable [59] with the so called Zones of Visual Influence/Impact [60]. Furthermore, from our literature review, it can be noticed that the ZTV method shares the common foundation of requiring the calculation of cumulative viewshed [24] with various other methods for mapping the visibility of projects, e.g. maps of visually affected areas [23,25] or visual influence [56].

2.2 Reflections on the timing of visibility analyses

In spite of the identification of landscape impacts of RE as one of the major causes for social opposition against renewable energy [6,9,14], the quantitative tools for their assessment have been so far generally left out from the early stages of RE planning. Indicatively, ZTV analysis, which is the most widely utilized quantitative method for visual impact quantification, has been implemented not earlier than within the Environmental Impact Assessment (EIA) studies, which typically follow the technical, i.e., planning and design, ones. In the spatial scale of EIA, however, such analysis loses its capacity to act as a decision support tool that can detect siting alternatives, in order to mitigate potential landscape impacts, and is downgraded to a modelling procedure for assessing the impacts of a particular project in its finalized location. Therefore, at this phase, visibility analysis should be considered a principally *ad hoc* calculation, for the evaluation of landscape impacts of projects and after their preliminary or final siting [19,49,50]**.** This is the case especially with wind energy projects, since wind turbines cannot be concealed in the natural terrain through short-distance siting adjustments, which are the sole available option at that stage of planning; in the case of solar panels though, this may be feasible [9,61,62]. Furthermore, even though ZTV-type visibility analyses can be carried out in large spatial scales, this has only been done in *a posteriori* studies, for the assessment of cumulative visual impacts of already constructed RE projects, at the regional [24,54,57,63] or national scale [23,56]. It is possible that a ZTV-type visibility analysis can also be carried out *a priori*, but only under the condition that hypothetical-potential locations for examined projects have to be determined beforehand, such us in the study of Rodrigues et al. [25].

Overall, in the investigation of the early-stage and large-spatial-scale planning analyses [35,36] or strategic environmental impact assessment studies [64] that support decisions on RE siting studies, it can be observed that ZTV and viewshed analyses have been hardly utilized. Indicatively, in the systematic review by Shao et al. [35] on multi-criteria decision making methods, only eight out of 85 studies mentioned visual impacts, and only three of them actually included any form of viewshed or visibility analysis [28,65,66]. In particular, only Tegou et al. [28] have explicitly utilized viewshed analysis in the planning procedure, by employing an interesting mixture of reverse viewshed calculations and buffer zones, to produce a generic map for visual impact assessment of potential projects in the examined island. In another review of spatial planning of renewable energy [36], from 12 compiled studies only two discuss the importance of integrating visual impact assessment within RE planning [67,68], yet without making reference to practical methods for addressing this issue.

On the other hand, other multi-criteria approaches that actually consider visual impacts, are subject to important limitations. For example, in the studies by Daskalou et al. and Gigović et al. [69,70], the evaluation of the visibility criterion is simplified to the application of buffer zones around protected areas, without the use of viewshed analyses. In the analysis by Kazak et al. [46], visual impacts were evaluated in more detail, by using viewshed-type visibility analysis; nevertheless, its implementation was limited to the examination of already highlighted potential positions for projects. This is reasonable, since viewshed analysis requires as input the siting of the proposed projects. Altogether, the integration of landscape impact indexes informed by complete visibility analyses is found to be almost completely absent from early-stage and large-scale spatial planning analyses, where the project locations are not yet specified.

2.3 Reversing visibility analyses

Even though there is precedent for visual impact assessment with predictive characteristics [28,71,72], which could be utilized to handle the above-mentioned issues, the significance and methodological differentiation of these tools has not been emphasized, leading to their scarce and rather inconsistent application, as described in Section 2.2. In order to support the transition from the current practice of *a posteriori* landscape impact assessment, i.e., after the design phase, to *a priori* assessment, i.e., in early planning stages, the essential adaptations of existing landscape impact assessment methods need to be explicitly explained and realized.

The major shortcoming of mainstream visibility analyses that makes the early prediction of landscape impacts too difficult, is that they require project-specific information as their input [53]; namely, the finalized layout of the RE system and the exact micro-siting of its components (e.g., wind turbines, solar panels) is required in order to carry out viewshed analyses. In contrast, a map of projected landscape impacts that would be compatible with the format of spatial planning studies would need to be generic and independent of project-specific information, as are all spatial data that are commonly used in such studies, such as spatial layers on resource availability, buffer distances from road and electricity grids, etc. [28,35,73]. These are all generic spatial information that can be used to guide the planning of RE projects in advance, without requiring a finalized design of RE infrastructures.

To overcome this obstacle, we propose reversing the running paradigm of visibility analysis, by shifting their focus from the proposed infrastructure to the landscape sites that need to be protected. In conventional Zone of Theoretical Visibility (ZTV) method [23–25], the RE system is the focal point of the analysis and the generated map represents an extent around each component. Conversely, we propose the so-called Reverse Zone of Theoretical Visibility (R-ZTV) analysis, in which the focal points are the protected landscape elements themselves. Thus, an R-ZTV map illustrates all the locations around protected landscape elements from where a given type of RE infrastructure would be visible to those elements (Figure 1). In GIS terms, ZTV is based on calculations of viewshed, while R-ZTV is based on reverse viewshed.

The use of ZTVs in planning, consists of (a) computing the ZTV using the predetermined location of the RE project of interest as input and then (b) looking for potential overlap of the ZTV with important landscape elements, which would indicate the generation of significant visual impacts. In the proposed concept, R-ZTVs are a priori computed for selected landscape elements and then these R-ZTV areas can be "avoided" during the planning procedure, in order to protect the selected landscape elements from non-desirable visual impacts. In hindsight, it is reasonable that landscape elements should be the focal point of the analysis, during the planning procedure, since they are static and in fixed positions, while the RE projects under study are the ones that can be moved and be sited according to the results of R-ZTV analysis.

By means of R-ZTV maps, visibility analysis can be utilized preemptively to indicate the areas to be preferred for the installation of RE projects, under the primal (yet not exclusive) criterion of minimizing landscape impacts. The protected landscape elements to be included in the calculation of R-ZTV maps can include any selection of areas and landscape features of cultural or natural significance that is considered important for the protections of landscapes' quality: e.g. historical or archeological sites, traditional settlements [74], tourism-related infrastructure [75,76], etc. It also has to be noted that in in the context of strategic planning, the spatial scale of R-ZTV maps should be relatively extensive, since such studies are by definition carried out across large scales; e.g. multi-criteria planning analyses are usually implemented at the regional or national scale [35,36,73,77]. The scale of application is another key difference with typical visibility analyses, which essentially refers to the specific project-site scale. Through reversing visibility analyses, the implementation of visibility analysis in large spatial scales becomes possible, as it is no longer dependent on the siting details of single projects, but can be carried out for multiple landscape elements at once, stretching over whole regions or even countries. Contemporary spatial planning frameworks usually include mapping of such elements at these spatial scales, and thus can be used as inputs to R-ZTV analyses.

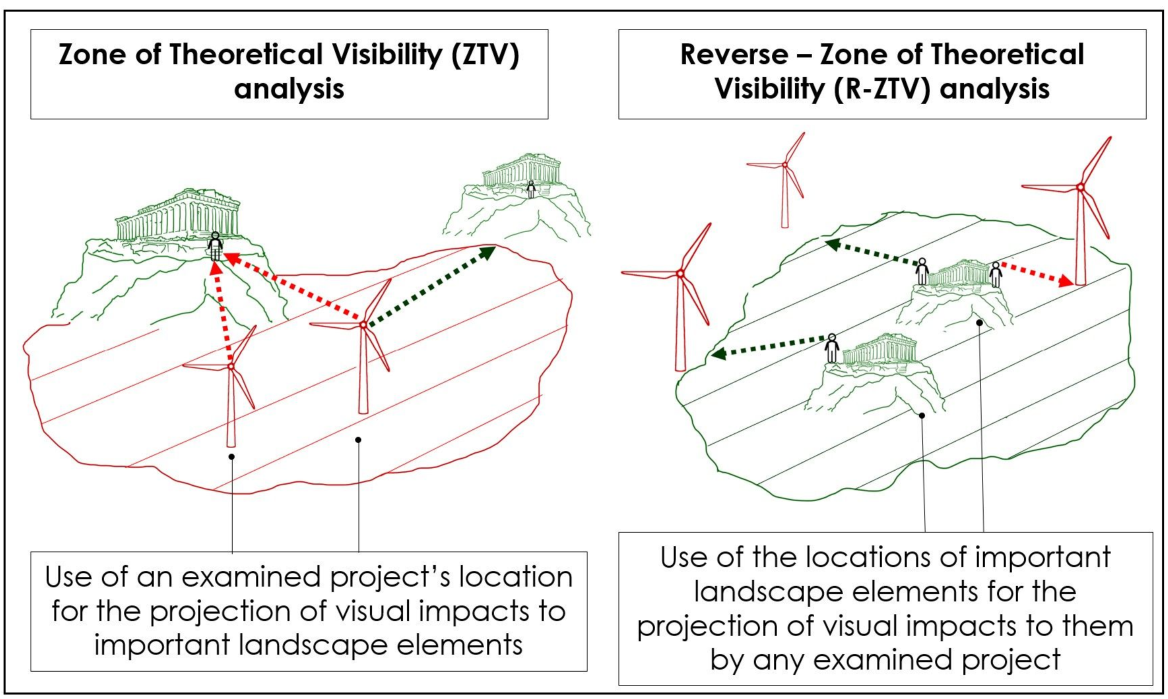


Figure 1 Graphical presentation of differences of conventional ZTV vs. proposed R-ZTV analysis.

The early projection of landscape impacts of RE projects can facilitate the timely dismissal of problematic locations and thus contribute both to the mitigation of landscape impacts and the reduction of associated public opposition. In theory, maps that expedite the prediction of visual impacts could be used for guidance in the sitting of projects at the initial development stages before conflicts emerge, that way lowering the risks of investment plans [78] and limiting the time and effort that is lost when projects are rejected at the stage of EIA. For example, it is a common regulatory requirement for proposed projects that mean wind speeds have been recorded in the examined location for more than one year and that complete business plans have been submitted [69,79]; all this effort is wasted if the projects are later rejected in the stage of EIA, which is quite often the case in Greece [79].

