A review of land use, visibility and public perception of renewable energy in the context of landscape impact

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Highlights:

- Wind energy ranks 1st, solar 2nd and hydro 3rd on land use and visibility
- In the negative perception index wind energy scores 60%, solar 22% and hydro 15%
- Depending on landscape type any technology can potentially be the least impactful

Landscape impact-induced opposition cannot be uncritically attributed to NIMBY

- Hydroelectric dams have untapped potential for high quality architectural design

Keywords:

Renewable energy landscapes, Visual impact, Public perception, Hydroelectric dam land-use, Wind turbines, Solar panels

Abstract

Landscape impact has been a persistent cause of opposition against the expansion of renewable energy (RE). However, there is still ambiguity over the spatial extents and the rationality of reported landscape impacts that impedes the development of optimal mitigation strategies. In this paper, we review three metrics that have been extensively used in the analysis of landscape impacts of RE: land use, visibility and public perception. Through the review of these metrics we form a typology of impacts for major RE technologies and a generic landscape-impact ranking, based on the quantification of average impacts from realized projects.

We conclude that, per unit energy generation, hydroelectric energy has been, on average, the least impactful to landscapes followed by solar and wind energy, respectively. More importantly, the analysis highlights the strengths and weaknesses of each technology, in a landscape impact context, and demonstrates that, depending on landscape attributes, any technology can potentially be the least impactful. Overall, a holistic approach is proposed for future research and policy for the integration of RE to landscapes, on the basis of maximum utilization of the advantages of each technology for the reduction of cumulative impacts.

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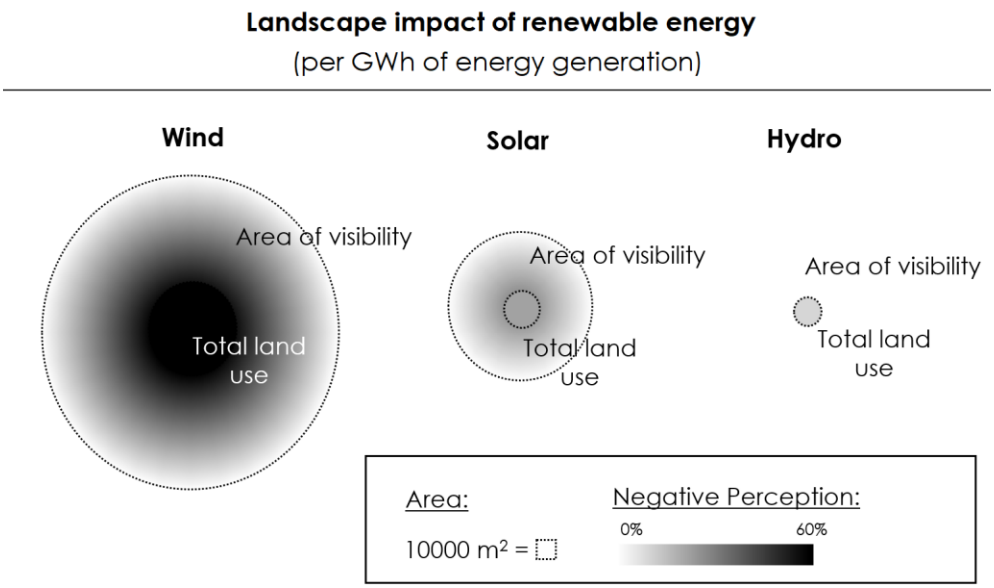
Graphical abstract



1 Introduction

In the hierarchy of scientific research on renewable energy (RE), landscape impact analysis is generally considered to rank low. Drawing an analogy with the physiological needs of humans, that are more fundamental to survival than the needs of belonging and self-completion [1], the generation of energy is arguably of greater priority to humanity than the impact of the technology used, on the landscape. Accordingly, matters of efficiency, costs and environmental impacts are generally prioritized over landscape impact analysis of RE.

In countries with developed economies, however, the impact of RE on landscape has been intertwining with its expansion, raising complex questions of social and cultural kind and creating unexpectant economic and developmental implications. Landscape impact analysis has a dual nature, quantitative and qualitative, and is thus described both by variables that can be objectively quantified, such as land use, and more subjective qualitative variables, such as public perception. This complexity, renders the management and mitigation of landscape impact a challenging problem, requiring interdisciplinary analysis. In this study, landscape impact of RE is placed thematically on the field of research on the sustainability and expansion of RE, but its analysis is generally recognized to pertain to several disciplines of applied natural and social sciences, which may approach the issue from different scientific perspectives.