2.4 Implementation of R-ZTV analysis at the regional scale: Case of wind energy development in the Region of Thessaly

In order to reveal the methodological requirements of reversing visibility analyses within large-scale RE planning, the proposed method was applied in the region of Thessaly, Central Greece, which extends over an area of 14 000 km^2. In this context, R-ZTV maps were generated for already specified important landscape elements, in order to be used for the projection of impacts from proposed wind energy projects. The region of Thessaly was selected due to two major reasons. On the one hand, because various wind energy projects, at different stages of maturity, are already planned [21]. On the other hand, because it is one the few regions of Greece having established a complete Regional Spatial Planning Framework, mapping various locations and areas of importance for the regional landscape [80]. The associated data are available through an online GIS platform (http://mapsportal.ypen.gr/maps/694).

The first step for the production of R-ZTVs for wind energy projects in Thessaly was the implementation of reverse viewshed analyses for the important landscape features of the region. The computation of reverse viewshed were selected to be binary, or Boolean – as they are also called, in order to maintain the reciprocity between viewshed and reverse viewshed calculation [81]. The required inputs in GIS were the digital elevation model (DEM), the observer's and observed object's height and the maximum distance of the observer's visibility. In our study, we utilized a DEM of the region Thessaly with a cell size of 25 m, the height of the observer was set at two meters above the z-value of the observation point, and the height of the wind turbines was set at 90 m, which is representative of the size of turbine towers used in recent wind energy projects in Greece.

The maximum distance of visibility, also called visibility threshold or discernibility range, was identified as the most important parameter of reverse viewshed analysis, thus requiring a thorough justification over its selection. The visibility threshold defines the radius of the analysis, i.e., the distance limit used when investigating the areas that are visible from each observation point, and therefore has a significant impact on the size of generated viewshed zones. In the literature, the visibility of a wind turbine under clear weather conditions is reported as long as 58 [55] or 42 km [82]. On the other hand, the estimations of distances of moderate visibility of wind turbines exhibit a wide range from 3 to 40 km [55,59,83,84]. We should remark that for distances less than 2 to 3 km, the visibility is considered dominant [59,83,85]. In recent studies, it is more common that distances on the highest end of the spectrum are preferred. For instance, Sullivan et al. [55] propose distances from 16 to 48 km, Bishop [84] 20 km, and Vissering et al. [86] from 16 to 40 km. Moreover, in the latest version of the acclaimed SNH guidelines [9], the use of a 35 km distance is proposed for ZTV analyses of modern wind turbines from 101 to 130 m height. In this study, two applications of reverse viewshed were carried out, one for a 10 km and one of 30 km visibility threshold, in an attempt to cover the broad range of visual thresholds that are reported in the literature, and also taking into account that these are the most common ones in large-scale ZTV-type analyses [9].

In regard to the data sets used to represent the protected landscape elements in the reverse viewshed calculations, the following spatial layers were selected from the Regional Spatial Planning Framework of Thessaly [80], as they were identified to be relevant to the protection of the cultural and natural landscape of the Region: (i) "Archaeology/landscape" in which the delimited archeological sites of the region are mapped, (ii) "Cultural routes" that includes a section of the E4 European long distance path as well as other proposed routes of natural and cultural interest, (iii) "Traditional settlements", and (iv) "Natural/Cultural Heritage and Landscape" that includes proposed important lands of cultural heritage and natural environment (iv-a) as well as landmarks of international, national or regional touristic interest (iv-b). The above-mentioned landscape elements of the region of Thessaly are depicted in Figure 2.

Since the spatial information for the protected landscape elements was represented in various forms in GIS (points, polylines and polygons), different assumptions had to be made in reverse viewshed computations, regarding the position of theoretical observers within these areas. The basic logic for the placement of theoretical observers was the depiction of locations of indicative visitors within the examined areas. In the case of the polygon layer (layer i), theoretical observers were placed in each angle of their perimeter as well as the mid points of each side. The analysis was not carried out for theoretical observer points within the polygons, since these areas were considered to be by definition less preferable for wind energy projects, provided that they are already demarcated as archaeological sites-landscapes. In the case of the polyline layer (layer ii), theoretical observers were placed every 500 m along the length of the paths. Finally, in the case of point-type layers (layers iii and iv), the points themselves were used as locations of the theoretical observers.

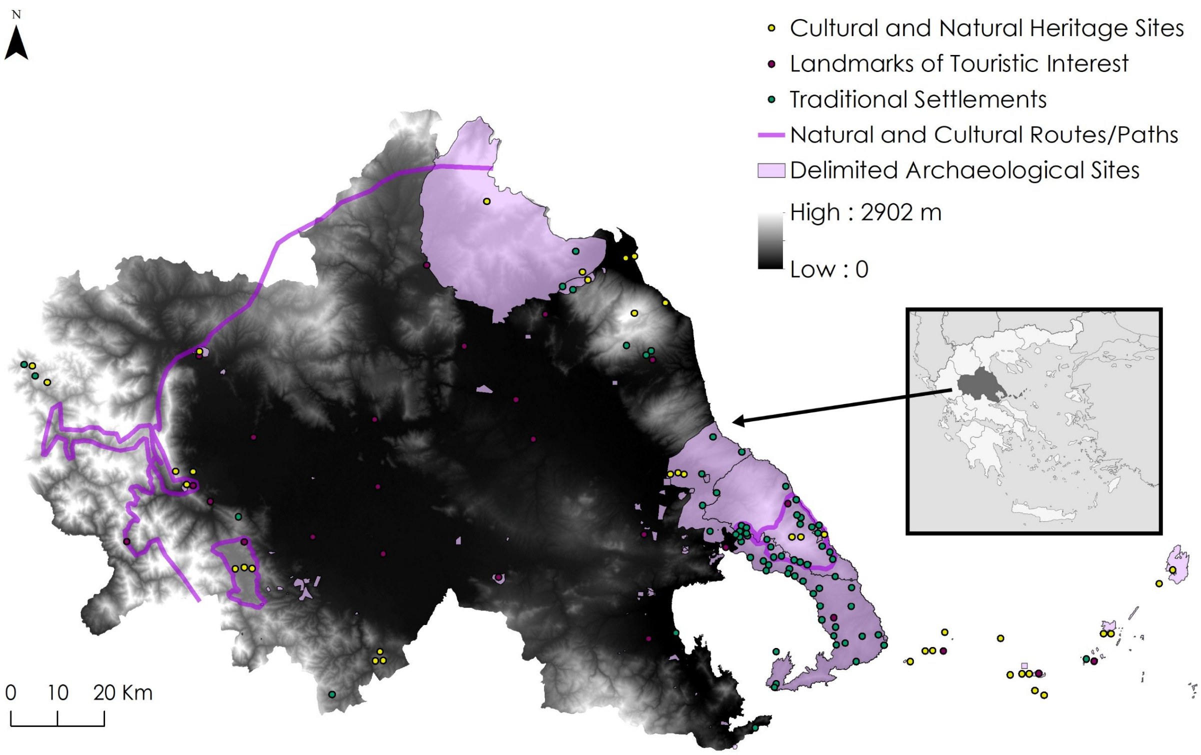


Figure 2 Map of the landscape elements of the region of Thessaly that were used in the R-ZTV analysis. Source of data: Regional Spatial Planning Framework of Thessaly [80].

3 Results

3.1.1 Reverse Zone of Theoretical Visibility (R-ZTV) maps

The reverse viewshed calculations for all examined spatial data were merged together in the final R-ZTV maps. The generated R-ZTV maps and the results of the individual reverse viewshed analyses that were carried out for each of the protected landscape elements are presented in Figure 3. The colored areas demarcate all locations from which an installed wind turbine would be visible to any of the protected elements. The results of all reverse viewshed computations for the five types of landscape elements of Figure 2 are presented as spatial layers with a 50% transparency in Figure 3, so that the overlap of reverse viewsheds can be discernible in the cumulative R-ZTV map.

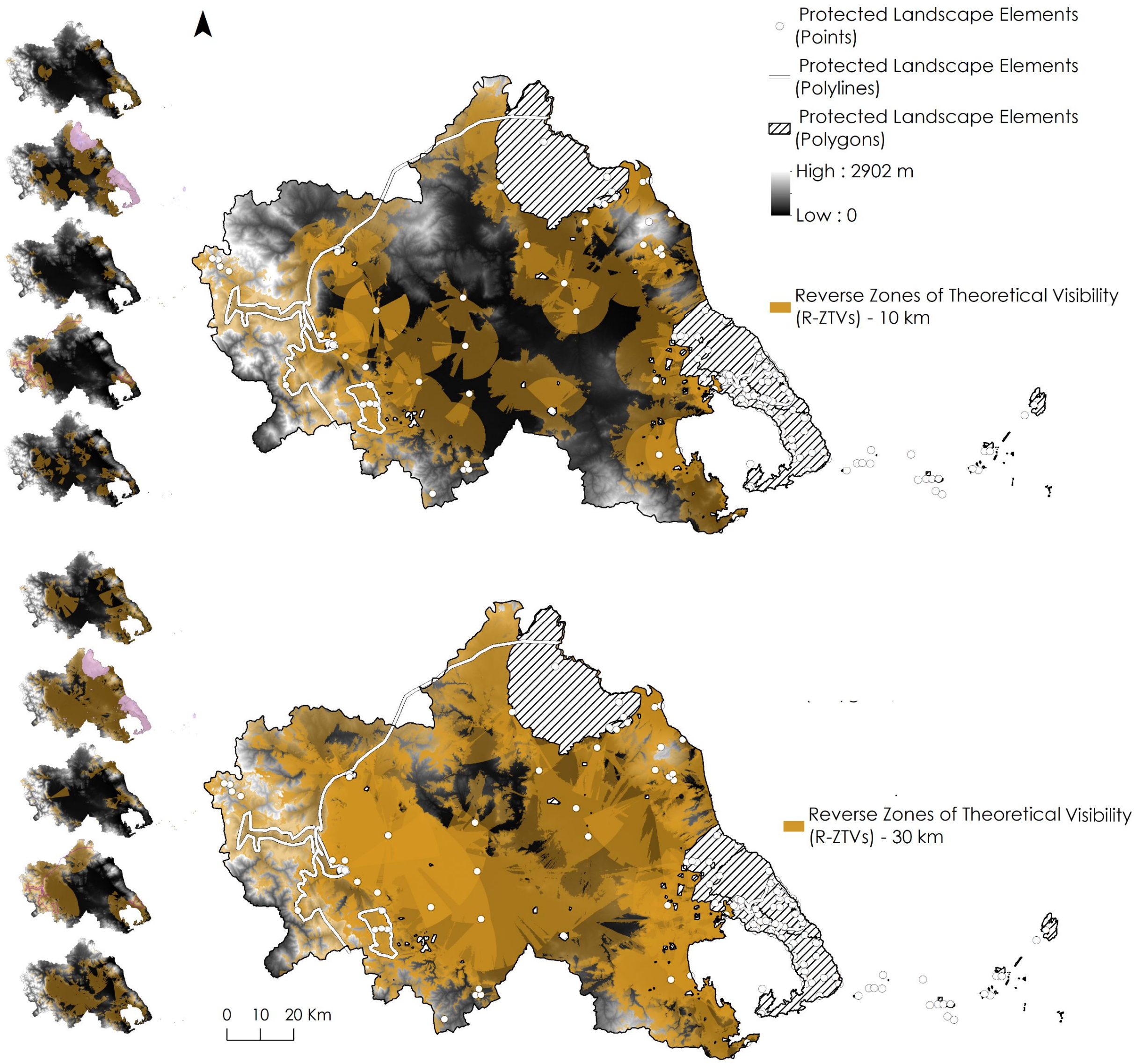


Figure 3 R-ZTVs analysis of protected landscape elements in the region of Thessaly for the case of wind energy projects (right), and reverse viewshed calculations for examined landscape elements (left). The upper and lower maps refer to visibility thresholds of 10 and 30 km, respectively.

In theory, the areas calculated through R-ZTV analysis could potentially expand to outside the borders of the examined region, as presented in Figure 4. It is thus demonstrated that offshore projects or projects in adjacent regions could also have some impact to the protected landscape elements within the region of Thessaly. However, in the context of this study, the investigation was focused to the planning of projects within the borders of the region and thus within the mainland. This was both due to limited data availability for adjacent regions and lack of information regarding the emergent field of marine spatial planning [87].

Nevertheless, to our knowledge, the exploitation of the actually large offshore wind energy potential of the country involves marine areas thar are far away from the region of interest [88].

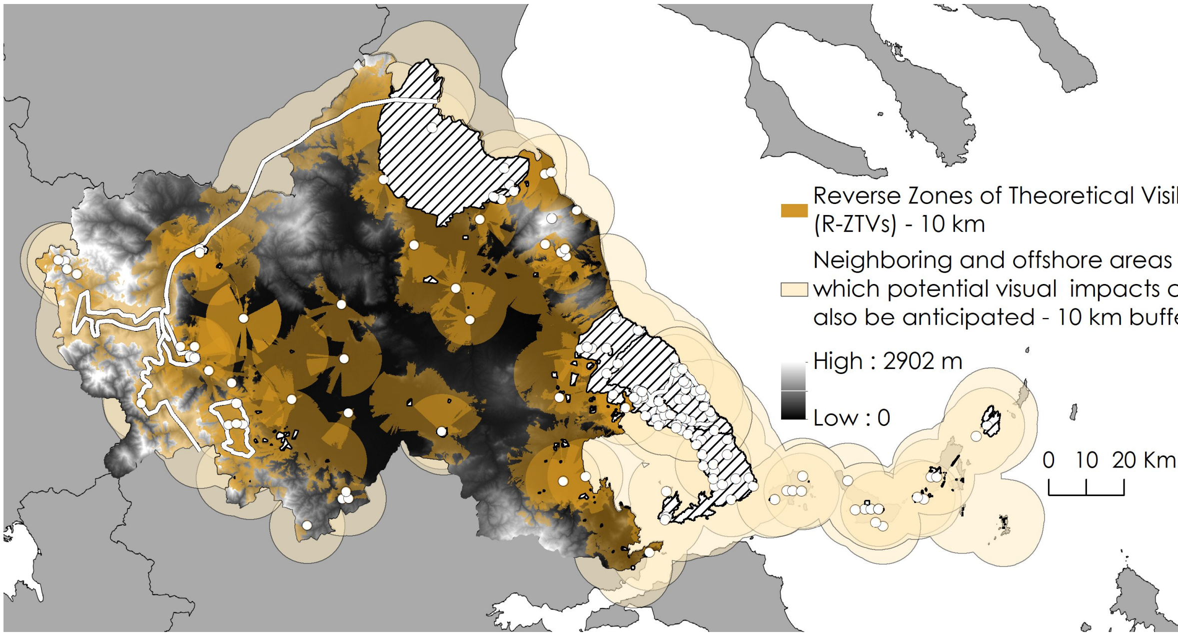


Figure 4 Expansion of R-ZTVs calculated for the protected landscape elements in the region of Thessaly (Figure 3) beyond the region's borders to offshore areas and to adjacent regions with the use of 10 km buffer zones.

3.1.2 Utilization of R-ZTV maps in spatial planning

The overall purpose of R-ZTV maps is their utilization for the *a priori* assessment of landscape impacts of renewable energy projects, with emphasis on early-stage spatial planning analyses and decision making. In this section, the method is investigated in regard to its capacity to provide information than can support these aims and facilitate the mitigation of landscape impacts.

Initially, we investigate how R-ZTVs can be optimally mapped, in order to be compatible with multi-criteria spatial planning analyses and, more broadly, to be comprehensible and useful to stakeholders in the mitigation of landscape impacts of renewable energy.

As was expected, from the results of section 3.1.1 we conclude that the visibility threshold used in the reverse viewshed analyses has a significant influence on the size of the generated R-ZTVs. In particular, as shown in Figure 3, with the use of a 10 km visibility threshold, 37% of the land area of the region of Thessaly would be suitable for the installation of new wind energy projects without causing any visual impact to the protected landscape elements of the region. However, this percentage is reduced to only 12% of the region if a 30 km visibility threshold is applied. As expected, the 10 km R-ZTVs allows for a wider freedom for site selection under the goal of minimizing landscape impacts. However, since both visibility thresholds (10 or 30 km) have been used widely in literature [9], and also given that various other thresholds are also used, as discussed in section 2, it is clear that R-ZTVs should be compatible with both large and small visibility thresholds, in order to be useful in the spatial planning of RE.

To this aim, two different logics of implementation can be proposed, depending on the size of the visibility threshold:

(i) When smaller visibility thresholds are applied, such as 10 km, R-ZTVs can be used as a binary spatial layer demonstrating in which spatial units the installation of RE infrastructure would cause visual impacts to important landscape elements, as demonstrated in Figure 5. This binary R-ZTV is generated through the union of the reverse viewsheds of the protected landscape elements.

(ii) When larger visibility thresholds are adopted, such as 30 km, R-ZTVs can be used as a weighted spatial layer in which each pixel is characterized by the level of visual impact that would be generated to protected landscape elements if RE infrastructure was installed within it. The weighted R-ZTVs can be generated, for example, by overlaying the reverse viewsheds of protected landscape elements and giving each pixel a weight according to the number of overlaying reverse viewsheds within it. In the example of Figure 6, we present an adjusted R-ZTV map for wind energy projects in Thessaly, weighted by the number of reverse viewsheds of the protected landscape elements that overlay in each cell of the map.

As a first assessment of the utility of R-ZTVs in a real-world planning scenario, the R-ZTV maps of Figures 5 and 6 were used to evaluate the potential impacts of proposed wind energy projects in the region of Thessaly. Spatial data on wind energy projects in various stages of development were collected from the Greek Regulatory Authority for Energy (RAE) [21]. We highlight that the examined wind energy projects were already in advanced stages of their licensing procedure, while R-ZTV maps can also be used even in earlier stages before the licensing processes of projects begin. However, even in this case the use of R-ZTV maps is again useful as it discards the requirement for carrying out individual visibility studies for all the examined projects, since now one map (e.g., the maps of Figures 5 or 6) can be used for the evaluation of the visual impacts of all of them at once (Figure 7).

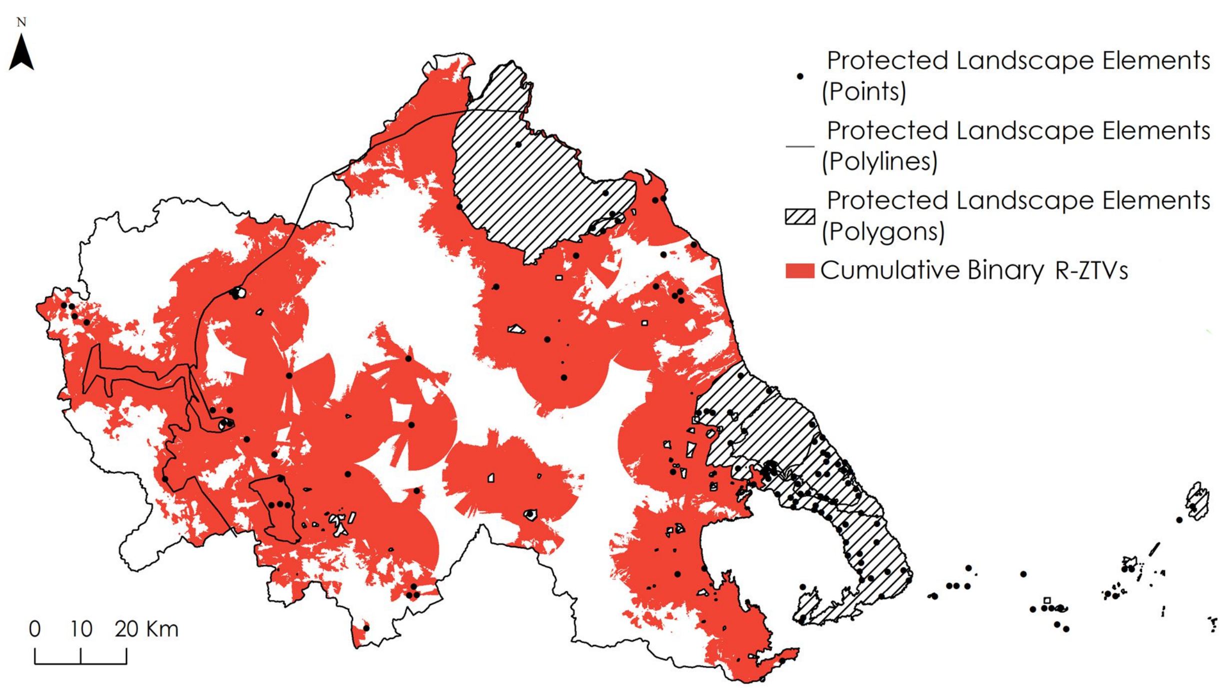


Figure 5 Binary R-ZTVs (with the use of 10 km visibility threshold)