1.1 A lose-lose situation for landscapes and the development of renewable energy

The motivation of this study lies in addressing and reversing the problematic relationship of RE and landscapes. In brief, we characterize relationship as lose-lose because in the absence of targeted impact management and mitigation plans it can become detrimental to both the RE expansion and the quality of landscapes. On the one hand, the development of RE is delayed, due to landscape-impact opposition, and on the other, if the integration of RE into landscapes is not properly addressed, significant and problematic landscape transformations are actually generated.

In the short term, opposition against RE developments on landscape impact grounds, has been consistently causing delays and cancellations, impeding the effort to reduce dependency from fossil fuel and causing significant economic implications. The relevant examples are abundant. In the USA, for instance, lawsuits with legal arguments related to landscape, visibility and aesthetics have been consistently filed against wind, and to a lesser extent solar, energy developments[1] [3–8]. Renewable energy projects constitute a significant percentage of the large number of projects that are challenged on environmental grounds, with reference to the National Environmental Protection Act, federal Environmental Quality Acts and Environmental Protection Acts [9,10]. The economic repercussion of such legal challenges was addressed in a study of 351 challenged and delayed energy projects, by the US Chamber of Commerce. In that study, it is estimated that the US economy was deprived of a $1.1 trillion short-term boost 1.9 million jobs annually [10]; out of such litigations, 45% relate to RE projects. Given that this study reported on RE challenged RE projects until 2010, it can be assessed that legal challenges based on visual and landscape impact opposition can be associated with billions of dollars and hundreds of thousands of jobs.

Relevant problems have also emerged in the European Union[11–14]. We present the case of Greece as an example [15]. In Greece, in 2017 and 2018, a list of some of the major wind energy projects that have been challenged adds up to a total installed capacity of 1237.7 MW (Table 1). Landscape impact is not the main argument of opposition in all of these cases but is consistently mentioned, both in legal complaints as well as in the public statements and websites of opposing groups. Furthermore, in some litigations, landscape impact might not be mentioned, but it is evident from the channels of communication of the opposing groups that in reality it is a basic implicit motivation for opposition. However, in such litigations other sections of environmental impact assessment studies which are more technical and objective than landscape impact, are mainly targeted, as they are expected to increase the odds of winning the cases [16]. These legal challenges were added to the various other challenges against wind energy developments that explicitly included legal arguments on landscape impact, which have been handled by the Hellenic Council of State [17–22]. The significance of the problem in Greece, is demonstrated by the fact that even though current installed capacity of wind energy is 2651 MW (for 2017) [23], the national target set for 2020, in accordance to directives from the European Union [24], is 7500 MW [25]. Therefore, the delay or cancellation of projects prompts the imposition of fines from the European Union, from 2020 onward. The exact method of calculation and enforcement of the fines has not been published yet, but in a relevant study for Ireland, which is almost double the percentage of Greece away from the target of RE utilization, the fines are anticipated in the range of €300-600 million [26].

Overall, it is evident that, in the long term, RE projects will indeed be the cause of massive landscape changes. It is the first time in human history that energy generation has so high land use demands [27–30] and that the infrastructure that is utilized generates such extensive visual impacts [31–33]. The scale of landscape and visual impacts generated, is excellently demonstrated in the calculations of zones of theoretical visibility (ZTV) for wind energy, in literature. Results from large-scale ZTV analyses showed that wind turbines were visible from approximately 17% of the land area of Spain[2] [34], 21% of the Netherlands [35], 46% of Scotland [33] and 96% of the region of North Jutland, in Denmark [31]. Furthermore, the global effort to increase energy generation from RE, will inevitably further perplex the problematic relationship between energy generation and landscapes. In Europe, for example, the share of RE in energy consumption that is now 17%. is planned to increase to 27%, by 2030 [36]. Hence, it becomes evident that the RE transition will continue to be one the greatest forces of transformation of European landscapes during the following decades. Moreover, this transformation is expected to be even more

[1] The term developments was used in reference to wind and solar projects rather than the term "farms", in agreement with the critique of Jefferson [2] that the term "farms" is an euphemism.

[2] From the examination of a hypothetical scenario of wind energy utilization in Spain, referring to national installed capacity nearly equal to the current installed capacity of wind energy Spain.

perceivable than the transition from 17% to 27% might indicate. This is due to the fact that RE projects will gradually have to be sited closer to more sensitive locations, from a landscape impact perspective, as suitable locations have decreased from the current RE expansion [15,37,38]. In conclusion, it becomes apparent that without specialized impact management and mitigation strategies long-term landscape impacts from RE can be particularly extensive and intrusive.