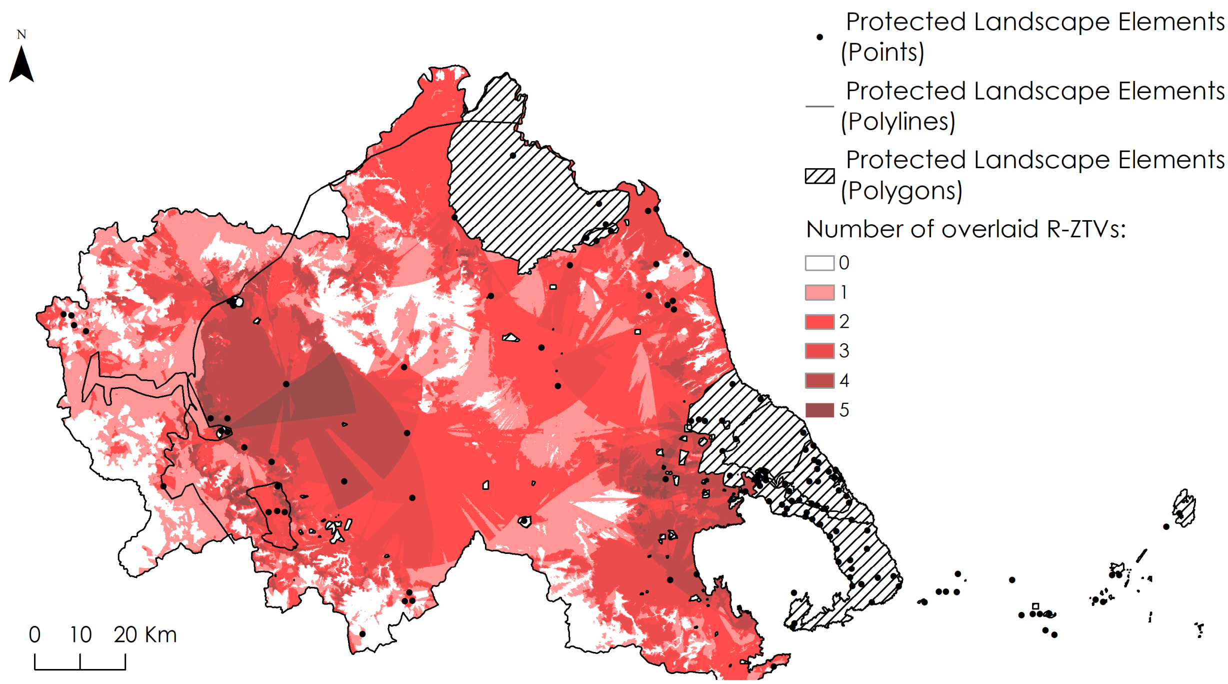


Figure 6 Weighted R-ZTVs (with the use of 30 km visibility threshold)

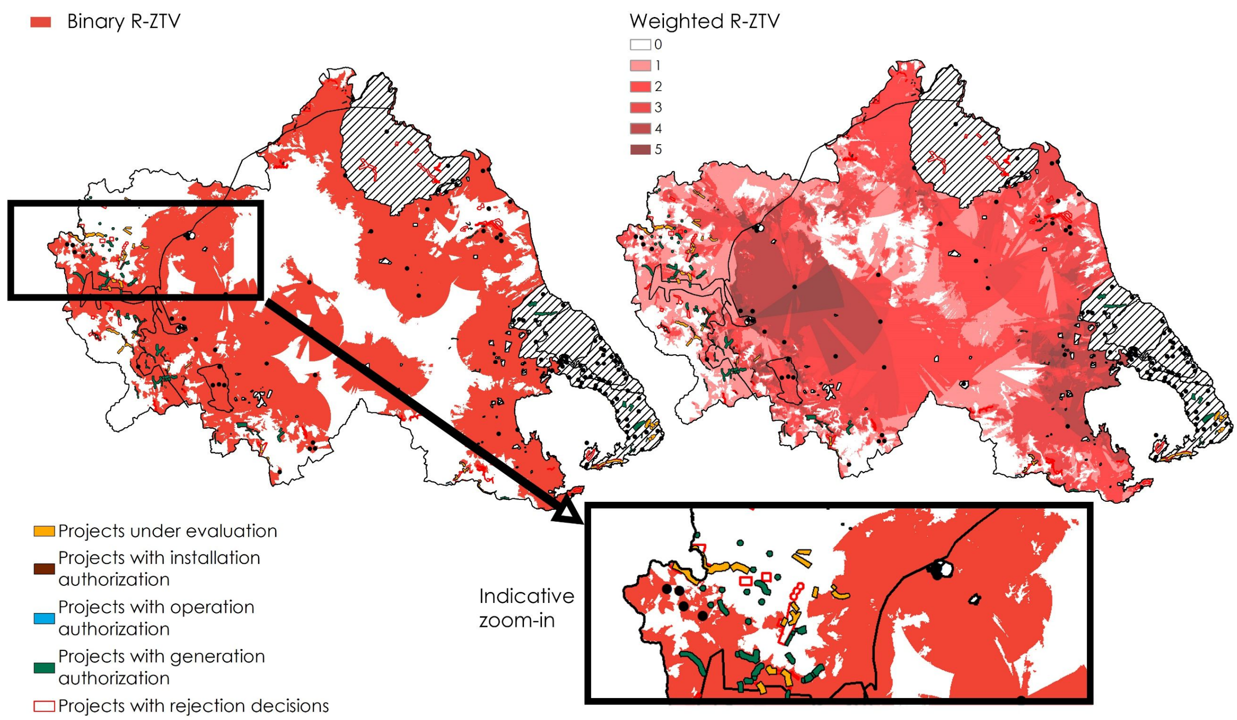


Figure 7 Wind projects in Thessaly region (in various development stages) assigned to R-ZTV maps (Figures 5 and 6).

We also remark that projects that are referenced by RAE as rejected during the licensing procedures (for various reasons, including environmental and legal justification), were also included in the analysis. On the other hand, proposed projects located inside the delimited archaeological areas that are presented in Figure 2 were excluded, as the severity of their landscape impacts were considered as self-evident.

The final list of examined projects, that sum 4.3 GW of nominal power capacity, was incorporated in the aforementioned maps, to evaluate the R-ZTV method over its capacity to propose favorable locations for the installation of wind turbines, under the criterion of landscape protection. In Figure 7, the R-ZTV maps of Figures 5 and 6 are presented in combination with the projects of the region that are currently under development. Next, the results in regard to the overlap of the wind energy projects with R-ZTVs are presented in Tables 1 and 2.

In the case of the binary R-ZTV with a 10 km visual threshold, 29.2% of the examined wind energy projects were outside its borders and would thus be considered to be causing minimal impacts to the protected landscape sites (Table 1). In the case of the weighted R-ZTV with a 30 km visual threshold, the projects that are completely outside the borders of the R-ZTV were only 2.2% of the total set, mainly located in the North-Western and Southern border areas of the region. However, this is not to say that site selection would be limited to these areas. In fact, the weighted R-ZTV map demonstrates the number of protected landscape elements that would be impacted from the installation of wind energy projects, with a spatial resolution equal to the cell size of the DEM. Therefore, weighted R-ZTVs could be used, for example, to prioritize locations that generate visual impacts to a smaller amount of protected landscape elements [76]. With the use of this type of weighted R-ZTVs, we can compute that 19.7% of the analyzed projects would be visible by only one protected landscape element, while another 34.2% would be visible by two elements (Table 2). Overall, the weighted R-ZTVs seem to be better suited to the setup of mainstream multi-criteria spatial planning analyses, in which various criteria have to be rated and taken into account, while the binary R-ZTVs could be used for the computation of exclusion zones or for independent guidance to stakeholders on significant anticipated landscape impacts. An additional observation that might be indicative to the utility of R-ZTV analyses is that rejected projects in the datasets of RAE present a slightly increased overlap with R-ZTV zones than projects in other stages of development. In particular, in Table 1 there is a 77.4% overlap of rejected projects with the R-ZTV, in contrast to 70.8% for the rest of projects. Additionally, in Table 2 the sum of rejected projects in overlap with zones 3, 4 and 5 is 55.9%, in contrast to 43.1% for the same sum in non-rejected ones. This could be a first indication that R-ZTVs can anticipate problematic locations, but this is certainly not definitive, since a detailed investigation of the reasons of rejection would be essential.

Overall, the results demonstrate that R-ZTV maps can be utilized for the projection of potential landscape impacts by RE projects, both applying large or small visibility thresholds. The inclusion of projections of landscape impacts that are informed by visibility analysis in early strategic planning and decision making, in general, and in operational multi-criteria siting studies, in particular, would be an improvement over the current practices. We remind that visual impacts so far are typically neither projected nor mapped in these stages [35,36], while the few cases of application are in the form of predominantly qualitative rather than quantitative assessments [66–68,89].

Table 1 Wind energy projects under development in Thessaly region vs. binary R-ZTV of Figure 5.

Project authorization stage	**Number of projects in category**	**Number of projects overlapping with the binary R-ZTV**	**Percentage of projects overlapping with the binary R-ZTV**
1 - Under evaluation	38	23	60.5%
2 - Generation authorization	92	70	76.1%
3 - Installation authorization	5	3	60.0%
4 - Operation authorization	2	1	50.0%
Totals of not rejected projects	137	97	70.8%
Rejected projects (rejection decision)	84	65	77.4%

Table 2 Wind energy projects of Thessaly region under development vs. weighted R-ZTV of Figure 6.

Project authorization stage	**Number of projects in category**	**Percentages of projects overlapping with the following number of protected landscape element types**					
		0	**1**	**2**	**3**	**4**	**5**
1 - Under evaluation	38	2.6%	10.5%	36.8%	34.2%	13.2%	2.6%
2 - Generation authorization	92	1.1%	22.8%	35.9%	21.7%	15.2%	3.3%
3 - Installation authorization	5	20.0%	40.0%	0.0%	0.0%	20.0%	20.0%
4 - Operation authorization	2	50.0%	0.0%	0.0%	0.0%	0.0%	50.0%
Totals of not rejected projects	137	2.9%	19.7%	34.3%	24.1%	14.6%	4.4%
Rejected projects (rejection decision)	84	1.2%	11.9%	31.0%	33.3%	20.2%	2.4%

4 Discussion

4.1 The shift from *a posteriori* to *a priori* assessment of landscape impacts

The aim of reversing visibility analyses of RE is to allow for an early assessment of potential landscape impacts and to enable the timely dismissal of highly impactful ones, thus reducing conflicts and social opposition, and eventually favoring the development of RE.

So far, visibility analysis has been a very useful tool for the quantification of landscape impacts of RE projects across various spatial scales [9,49]. The reconceptualization of this tool so that it can be incorporated in the earliest stages of planning for RE can consequently be considered an important step towards the improvement of the quantification and optimal mitigation of landscape impacts. Until this point, an *a priori* application of visibility analysis in the stage of multi-criteria planning for RE investments and in large spatial scales has been very rare [35,36]. Visibility analyses have either been carried out (a) in large scale but *ad hoc* [23,25,54,56,63], therefore mostly having academic rather than planning utility, or (b) *a priori* but in local project's site-scale, reviewing the project's location as part of EIA [26,49,51,59]. However, this timing is not optimal, both for investors and the local communities, since at that stage there are very limited options for modifying the siting of projects. Thus, given the fact that public discourse [30,31,90–92] and co-production [93,94] have been identified as one of the basic means to improve the social acceptance of RE projects, technological updates, such as the proposed R-ZTV analysis, will be required for the facilitation of public participation in the planning phase of RE projects, in a meaningful way. It has to be noted that a well-justified siting is actually the only major way to mitigate the landscape impacts of RE projects. In contrast to other types of infrastructure works in which landscape integration can be improved through architectural design [10], this not a potentiality for two out of the three primary types of RE projects, since their shape is predefined by industrial specifications and cannot be modified [9]. In particular, wind turbines and utility-scale solar panels have a predetermined shape that cannot be altered, in contrast to works like bridges or dams that be treated architecturally through architectural and landscape studies. Out of RE works, architectural and landscape design is only applicable to civil engineering infrastructures that are associated with hydroelectric projects, such as dams and their appurtenant structures [10]. Parts of wind turbines have also started to be used for architectural purposes [95,96], but this becomes possible after their decommission and does not refer to wind projects thereof.

R-ZTV analysis is formalized particularly to allow for *a priori* and *large-scale* assessment of potential landscape impacts of RE projects. The facilitation of this shift is the major challenge of this study, since it can enable the inclusion of landscape impact projections, by means of visibility analysis, at the very early stages of project planning, and apparently far before their design (and thus siting) study. Through the proposed R-ZTV maps: (a) landscape impacts can be included in the well-established planning method of multi-criteria analysis among other criteria that have so far been commonly utilized [35,36], and (b) can be used even earlier than the beginning of licensing stages (e.g. for wind energy: suitability studies for mean wind speeds and efficacy of intended turbines, etc.), thus saving significant time and effort for projects that would go on to face important landscape-impact induced opposition. Regarding the shortcomings of current practices in RE planning, it is indicative that in a 2016 multi-criteria spatial planning study for the examined region of Thessaly [69], the mitigation of landscape impacts was addressed with 1 km buffer zones around protected landscape sites. This is one of the relatively lenient and simplistic measures for landscape protection suggested by the Greek Framework for Spatial Planning and Sustainable Development of RE [97], that has also been also in other studies in Greece [37]. We remark that similar practices are reported in multi-criteria studies in other countries, as well [38].

The outcomes of this analysis, as presented in Figures 5, 6 and 7 and Tables 1 and 2, demonstrate how R-ZTV maps can indeed facilitate the incorporation of visibility analysis in RE planning, at the regional or even coarser spatial levels. The format of R-ZTV maps, i.e., a generic spatial layer calculated for a whole region or country, is compatible with spatial multi-criteria analyses [35,36,98] or strategic environmental impact assessment studies [64] that are commonly used for RE planning across such scales. R-ZTV maps can improve the assessment of landscape impacts within such well-established design and planning practices, since they are based on accurate reverse viewshed calculations. By reducing subjectivities, such tools can facilitate decision-making for the social environmental and techno-economic optimization of RE projects. An additional advantage of R-ZTV maps is that after a single calculation at the regional or national scale for any selected protected landscape features (historical and cultural monuments, traditional settlements, touristic areas, etc.) they can be re-used for any project with similar characteristics in the proximity of these protected areas. Furthermore, they are quite easily expandable, whenever additional information has to be added (e.g., new features of interest or new restrictions), by means of overlapping layers. This disconnects visibility analysis from the locations of particular examined projects, as has been the common practice so far; therefore, the R-ZTV method has the potential to reduce the load of EIA and simplify policy, if utilized in large spatial scales. The use of visibility analyses based on reverse viewshed calculations in early stages of development is also supported by the similar yet even more generic method of Zones of Potential Visual Impact on Protected Landscapes presented by Natural England [72] or the already mentioned study by Tegou et al. [28].

R-ZTV maps are relevant to private or state-owned enterprises involved in the development of RE, as well as to institutions and local authorities that are active in cultural heritage management and landscape planning and preservation. In this respect, these maps can be used for the projection of impacts either as part of multi-criteria planning studies or independently, especially from the investors' part, usually lacking local knowledge. In fact, many companies that are active in the field of RE development are multinational and have limited information about landscape-quality issues, such as cultural heritage, tourism, etc. As a result, in many cases, conflicts with local communities and opposition that emerges over landscape effects could be potentially avoided if tools for early projection of these impacts were available. Thus, the R-ZTV maps can be used for the classification of cases of projects in regard to their landscape impacts and additionally such institutions can also have an active role in the selection of protected landscape sites that are used to generate the R-ZTVs. This last point can be of particular significance given the broadly accepted importance of public participation in RE planning [31,90,92], and also illustrates a potential for synergies with participatory GIS tools [99,100]. R-ZTV maps can facilitate the communication between stakeholders, by providing spatial quantification and classification of impacts. Eventually, such maps can be used in this process to aid in the justification of objections, trade-offs or compromises, overall easing the handling of conflicting objectives in the planning process of projects [75] and contributing to reducing the social turmoil, delays and costs associated with conflicts over landscape impacts.

4.2 Study limitations

Even though R-ZTV mapping can contribute to improved projections of landscape impacts of RE during the planning procedure, it should not be considered as an indisputable quantification, similarly to any method of quantifying landscape and visual impacts. Even though the calculation of visibility is relatively accurate, visibility cannot be considered equivalent to visual impact [101]. Visual impact is a rather qualitative than quantitative concept, which is subject to personal opinions and biases [102–106], and thus depends on multiple other factors besides visibility; for example, on the perception of individuals on the quality [107,108] or the scenicness [109] of the transformed landscapes prior to their transformation, on place attachment [110], etc. Additionally, various other project-related or site-specific visual phenomena, such as glare from PV panels [111] or movement of turbine blades [112], can also affect the visual impacts of RE projects. Finally, viewshed calculations and the ZTV method, which is the basis of R-ZTV, also have additional computational flaws of their own [113,114]. Therefore, the proposed method of R-ZTV mapping is not manifested as a definite quantification of landscape impacts. It is rather a tool that can be used to support planning practices or policy frameworks and national directives for RE planning, in terms of improving the quantitative aspect of landscape impact assessments.

In addition to the aforementioned shortcomings of visibility analyses in general, the R-ZTV method has some additional more specific prerequisites and limitations. In particular, the basic requirement for its implementation in the large scale (national and regional), where it is more meaningful, is that sites of landscape importance must have been already designated and mapped and be available in GIS compatible formats. In some countries, such data are already mapped in those scales by environmental and cultural institutions and agencies [38,72]. However, this is not necessarily the norm. For instance, in Greece, only three out of the 13 basic administrative regions have published such data in GIS format.

Lastly, there are additional limitations that are specific to the present study and are related with technical assumptions and decisions. The first of them is that a DEM (Digital Elevation Model) was used for the analysis rather than a DSM (Digital Surface Model) that includes adjusted land surface heights according to land uses [115]. The latter was not found for the examined region, and in general, the differences between a DEM and a DSM in the scale of examination of this study are not expected to be significant. Nevertheless, we remark that the use of DEMs is approved by practice guidelines for ZTV analysis [51]. Second, another space for improvement involves the positioning of theoretical observers within protected areas. For example, traditional settlements were presented as points within the utilized data sets, while more accurate representations of them would allow for the inclusion of more theoretical observers, thus improving the accuracy of the derived R-ZTV maps. Differences between R-ZTVs could also be investigated by means of using centroids or peripheral points or combinations of the two for calculations in polygon type protected areas. The number of points that are generated to represent a structure in the landscape have already found to affect the calculation of area of visibility [81] in R-ZTV analyses at the smaller spatial scale and may also have some impact, probably less significant, in larger scales.

5 Conclusions

The inability to integrate visibility analyses into the strategic planning of RE projects has hindered the timely projection of landscape impacts, thus impeding their mitigation and arguably contributing to significant landscape-impact induced public opposition. In this study, the realization of a methodological twist in visibility analyses is proposed as a solution to the above-mentioned shortcoming: shifting the focus of visibility analysis from RE infrastructures that cause visual impacts to the landscape elements that should be protected from such impacts. With this twist, R-ZTVs (Reverse Zones of Theoretical Visibility) can be calculated and be used to anticipate landscape impacts of projects, much before their design studies and before the crucial steps of licensing and EIA.