Table 1. Examples of challenged wind energy projects in Greece in 2017 and 2018.

Location	Installed capacit (MW)	Number of turbines	Type of opposition
Paros, Naxos, Tinos and Andros	218.5	95	Legal action from local government
Samothrace	110.7	39	Votes by groups of citizens and associations
Vermio	465	174	Negative decision from local government
Agrafa	86	40	Legal action from citizens
Sitia	81	27	Negative decision from local authorities
Karistos	167.9	73	Legal action from local government
Mani	103.2	48	Legal action from citizens and associations
Monemvasia	5.4	5	Legal action from local government

Data were collected from news articles in the websites of major national media (links are presented in the order of reference in the table): http://www.kathimerini.gr; https://www.ert.gr/; http://www.alterthess.gr/; https://www.efsyn.gr/; https://www.efsyn.gr/; https://www.alfavita.gr/; http://www.kathimerini.gr; https://www.rizospastis.gr/.

1.2 Research questions and academic contribution

In the last few decades, significant effort has been put into estimating, managing and reducing the landscape impact of RE projects. However, so far, research has mostly focused on localized analyses of impacts rather than generic cumulative analyses. With global RE capacity surpassing 1856 GW [39–41] at the moment, extensive national and regional data for RE have emerged, allowing for fact-based analyses that were so far impossible and which can now start replacing theoretical and intuitive estimates of landscape impacts. This study focuses in this exact direction, through the review of literature and data regarding the major and established metrics of landscape impact. In this analysis, the following research questions are addressed: What are the typical landscape impacts of major RE technologies and how do they differentiate? What is the generic ranking of major RE technologies, in terms of landscape impact, based on data from realized projects?

Through the investigation of these questions, the characteristics that render RE technologies impactful are identified and quantified. This contributes to a better and clearer definition of the problem at hand and thus to laying the proper foundations for a scientific approach to impact mitigation. Even though some level of landscape impact from the development of RE is unavoidable there is arguably still room for optimization of the spatial and architectural design of RE developments. As was demonstrated in the examples of section 1.1, if landscape impacts are not adequately considered in project planning, a vicious-cycle triggering continuous opposition is generated. It is acknowledged therefore, that the optimal integration of RE to landscapes is essential to ensure the sustainability of the RE expansion. This analysis identifies and quantifies the distinct landscape-impact characteristics of major RE technologies, contributing to better informed fact-based spatial planning policy and demonstrating novel directions for research on managing and minimizing landscape impacts of RE [7,42]. Landscape is undoubtedly expected to play a significant role [43] in the RE transition, especially in cases where cultural or natural heritage is affected and key elements of local economies, such as tourism or real estate, are threatened

1.3 Observations and hypothesis

An initial observation in the review of data and literature was that the various RE technologies have been disproportionately researched over their landscape impact. In particular, wind turbines are the basic topic of most literature [44–46], design guidelines [47–51], institutional publications [52–56] and news articles [14,57,58] on landscape impact, followed by solar panels [5,59]and lastly hydroelectric dams. In more detail, as regards to visibility, for example, one of the most researched metrics of landscape impact, wind energy has again been the main focus of national design guidelines and publications [52–56]. Solar energy has been addressed to a much lesser extent [5] and hydroelectric energy has hardly been mentioned, in the context of landscape impact. This observation was partially unexpected since the type of RE with the highest installed capacity globally is hydroelectricity, followed by wind energy and lastly, solar energy, which could suggest that research interest of the impact of each technology to landscapes would be analogous. Since that was not the case, a hypothesis was formed, that this disproportionate distribution of scientific interest, might be indicative of the actual magnitude of impacts generated from each technology; in which case wind energy developments would be generating the largest impact, followed by solar and hydroelectric developments, in order. Even though parts of this conclusion have already been produced in literature [60–63], it has neither been completely formulated yet nor been supported by large-scale data and specialized analysis.

1.4 Article structure

In the introductory section 1 we presented the context of this study, the research questions posed and the initial observations and hypothesis. In section 2 we review three metrics that have been consistently used in the analysis of landscape impact from RE; land use, visibility and public perception. We first describe the arguments for the selection of these specific metrics (2.1) and the study-screening procedure (2.2). Subsequently, we describe the literature analyzed, the methods used and the results obtained for each of the three metrics, in sequence (2.3, 2.4, 2.5). Then, in section 2.6, we distinguish a selected few of the analyzed estimates, on the basis of their generic applicability. These estimates are used as a reference point for the quantification of landscape impacts of major renewable energy technologies, in a global context. In section 3, we discuss the results and explore their significance and their correlations with published literature. Finally, we present the conclusions in section 4 and indicate directions for policy and future research in section 5.