The practical challenges of this shift were investigated in the region of Thessaly, Greece, where the R-ZTV analysis was implemented at a regional scale of 14.000 km^2. This proof-of-concept demonstrated how the proposed reverse visibility analysis can be used to support the sitting of projects is various levels of maturity (initial evaluation of wind speeds and business plans, EIA, finalized licensing, etc.) with the landscape-protection criterion, *a priori* and in large spatial scales. It has to be noted though that the generated maps can also be used for the projection of landscape impacts of proposed projects within the region, even in earlier preliminary stages of development, namely in early planning or conception.

Through both the theoretical and the practical investigations of the study it was demonstrated that reversing visibility analyses can contribute to overcoming some of the common landscape-associated difficulties of RE planning, in the following ways:

1) The reversal of visibility analyses enables their integration into the early planning stages of RE, which has been impractical so far. Mainstream ZTV and viewshed analyses could not be carried out at these stages since they require the detailed project layout as input, while in that time the project design (including its micro-siting) is still under investigation. However, since important landscape features (historical-archaeological sites, cultural monuments, touristic areas, etc.) are in already known locations, visibility analysis can be instead carried for them in the form of reverse viewshed, using their locations as input. The combination of the computed reverse viewsheds in R-

ZTV-type maps formulates a novel spatial layer that projects potential visual impacts to the examined landscape elements. This layer can be used as early as in the conception phase or can be integrated into multi-criteria strategic planning studies, along with other technical, economic and environmental criteria, thus allowing for the early anticipation of potential landscape impacts.

2) After a single calculation, R-ZTV maps of protected landscape elements can be then used in the future for multiple planned RE projects in their proximity. Thus, in terms of policy implications, they can potentially render the requirement for individual visibility analyses for each new project obsolete, overall accelerating the EIA of RE. Since protected landscape sites are static, the computation of the reverse viewshed of every site is only required once, and would not need to be re-calculated for each new project, as is the case with common visibility analyses. A new implementation will only be required if basic geometrical features of the examined RE projects, such as wind turbine or solar photovoltaic panel heights, are modified significantly.
3) Finally, R-ZTV maps can be used independently by stakeholders in the early planning phases of RE development, when the siting or projects is still under consideration, thus allowing for better-informed siting decisions. From the perspective of *investors*, R-ZTV maps can be used for the selection of locations with low anticipated landscape impacts, thus reducing investment risks. From the perspective of *stakeholders* that are active in the protection of landscapes, R-ZTV maps can provide quantitative data that can be used to facilitate communication and public discourse over projected landscape impacts. Furthermore, R-ZTV maps can be co-produced with local communities and landscape protection institutions, who can be involved in the selection of landscape features to be included in the R-ZTV analysis.

Overall, it can be expected that the continuous effort to expand RE in combination with the fact that low-impact sites for such projects are declining [116–118], will render the RE transition one of the most significant drivers of landscape change in the following decades. It is evident that the mitigation of impacts to landscapes will be a key goal for both investors and local communities that aim to protect their landscapes [9], with conflicts being detrimental to both groups, as being especially manifested in countries with highly developed economies [119]. Technological tools, such as the proposed R-ZTV analysis, can aid towards this effort, by providing quantitative data that can have a synergetic relation with the methods proposed in the ongoing research on public discourse and participation schemes [93,100,120] and decision making policies [94,109,121] with respect to RE development. In regard to future research, further steps for the evaluation and utilization of R-ZTV analysis include its implementation across even larger spatial scales, as well as the incorporation of R-ZTV maps within multi-criteria studies. Qualitative analysis of the efficacy of the proposed method in assessing potential landscape impacts, e.g., by means of photomontage and questionaries for visitors of important landscape sites, would also be useful.

Funding: Romanos Ioannidis was supported by the Eugenides Foundation through its Scholarships Program for Doctorate Research in the National Technical University of Athens.

REFERENCES

[1] Trainor AM, McDonald RI, Fargione J. Energy Sprawl Is the Largest Driver of Land Use Change in United States. PLOS ONE 2016;11:e0162269. https://doi.org/10.1371/journal.pone.0162269.

[2] Ong S, Campbell C, Denholm P, Margolis R, Heath G. Land-use requirements for solar power plants in the United States. National Renewable Energy Laboratory Golden, CO; 2013.

[3] Denholm P, Hand M, Jackson M, Ong S. Land-use requirements of modern wind power plants in the United States. Golden, CO: National Renewable Energy Laboratory 2009:57.

[4] Sargentis G, Siamparina P, Sakki G-K, Efstratiadis A, Chiotinis M, Koutsoyiannis D. Agricultural Land or Photovoltaic Parks? The Water–Energy–Food Nexus and Land Development Perspectives in the Thessaly Plain, Greece. Sustainability 2021;13:8935.
[5] Apostol D, Palmer J, Pasqualetti M, Smardon R, Sullivan R. The Renewable Energy Landscape: Preserving Scenic Values in our Sustainable Future. Routledge; 2016.
[6] Frolova M, Prados M-J, Nadaï A. Renewable Energies and European Landscapes. Springer; 2015.
[7] Sebestyén V. Renewable and Sustainable Energy Reviews: Environmental impact networks of renewable energy power plants. Renewable and Sustainable Energy Reviews 2021;151:111626. https://doi.org/10.1016/j.rser.2021.111626.
[8] Frolova M, Centeri C, Benediktsson K, Hunziker M, Kabai R, Scognamiglio A, et al. Effects of renewable energy on landscape in Europe: Comparison of hydro, wind, solar, bio-, geothermal and infrastructure energy landscapes. Hungarian Geographical Bulletin 2019;68:317–39. https://doi.org/10.15201/hungeobull.68.4.1.
[9] Ioannidis R, Koutsoyiannis D. A review of land use, visibility and public perception of renewable energy in the context of landscape impact. Applied Energy 2020;276:115367. https://doi.org/10.1016/j.apenergy.2020.115367.
[10] Ioannidis R, Koutsoyiannis D, Sargentis G-F. Landscape design in infrastructure projects - is it an extravagance? A cost-benefit investigation of practices in dams. Landscape Research 2022. https://doi.org/10.1080/01426397.2022.2039109.
[11] Mamassis N, Efstratiadis A, Dimitriadis P, Iliopoulou T, Ioannidis R, Koutsoyiannis D. Water and Energy. In: Bogardi JJ, Gupta J, Nandalal KDW, Salamé L, van Nooijen RRP, Kumar N, et al., editors. Handbook of Water Resources Management: Discourses, Concepts and Examples, Cham: Springer International Publishing; 2021, p. 619–57. https://doi.org/10.1007/978-3-030-60147-8_20.
[12] Ioannidis R, Koutsoyiannis D. The architectural and landscape value of dams: From international examples to proposals for Greece. Proceedings of the 3rd Hellenic Conference on Dams and Reservoirs, Zappeion, Athens: Hellenic Commission on Large Dams; 2017.
[13] Council of Europe. European landscape convention. Florence: 2000.
[14] Jefferson M. Safeguarding rural landscapes in the new era of energy transition to a low carbon future. Energy Research & Social Science 2018;37:191–7. https://doi.org/10.1016/j.erss.2017.10.005.
[15] Roth M, Eiter S, Röhner S, Kruse A, Schmitz S, Frantal B, et al. Renewable energy and landscape quality. Pan 2018;128:2.2.
[16] Phillips J. A quantitative-based evaluation of the environmental impact and sustainability of a proposed onshore wind farm in the United Kingdom. Renewable and Sustainable Energy Reviews 2015;49:1261–70. https://doi.org/10.1016/j.rser.2015.04.179.
[17] Sibille A del CT, Cloquell-Ballester V-A, Cloquell-Ballester V-A, Darton R. Development and validation of a multicriteria indicator for the assessment of objective aesthetic impact of wind farms. Renewable and Sustainable Energy Reviews 2009;13:40–66.
[18] Ioannidis R, Dimitriadis P, Sargentis G-F, Frangedaki E, Iliopoulou T, Koutsoyiannis D. Stochastic similarities between natural processes and art: Application in the analysis and optimization of landscape aesthetics of renewable energy and civil works. European Geosciences Union General Assembly 2019, EGU; 2019.
[19] Hurtado JP, Fernández J, Parrondo JL, Blanco E. Spanish method of visual impact evaluation in wind farms. Renewable and Sustainable Energy Reviews 2004;8:483–91.
[20] Manta E, Ioannidis R, Sargentis G-F, Efstratiadis A. Aesthetic evaluation of wind turbines in stochastic setting: Case study of Tinos island, Greece. European Geosciences Union General Assembly 2020, Geophysical Research Abstracts 2020.
[21] Regulatory Authority for Energy. RAE - Geoinformation Map 2015.
[22] Ελληνική Δημοκρατία - Υπουργείο Περιβάλλοντος και Ενέργειας[Greek Democracy - Ministry of Environment and Energy]. Εθνικό Σχέδιο για την Ενέργεια και το Κλίμα [National plan for Energy and Climate]. Athens: 2019.

[23] Statistics Netherlands [CBS], Netherlands Environmental Assessment Agency [PBL], National Institute for Public Health and the Environment [RIVM], Wageningen University and Research [WUR]. Visual disturbance of landscape amenity by wind turbines 2014.

[24] Möller B. Spatial analyses of emerging and fading wind energy landscapes in Denmark. Land Use Policy 2010;27:233–41. https://doi.org/10.1016/j.landusepol.2009.06.001.

[25] Rodrigues M, Montañés C, Fueyo N. A method for the assessment of the visual impact caused by the large-scale deployment of renewable-energy facilities. Environmental Impact Assessment Review 2010;30:240–6.

[26] Jerpåsen GB, Larsen KC. Visual impact of wind farms on cultural heritage: A Norwegian case study. Environmental Impact Assessment Review 2011;31:206–15.

[27] Spielhofer R, Thrash T, Hayek UW, Grêt-Regamey A, Salak B, Grübel J, et al. Physiological and behavioral reactions to renewable energy systems in various landscape types. Renewable and Sustainable Energy Reviews 2021;135:110410. https://doi.org/10.1016/j.rser.2020.110410.