2 Methods and results

2.1 Selection of metrics and technologies

2.1.1 Metrics

Landscape impact has no units, cannot be measured unequivocally and is, to an extent, subjective. This subjectivity is by definition inherent to landscape impact, since impact perception differentiates among individuals and is affected by personal biases. However, even though landscape impact cannot be calculated in a conventional way, it has been estimated in literature, through a combination of quantitative and qualitative metrics. Quantitative (spatial) metrics measure the size of the affected area, measured either through the area of direct impact, which is the area that is impacted from the installation of equipment and from works of infrastructure, or through the area of visual impact, i.e. the area from which the latter "direct impacts" are visible. The qualitative (perceptual) metrics, on the other hand, measure how all of these aforementioned landscape changes are perceived by individuals.

In this study, a mixture of quantitative and qualitative metrics was reviewed, to cover the complete spectrum of landscape impact metrics. Namely, the following three metrics were selected due to the fact that they encompass, to different degrees, both the quantitative and qualitative aspect of landscape impacts and also because they have been extensively and consistently used in relevant analyses:

- Land use: Land use has been widely used in the analysis of landscape impact from RE [28,29,64–66]. It is arguably the most objective quantitative metric of landscape impact, since it is used to measure the area that is directly occupied by RE developments, which is unquestionably impacted [28,29] from a landscape-impact perspective; On the contrary, for example, visibility which is also used as a metric of landscape impact, includes biases as visibility is only considered a negative impact by individuals who dislike the view of RE facilities.
- Visibility: The area from which a RE project is visible can be estimated a through visibility analyses with geographic information systems (GIS) [34,48–50,67]. Even though quantifiable, visibility is however not a fully quantitative metric since its association with landscape impact is dependent on whether the viewed element is perceived negatively or not. Regarding RE, the perception of individuals on the view of new projects has been found to vary significantly, ranging from annoying to pleasing. As a result, visibility can be considered a mixed qualitative/quantitative metric, which can be quantified spatially but also encompasses subjectivity related to individual perception.
- Public perception: Public perception, in the context of landscape impact, refers to the opinions of individuals on the aesthetics of RE projects [43,68], as shaped by their senses, their culture and their ideology [69–72]. It has been assessed in various forms [69,71] and can be considered a purely qualitative metric. Nevertheless, public perception is arguably of particular significance since it determines the existence of visual impacts and thus also determines the spatial extents of landscape impacts; e.g. if the view of a project is perceived positively negative visual impacts do not exist.

Other quantifiable aspects of landscape impact from RE that are acknowledged but were not reviewed are listed below, along with a brief description on why they were not included:

a) Full life-cycle landscape impact: For a comprehensive understanding of the overall impact of RE on landscapes a full life-cycle impact analysis is imperative [73,74]. However, the analysis of impacts from facilities and processes of manufacturing and decommissioning RE machinery and infrastructure components is a complex task that requires specialized research, and unfortunately relevant studies are scarce [73]. Additionally, it exceeds the boundaries of national and regional planning and sitting practices, which are in focus in this analysis, since life-cycle impacts do not concern a single region or country but are spread across several countries [75]; for example, the materials required for manufacturing wind turbines include steel, carbon fiber, cast iron, fiberglass and aluminum [76,77], most of which are imported to the countries that manufacture RE technology.

b) Duration of impact: Duration of impact [7,78] was not examined in this analysis. Since renewable energy is designed to be a permanent replacement for fossil fuel, RE developments are expected to provide continuously to the new fossil fuel- free energy world until new technologies can replace them. The type and extents of landscape impact remaining after large-scale decommission would differ for each technology [76], but overall, were considered a largely distant problem.

c) Short-term construction related landscape impact: Short term construction related landscape impact was not examined. Emphasis was placed on large scale and long-term impacts and therefore impacts during the life span of the project were prioritized.

2.1.2 Technologies

Moderately developed or experimental RE technologies were not examined in this analysis. In the context of global landscape transformation, the major technologies that lead in installed capacity globally were considered more relevant to reported landscape impacts. These are large hydroelectric dams, onshore wind turbines and utility scale solar panels. The most developed out of the technologies that were not included in the analysis were small hydroelectric dams, amounting to approximately 11% of the total installed capacity of hydropower globally (148 GW in 2016) [79], and offshore wind energy, with 18,8 GW of installed capacity globally [80]. In comparison, the global installed capacity of solar energy, which is the least utilized out of the three examined technologies, was 222 GW [41]. It is pointed out that both small hydroelectric dams [81] and offshore wind turbines have distinct characteristics and should be analyzed separately regarding their landscape impact.