[28] Tegou L-I, Polatidis H, Haralambopoulos DA. Environmental management framework for wind farm siting: Methodology and case study. Journal of Environmental Management 2010;91:2134–47.

[29] Mirasgedis S, Tourkolias C, Tzovla E, Diakoulaki D. Valuing the visual impact of wind farms: An application in South Evia, Greece. Renewable and Sustainable Energy Reviews 2014;39:296–311. https://doi.org/10.1016/j.rser.2014.07.100.

[30] Wolsink M. Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives.' Renewable and Sustainable Energy Reviews 2007;11:1188–207. https://doi.org/10.1016/j.rser.2005.10.005.

[31] Wolsink M. Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support. Renewable Energy 2000;21:49–64.

[32] Betakova V, Vojar J, Sklenicka P. Wind turbines location: How many and how far? Applied Energy 2015;151:23–31.

[33] Petrova MA. NIMBYism revisited: public acceptance of wind energy in the United States: NIMBYism revisited. Wiley Interdisciplinary Reviews: Climate Change 2013;4:575–601. https://doi.org/10.1002/wcc.250.

[34] Cass N, Walker G. Emotion and rationality: The characterization and evaluation of opposition to renewable energy projects. Emotion, Space and Society 2009;2:62–9.

[35] Shao M, Han Z, Sun J, Xiao C, Zhang S, Zhao Y. A review of multi-criteria decision making applications for renewable energy site selection. Renewable Energy 2020;157:377–403.

[36] Osorio-Aravena JC, Frolova M, Terrados-Cepeda J, Muñoz-Cerón E. Spatial Energy Planning: A Review. Energies 2020;13:5379.

[37] Latinopoulos D, Kechagia K. A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece. Renewable Energy 2015;78:550–60. https://doi.org/10.1016/j.renene.2015.01.041.

[38] Watson JJW, Hudson MD. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landscape and Urban Planning 2015;138:20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001.

[39] Bertsiou MM, Theochari AP, Baltas E. Multi-criteria analysis and Geographic Information Systems methods for wind turbine siting in a North Aegean island. Energy Science & Engineering 2021;9:4–18.

[40] Detsika M, Feloni E, Karpouzos D, Baltas E. Development of a GIS-assisted multi-criteria approach for the proper location of wind farms in Florina region, 2018.

[41] Pappa I, Dimakos Y, Dimas P, Dimitriadis P, Kossieris P, Koutsoyiannis D. Spatial and temporal variability of wind speed and energy over Greece. 2014. https://doi.org/10.13140/RG.2.2.11238.63048.

[42] Kruse A, Marot N, Dolacek Z, Karl B, Bottarelli M, Brito P, et al. GLOSSARY ON RENEWABLE ENERGY AND LANDSCAPE QUALITY-THE GLOSSARY. Journal of Landscape Ecology 2019;16:7–96.

[43] Sargentis G-F, Ioannidis R, Chiotinis M, Dimitriadis P, Koutsoyiannis D. Aesthetical Issues with Stochastic Evaluation. In: Belhi A, Bouras A, Al-Ali AK, Sadka AH, editors. Data Analytics for Cultural Heritage: Current Trends and Concepts, Cham: Springer International Publishing; 2021, p. 173–93. https://doi.org/10.1007/978-3-030-66777-1_8.

[44] Thayer RL, Freeman CM. Altamont: public perceptions of a wind energy landscape. Landscape and Urban Planning 1987;14:379–98.

[45] Frolova M, Jiménez-Olivencia Y, Sánchez-del Árbol M-Á, Requena-Galipienso A, Pérez-Pérez B. The evolution of renewable landscapes in Sierra Nevada (Southern Spain). Renewable Energies and European Landscapes, Springer; 2015, p. 117–34.

[46] Kazak J, van Hoof J, Szewranski S. Challenges in the wind turbines location process in Central Europe – The use of spatial decision support systems. Renewable and Sustainable Energy Reviews 2017;76:425–33. https://doi.org/10.1016/j.rser.2017.03.039.

[47] Pasqualetti M, Stremke S. Energy landscapes in a crowded world: A first typology of origins and expressions. Energy Research & Social Science 2018;36:94–105. https://doi.org/10.1016/j.erss.2017.09.030.

[48] Baraja-Rodríguez E, Herrero-Luque D, Pérez-Pérez B. A Country of Windmills. Renewable Energies and European Landscapes, Springer; 2015, p. 43–61.

[49] Scottish Natural Heritage [SNH]. Visual Representation of Wind Farms - Guidance - Version 2.2. Inverness, Scotland: Scottish Natural Heritage; 2017.

[50] Manchado C, Gomez-Jauregui V, Otero C. A review on the Spanish Method of visual impact assessment of wind farms: SPM2. Renewable and Sustainable Energy Reviews 2015;49:756–67. https://doi.org/10.1016/j.rser.2015.04.067.

[51] Scottish Natural Heritage. Visual representation of windfarms: good practice guidance. Newcastle; 2006.

[52] Toke D, Breukers S, Wolsink M. Wind power deployment outcomes: How can we account for the differences? Renewable and Sustainable Energy Reviews 2008;12:1129–47. https://doi.org/10.1016/j.rser.2006.10.021.

[53] Gobster PH, Ribe RG, Palmer JF. Themes and trends in visual assessment research: Introduction to the Landscape and Urban Planning special collection on the visual assessment of landscapes. Landscape and Urban Planning 2019;191:103635.

[54] Tsilimigkas G, Pafi M, Gourgiotis A. Coastal landscape and the Greek spatial planning: evidence from windpower in the South Aegean islands. Journal of Coastal Conservation 2018:1–14.

[55] Sullivan RG, Kirchler LB, Lahti T, Roché S, Beckman K, Cantwell B, et al. Wind turbine visibility and visual impact threshold distances in western landscapes. UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory; 2012.

[56] Scottish Natural Heritage [SNH]. Natural Heritage Indicator - N3 Visual influence of built development. Natural Scotland - Scottish Government; 2014.

[57] Degórski M, Kaczmarek H, Komornicki T, Kordowski J, Lamparski P, Milewski P, et al. Energetyka wiatrowa w kontekście ochrony krajobrazu przyrodniczego i kulturowego w województwie kujawsko-pomorskim {[Wind energy in the context of protection of the natural and cultural landscape in the Kuyavian-Pomeranian Voivodeship]. IGiPZ PAN, Warszawa styczeń; 2012.

[58] Hankinson M. Landscape and Visual Impact Assessment. Handbook of Environmental Impact Assessment 1999;Volume 1.:347–73.

[59] Buchan N. Visual Assessment of Windfarms Best Practice. Newcastle: University of Newcastle; 2002.

[60] Wood G. Is what you see what you get? : Post-development auditing of methods used for predicting the zone of visual influence in EIA. Environmental Impact Assessment Review 2000;20(5):537–56.

[61] Oudes D, Stremke S. Next generation solar power plants? A comparative analysis of frontrunner solar landscapes in Europe. Renewable and Sustainable Energy Reviews 2021;145:111101. https://doi.org/10.1016/j.rser.2021.111101.

[62] Ioannidis R, Iliopoulou T, Iliopoulou C, Katikas L, Petsou A, Merakou M-E, et al. Solar-powered bus route: introducing renewable energy into a university campus transport system. Adv Geosci 2019;49:215–24. https://doi.org/10.5194/adgeo-49-215-2019.

[63] Möller B. Changing wind-power landscapes: regional assessment of visual impact on land use and population in Northern Jutland, Denmark. Applied Energy 2006;83:477–94.

[64] Pang X, Mörtberg U, Brown N. Energy models from a strategic environmental assessment perspective in an EU context—What is missing concerning renewables? Renewable and Sustainable Energy Reviews 2014;33:353–62. https://doi.org/10.1016/j.rser.2014.02.005.

[65] Ramírez-Rosado IJ, Garcia-Garrido E, Fernandez-Jimenez LA, Zorzano-Santamaria PJ, Monteiro C, Miranda V. Promotion of new wind farms based on a decision support system. Renewable Energy 2008;33:558–66.

[66] Gamboa G, Munda G. The problem of windfarm location: A social multi-criteria evaluation framework. Energy Policy 2007;35:1564–83. https://doi.org/10.1016/j.enpol.2006.04.021.

[67] Scognamiglio A. 'Photovoltaic landscapes': Design and assessment. A critical review for a new transdisciplinary design vision. Renewable and Sustainable Energy Reviews 2016;55:629–61. https://doi.org/10.1016/j.rser.2015.10.072.

[68] Mostegl NM, Pröbstl-Haider U, Haider W. Spatial energy planning in Germany: Between high ambitions and communal hesitations. Landscape and Urban Planning 2017;167:451–62. https://doi.org/10.1016/j.landurbplan.2017.07.013.

[69] Daskalou O, Karanastasi M, Markonis Y, Dimitriadis P, Koukouvinos A, Efstratiadis A, et al. GIS-based approach for optimal siting and sizing of renewables considering techno-environmental constraints and the stochastic nature of meteorological inputs. EGU General Assembly Conference Abstracts, vol. 18, 2016, p. 12044.

[70] Gigović L, Pamučar D, Božanić D, Ljubojević S. Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia. Renewable Energy 2017;103:501–21. https://doi.org/10.1016/j.renene.2016.11.057.

[71] Alphan H. Modelling potential visibility of wind turbines: A geospatial approach for planning and impact mitigation. Renewable and Sustainable Energy Reviews 2021;152:111675. https://doi.org/10.1016/j.rser.2021.111675.

[72] GeoData Institute, University of Southampton. GIS Viewshed Analysis to Identify Zones of Potential Visual Impact on Protected Landscapes. Natural England; 2013.

[73] Katikas L, Kontos T. Suitability Assessment for Offshore Wind Farm Siting Using Exclusion Criteria and Spatial Economic Models: The Case of North and Central Aegean Sea. 2018. https://doi.org/10.13140/RG.2.2.34486.60483.

[74] Giannakopoulou S, Xypolitakou E, Damigos D, Kaliampakos D. How visitors value traditional built environment? Evidence from a contingent valuation survey. Journal of Cultural Heritage 2017;24:157–64. https://doi.org/10.1016/j.culher.2016.11.004.