2.2 Study screening

2.2.1 Primary screening

Study screening was more complex in the review of land use and visibility that quantitative (spatial) metrics, than in the review of the exclusively qualitative (perceptual) metric of public perception. This was due to the fact that land use and visibility estimates, are greatly dependent on parameters such as terrain, energy efficiency, scale of data sets used etc., while public perception is more simply approached with statistical analysis. This section is thus dedicated to screening methods for literature review on land use and visibility, which required clarifications over these various influential parameters; land use and visibility are reviewed in sections 2.3 and 2.4 The screening of studies for the review of public perception was carried out with a more simple statistical algorithmic procedure that is described within section 2.5, "Public Perception".

To collect data on land use and visibility of RE searches were carried out on Google Scholar, Elsevier, Wiley and Taylor & Francis data bases using the search strings " hydroelectric energy/ wind energy/ solar energy land use", " hydroelectric energy/ wind energy/ solar energy visibility" and " hydroelectric energy/ wind energy/ solar energy visual impact". The results of the search engines were searched for relevant studies until more than ten consequent results with irrelevant titles were found. Additional individual searches were carried out for relevant articles and reports that were referenced within the studies originally found. The estimates on the examined metrics that were compiled from this procedure are all presented in sections 2.3, 2.4 and 2.5.

2.2.2 Secondary screening

Other than presenting the general overview of literature and a typology of impacts, this study aims to provide a generic quantification of landscape impacts of the examined technologies. However, not all of the estimates that were compiled through the primary screening process could be used to this aim, due to biases that rendered their results non-generalizable. These biases were terrain extremes, assumptions over efficiency of energy generation, the scale of data sets used, use of theoretical estimates over data from realized projects and economic development status of origin countries. In the following subsections we describe the secondary screening criteria that were used to distinguish the estimates of land use and visibility that could be used in a generic context, with reference to the aforementioned biases.

Scale of datasets

The problem of landscape impact of RE was examined at the level of large-scale energy generation that is the most altering to landscapes [27,29]. In accordance to this logic, literature referring to large-scale energy generation was prioritized; i.e. studies analyzing large data sets compiled globally nationally or regionally were preferred, in order of reference. Limiting factors to the exclusive use of global data were their scarcity and the difficulty in maintaining an overview of the reliability of data, which was at times questionable for estimates based on the largest available datasets. Thus, the scale of datasets that had been used in the estimates that were distinguished for generic applicability, depended on data quality and availability. Indicatively, in the review of land-use studies based on national datasets were utilized [28,64,65] while in the review of visibility studies based on regional data were also included [31,32,82,83] since national-scale visibility analyses [33–35] were scarce and global scale visibility analyses were not found.

Terrain

Land use and visibility of RE developments are greatly dependent on terrain topography. Therefore, to reach generic and unbiased conclusions, data from areas of moderate terrain were preferred over data from extremely mountainous or flat areas. It was clear that if, for example, data from Switzerland [84,85] or Brazil [86] were used, in the estimation of average hydroelectric reservoir size, the results would be biased; Switzerland being an exceptionally mountainous and brazil an exceptionally flat country. Consequently, an index was required to determine which of the origin countries or regions of the datasets had moderate terrain. The topographic ruggedness index of Nunn and Puga [87] was utilized to this end. Ruggedness is defined as the average slope of a country's land area and is calculated by Nunn and Puga [87] by averaging the elevations of adjacent 30 by 30 arc-second cells in the GTOPO30 global elevation data set. In Figure 1, all countries from which terrain-related data were discussed in this article are pinpointed, to aid the characterization of their terrain, as moderate or extreme (flat or mountainous). For example, Switzerland (CHE), which is an exceptionally mountainous country, has a ruggedness index of 4.76 and Brazil (BRA), which is an exceptionally flat country, has 0.24. Results from countries with extreme terrain (based on their ruggedness index) are mentioned in the study but are not included in the generic results, as they were not considered of generic value.