[75] Efstratiadis A, Hadjibiros K. Can an environment-friendly management policy improve the overall performance of an artificial lake? Analysis of a multipurpose dam in Greece. Environmental Science & Policy 2011;14:1151–62.

[76] Sargentis G-F, Ioannidis R, Iliopoulou T, Dimitriadis P, Koutsoyiannis D. Landscape Planning of Infrastructure through Focus Points' Clustering Analysis. Case Study: Plastiras Artificial Lake (Greece). Infrastructures 2021;6:12. https://doi.org/10.3390/infrastructures6010012.

[77] Koukouvinos A, Nikolopoulos D, Efstratiadis A, Tegos A, Rozos E, Papalexiou SM, et al. Integrated water and renewable energy management: the Acheloos-Peneios region case study. 2015. https://doi.org/10.13140/RG.2.2.17726.69440.

[78] Bazilian M, Miller M, Detchon R, Liebreich M, Blyth W, Futch M, et al. Accelerating the Global Transformation to 21st Century Power Systems. The Electricity Journal 2013;26:39–51. https://doi.org/10.1016/j.tej.2013.06.005.

[79] Papastamatiou P, Vlamakis A, Armenis S. Ανάπτυξη αιολικής ενέργειας - Αδειοδότηση & κανονιστικό πλαίσιο [Development of wind energy - Licencing & regulatory framework]. Hellenic Wind Energy Association; 2019.

[80] Government Gazette. Περιφερειακό Χωροταξικό Πλαίσιο Περιφέρειας Θεσσαλίας [Regional Spatial Planning Framework of the Region of Thessaly]. Athens, Greece: Greek Government; 2020.

[81] Caha J. Representing Buildings for Visibility Analyses in Urban Spaces. In: Ivan I, Horák J, Inspektor T, editors. Dynamics in GIscience, Cham: Springer International Publishing; 2018, p. 17–29. https://doi.org/10.1007/978-3-319-61297-3_2.

[82] Sullivan RG, Kirchler LB, Cothren J, Winters SL. Offshore wind turbine visibility and visual impact threshold distances. Environmental Practice 2013;15:33–49.

[83] Scottish Natural Heritage [SNH]. Siting and Designing Windfarms in the Landscape. Version 1. Scottish Natural Heritage; 2009.

[84] Bishop ID. Determination of thresholds of visual impact: the case of wind turbines. Environment and Planning B: Planning and Design 2002;29:707–18.

[85] Stevenson R, Griffiths S. The visual impact of windfarms: lessons from the UK experience. Harwell Laboratory, Energy Technology Support Unit; 1994.

[86] Vissering J, Sinclair M, Margolis A. A visual impact assessment process for wind energy projects. Clean Energy States Alliance 2011.

[87] Chalastani VI, Tsoukala VK, Coccossis H, Duarte CM. A bibliometric assessment of progress in marine spatial planning. Marine Policy 2021;127:104329.

[88] Spyridonidou S, Vagiona DG, Loukogeorgaki E. Strategic Planning of Offshore Wind Farms in Greece. Sustainability 2020;12:905. https://doi.org/10.3390/su12030905.

[89] Kaya T, Kahraman C. Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. Energy 2010;35:2517–27. https://doi.org/10.1016/j.energy.2010.02.051.

[90] Devine-Wright P. Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy. Wind Energy 2005;8:125–39. https://doi.org/10.1002/we.124.

[91] Langer K, Decker T, Roosen J, Menrad K. A qualitative analysis to understand the acceptance of wind energy in Bavaria. Renewable and Sustainable Energy Reviews 2016;64:248–59.

[92] Eltham DC, Harrison GP, Allen SJ. Change in public attitudes towards a Cornish wind farm: Implications for planning. Energy Policy 2008;36:23–33. https://doi.org/10.1016/j.enpol.2007.09.010.

[93] Wolsink M. Co-production in distributed generation: renewable energy and creating space for fitting infrastructure within landscapes. Landscape Research 2018;43:542–61. https://doi.org/10.1080/01426397.2017.1358360.

[94] Wolsink M. Distributed energy systems as common goods: Socio-political acceptance of renewables in intelligent microgrids. Renewable and Sustainable Energy Reviews 2020;127:109841. https://doi.org/10.1016/j.rser.2020.109841.

[95] Leahy P, Zhang Z, Nagle A, Ruane K, Delaney E, Mckinley J, et al. Greenway bridges from wind blades Greenway pedestrian and cycle bridges from repurposed wind turbine blades, Limerick, Ireland: 2021.

[96] Nagle AJ, Mullally G, Leahy PG, Dunphy NP. Life cycle assessment of the use of decommissioned wind blades in second life applications. Journal of Environmental Management 2022;302:113994. https://doi.org/10.1016/j.jenvman.2021.113994.

[97] Hellenic Ministry of Environment, Energy & Climate Change. National Framework for Spatial Planning and Sustainable Development of renewable energy sources [Εθνικό Πλαίσιο Χωροταξικού Σχεδιασμού & Αειφόρου Ανάπτυξης για τις ανανεώσιμες πηγές ενέργειας]. Athens: 2008.

[98] Efstratiadis A, Koutsoyiannis D. One decade of multi-objective calibration approaches in hydrological modelling: a review. Hydrological Sciences Journal–Journal Des Sciences Hydrologiques 2010;55:58–78.

[99] Brown G, Raymond CM. Methods for identifying land use conflict potential using participatory mapping. Landscape and Urban Planning 2014;122:196–208. https://doi.org/10.1016/j.landurbplan.2013.11.007.

[100] Picchi P, van Lierop M, Geneletti D, Stremke S. Advancing the relationship between renewable energy and ecosystem services for landscape planning and design: A literature review. Ecosystem Services 2019;35:241–59. https://doi.org/10.1016/j.ecoser.2018.12.010.

[101] Wolsink M. Framing in Renewable Energy Policies: A Glossary. Energies 2020;13:2871. https://doi.org/10.3390/en13112871.

[102] Phadke R. Resisting and Reconciling Big Wind: Middle Landscape Politics in the New American West. Antipode 2011;43:754–76. https://doi.org/10.1111/j.1467-8330.2011.00881.x.

[103] Lee M. Knowledge and landscape in wind energy planning. Legal Studies 2017;37:3–24. https://doi.org/10.1111/lest.12156.

[104] Nadaï A, Van Der Horst D. Wind power planning, landscapes and publics. Elsevier; 2010.

[105] Kontogianni A, Tourkolias C, Skourtos M, Damigos D. Planning globally, protesting locally: Patterns in community perceptions towards the installation of wind farms. Renewable Energy 2014;66:170–7.

[106] Kontogianni A, Tourkolias C, Skourtos M. Renewables portfolio, individual preferences and social values towards RES technologies. Energy Policy 2013;55:467–76.

[107] Molnarova K, Sklenicka P, Stiborek J, Svobodova K, Salek M, Brabec E. Visual preferences for wind turbines: Location, numbers and respondent characteristics. Applied Energy 2012;92:269–78.

[108] van der Horst D. NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. Energy Policy 2007;35:2705–14. https://doi.org/10.1016/j.enpol.2006.12.012.

[109] Weinand JM, McKenna R, Kleinebrahm M, Scheller F, Fichtner W. The impact of public acceptance on cost efficiency and environmental sustainability in decentralized energy systems. Patterns 2021;2:100301.

[110] Buchmayr A, Van Ootegem L, Dewulf J, Verhofstadt E. Understanding Attitudes towards Renewable Energy Technologies and the Effect of Local Experiences. Energies 2021;14:7596.

[111] Chiabrando R, Fabrizio E, Garnero G. The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk. Renewable and Sustainable Energy Reviews 2009;13:2441–51.

[112] Bishop ID, Miller DR. Visual assessment of off-shore wind turbines: the influence of distance, contrast, movement and social variables. Renewable Energy 2007;32:814–31.

[113] Ioannidis R, Dimitriadis P, Meletopoulos IT, Sargentis GF, Koutsoyiannis D. Investigating the spatial characteristics of GIS visibility analyses and their correlation to visual impact perception with stochastic tools. Geophysical Research Abstracts, Vol. 22, Vienna: European Geosciences Union; 2020. https://doi.org/10.5194/egusphere-egu2020-18212.

[114] Johnson D. An assessment of the accuracy of the zone of theoretical visibility technique for wind farms. University of East Anglia, 2014.

[115] Minelli A, Marchesini I, Taylor FE, De Rosa P, Casagrande L, Cenci M. An open source GIS tool to quantify the visual impact of wind turbines and photovoltaic panels. Environmental Impact Assessment Review 2014;49:70–8.

[116] Kaldellis JK, Kapsali M, Katsanou E. Renewable energy applications in Greece—What is the public attitude? Energy Policy 2012;42:37–48.

[117] Deshaies M, Herrero-Luque D. Wind Energy and Natural Parks in European Countries (Spain, France and Germany). Renewable Energies and European Landscapes, Springer; 2015, p. 217–33.

[118] Nitsch J, Krewitt W, Nast M, Viebahn P, Gärtner S, Pehnt M, et al. Ecologically Optimized Extension of Renewable Energy Utilization in Germany. Stuttgart, Heidelberg, Wuppertal: Deutsches Zentrum für Luft- und Raumfahrt (DLR) Institut für Technische Thermodynamik, Institut für Energie- und Umweltforschung (ifeu), Wuppertal Institut für Klima, Umwelt und Energie; 2004.

[119] Diógenes JRF, Claro J, Rodrigues JC, Loureiro MV. Barriers to onshore wind energy implementation: A systematic review. Energy Research & Social Science 2020;60:101337. https://doi.org/10.1016/j.erss.2019.101337.

[120] Stober D, Suškevičs M, Eiter S, Müller S, Martinát S, Buchecker M. What is the quality of participatory renewable energy planning in Europe? A comparative analysis of innovative practices in 25 projects. Energy Research & Social Science 2021;71:101804. https://doi.org/10.1016/j.erss.2020.101804.

[121] Frantál B, Van der Horst D, Martinát S, Schmitz S, Silva L, Golobic M, et al. Spatial targeting, synergies and scale: Exploring the criteria of smart practices for siting renewable energy projects. Energy Policy 2018;120:85–93.