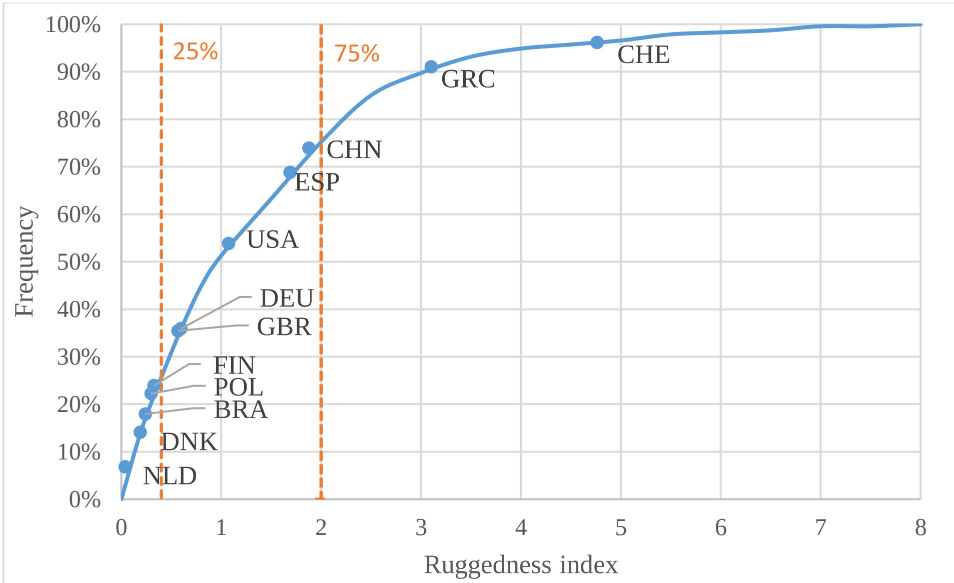


Figure 1. Global cumulative frequency chart of national ruggedness indexes. Countries that are referenced in this article, in regards to land use or visibility of RE, are presented using their isocodes. The countries whose ruggedness index was within the frequencies of 25% and 75% were considered of moderate topography. Original data from Nunn and Puga [87].

Energy generation efficiency

Land use and visibility of RE are commonly expressed as ratios of the affected area to either installed capacity or energy generation. Energy generation (in GWh) was considered preferable over installed capacity (in MW), as the denominator of the ratio, in the context of this study. Otherwise, if installed capacity was used as the denominator, the area affected would be overestimated for more efficient technologies, which generate more GWh of energy per MW of installed capacity. This would not allow for a fair comparison between different technologies. Since data where not always available in the desired format, conversions of installed capacity to expected average energy generation were made, using the capacity factors (CF) of the technologies examined (Table 2). The cases in which such conversions were carried out are reported in the text.

Realized data vs. theoretical estimates

Hydroelectric, wind and solar energy have already developed significantly, with 1212, 420 and 222 GW of total global installed capacity respectively, in 2016 [39–41]. Thus, data from realized projects were preferred over theoretical estimates for land use and visibility and for capacity factors. Even though theoretical estimates are also useful, especially when data from built projects have not been collected (as was the case with visibility analyses for solar energy [34]), there are various examples in which they have been found to differ from reality. Such a case, for example, is the discrepancy of theoretical from realized CF of wind energy, described by Boccard [88], which was one of the examples that acted as alerts for being thoughtful to the use of theoretical estimates. Based on this discrepancy, rather than using theoretical estimates we utilized realized CFs in all conversions of installed capacity to expected energy generation. In particular, global average CFs were calculated, using data of installed capacity and energy generation from the World Energy Council [39–41] (Table 2). The data sets of the World Energy Council are based on global data from realized projects.

Table 2. Capacity factors of renewable energy technologies. Global data of installed capacity and energy generation were retrieved from the World Energy Council ([39]- Hydropower, [40]- Wind and [41]- Solar).

Type of renewable energy	Total installed capacity of data set (GW)	Comments on data set	Capacity factor
Hydroelectric	1212	includes pumped storage	0.37
Wind	432	includes onshore and offshore	0.22
Solar	222	includes PV and CSP	0.13

National economic status

Studies utilizing data from countries with developed economies were prioritized in this analysis over studies that utilized data from countries with developing economies, for the following two reasons: Firstly, the subject at hand, landscape impact of RE, is more relevant to developed countries that have the "privilege" of optimizing their energy generation in terms of sustainability and landscape integration. Developing countries still battle with providing their citizens with basic commodities, in a much larger percentage than developed countries do, a fact that has been affecting their ability to mitigate environmental and landscape impacts and their effort to develop RE, overall. Secondly, it is the opinion of authors that RE projects that are built in developing countries, are more prone to be damaging to the environment and the landscape. This is mainly attributed to the lack of social structures of environmental and landscape protection and the increased presence of autocratic regimes and corrupt procedures. The combination of those two factors leads to a general disregard of the environmental aspects of projects of infrastructure, in such a scale that the analysis of landscape impacts in developing countries would require separate and specialized research.

2.3 Land Use

The land area that is used by RE developments is certainly altered from a landscape perspective, either directly or visually [28]. Thus, land use has been extensively used as a spatial metric of landscape impact [28,29,64–66]. Land use is additionally identified as the least subjective out of the three metrics that are analyzed, as it is the least dependent on personal opinions and biases, in comparison to visibility and public perception.

Overall, the literature review demonstrated a general consensus in estimates of solar and wind energy land-use and an adequacy of studies utilizing large and credible data sets. The review of hydroelectric land use however, was more complex, due to discrepancy in estimates and lack of in-depth studies. The discrepancy of hydroelectric land use estimates is demonstrated excellently in the data compiled from literature by Trainor et al. [28]. The largest and smallest estimates of direct land use were respectively: 6.45 and 86.95 km^2/TWh for hydroelectric, 0.34 and 1.37 km^2/TWh for wind and 12.30 and 16.97 km^2/TWh for solar energy; the ratio of largest to smallest estimate being 13.5 in the case of hydroelectricity, larger by almost one order of magnitude to the ratios of wind and solar energy, which were 4 and 1.4.

2.3.1 Solar and wind energy land use

In literature, land use of solar and wind energy are divided into two types: (a) Direct land use that is the area occupied by RE equipment, facilities and works of infrastructure and (b) total land use that is the area enclosed by the boundary of the property used [64,65]. Total land use, which is the most extensive of the two, was preferred as a metric, in the context of landscape impact. This was due to the fact that wind turbines and solar panels are visually and aesthetically dominant within the property they are installed[28], for different reasons in each case, as described subsequently.

In the case of solar energy, direct and total land are almost equivalent. For major solar photovoltaic (PV) projects direct land use constitutes of approximately 90% of the total land use area, as is demonstrated for example by Ong et al. [65] that estimate 13 759 m^2/GWh for average total land-use and 12 545 m^2/GWh for average direct land-use. This is to be expected since solar panels do not have extensive spacing requirements like wind turbines (as described below). As a result, the land properties required for their installation need only accommodate the panels, access roads and small auxiliary facilities and are thus almost completely filled. It is therefore reasonable to assume that the panels are dominant within this area from a landscape perspective, both visually and due to glare effects, which are stronger in their proximity [89].

In the case of wind energy, the difference between direct and total land-use is more significant. Indicatively, as described by Denholm et al. [64], direct land use of wind developments is 3000 ± 3000 m^2/MW and total land use is 340 000 ± 220 000 m^2/MW. This difference is justified by the fact that wind turbines are sited in distances of 3 to 10 rotor diameters apart (120-900 m for 40-90 m blades to optimize the absorption of wind energy. This generates the requirement for larger and more complex land properties for wind energy projects. But even though turbines and works of infrastructure only occupy a small percentage of the properties used, literature suggests that their presence is perceivable in a much larger area due to their size, the movement of their blades and the noise they generate under certain conditions [90,91].

In particular, relevant studies suggest that the visual/landscape prominence or domination of wind turbines exceeds from 1 to 6.4 km away from their location. Indicatively, The Sinclair – Thomas matrices [92] (as cited by Buchan [48]) present 4 km as the radius of dominant impact for wind turbines with heights ranging from 90 to 100 m. Similarly, Sullivan et al. present 6.4 km as the radius in which a wind turbine is considered a "commanding visual presence that may completely fill or exceed the visible horizon in the direction of view"[93]. Finally, Bishop, Stevenson and Griffiths, SNH and Buchan all agree on a distance of 2 km as distance in which a wind turbine is dominant visually [48,49,67,94] and finally Vissering et al. [95] conclude that the greatest impact is expected at up to 800 m and impact on "the integral part of scenic view" at up to 4 km.

In an investigation of the relation of the area of landscape dominance to the area of total land use a simplified calculation of the theoretical visual impact of a common 3 MW wind turbine of 2019 was carried out. Such a turbine (with a rotor diameter of 80m, tower height of 90m and tower diameter of 6m) occupies 50 m^2 at its base [96], but is expected to be visually dominating, in an area larger than its total land use equivalent, even when the smallest distance of highly-perceived visibility from literature is used. Using 800 m [95] as the radius of a circle of visual dominance around the turbine, the area of impact was calculated 670 000 m^2/MW. Even if the turbine is not fully visible in this area due to concealment from terrain, tall buildings etc., this estimate significantly surpasses the average total land use estimate of wind energy that is 176 000 m2/MW (as explained later). The distance of 800 m, which is used in this example, is also equal to the distance of 10 rotor diameters, which is a common distance for adjacent turbines in a wind energy development. Thus, the reduction to the average area of visual impact due to overlapping of visual impact from adjacent turbines is not expected to affect the estimation. Furthermore, if the larger distances of visual dominance from the previous paragraph are used the difference is even larger. For example, if a radius of 2 km is used [48,49,67,94] the area of maximum theoretical impact of a single turbine is 4 188 790 m^2/MW.

Thus, with total land use established as the type of land use that is more relevant to landscape impacts from solar and wind energy projects, we proceeded on analyzing relevant literature and concluding on generic estimates. Since literature on the subject was sufficient and in general agreement, own verification calculations were not required. Two NREL reports from USA [64,65], whose results have been already been cited in relevant studies [28,66], stood out and were distinguished as suitable for generic use. The reason for their selection was that they were the best match to the screening criteria of section 2.2.2. In detail, (i) the datasets analyzed were large and nationwide, (ii) the ruggedness index of USA is very close to the global average (Figure 1) and therefore the results are not expected to be biased due to terrain topography, (iii) they were presented in terms of installed capacity and thus allowed for the use of the global CFs of Table 2 for their conversion to corresponding energy generation (iv) they originated from realized wind and solar energy projects in the USA and did not embody theoretical estimates and finally (v) USA has a developed economy status. Furthermore, since they were specifically conducted to measure land use, these studies were very meticulous, allowing for a thorough review of the methods used and their results and they were also in general agreement with the other estimates from literature. Indicatively, the estimates of other relevant studies, that are analyzed in the next paragraph, average 163 300 m^2/GWh for total land use of wind energy, while Denholm et al. estimated 176 000 m^2/GWh [64]; and 46 204 m^2/GWh for solar energy while Ong et al. estimated 28 000 m^2/GWh [65]. In Table 3 we present the results of this section as well as the estimates of Ong et al. and Denholm et al. in m^2/MW before their conversion to m^2/GWh, with the use of the CFs of Table 2.

In other literature, total land use of wind energy, was estimated at 126 920 m^2/GWh by Trainor et al. [28], 103 777 ± 51 889 m^2/GWh by Ledec et al. [97] and 25 000 to 110 000 m^2/GWh by Gagnon et al. [98]. In the study of Hertwich et al. [66], the results of five studies on total land use were compiled, ranging from 43 240 to 475 646 m^2/MW [99–103] or 22 437 to 246 807 m^2/GWh, when converted in terms of energy generation, and averaging of 191 508 m^2/GWh. Van Zalk and Behrens [30] estimated average total land use of wind energy at 326 797 m^2/MW, i.e. similarly 169 571 m^2/GWh, analyzing literature from the USA. Finally, the estimates from the more recent studies of Fritsche et al. [104] and IINAS [105], which are much smaller, 1000 m^2/GWh and 700m^2/GWh respectively, refer to direct land use which, as previously mentioned, is indeed very small in the case of wind energy.

Regarding total land use of solar energy, Gagnon et al. [98] presented the highest and lowest estimates found in literature in 2002, 30 000 and 45 000 m^2/GWh respectively, Trainor et al. [28] estimated it at 15 100 m^2/GWh, while Van Zalk and Behrens produced the largest estimate so far, 126 582 m^2/MW [30] converted to 111 154 m^2/GWh using of the CF of Table 2. Finally in the website of UCS it was estimated in the range of 14 164 to 40 469 m^2/MW [106], which averages 21 063 m^2 when converted to corresponding energy generation using the global average CF of Table 2. Lastly, Fritsche estimated 10 000 m^2/GWh [104] and IINAS 8700 m^2/GWh [105] for direct land use of solar energy, which is in fact smaller than total land use.

Table 3. Estimates of total land use requirements of wind, solar and hydroelectric. The estimates were singled out from literature on the basis of highest generic applicability.

Type of renewable energy technology	Total land use per unit installed capacity (m^2/MW)	Total installed capacity of data sets used (GW)	Source of total land use data per unit installed capacity	Total land use per unit energy generation (m^2/GWh) [a]
Wind (Onshore >20 MW)	340 000	25	(NREL,2009)	176 000 [b]
Solar (PV >20 MW)	31 970	3.6	(NREL,2013)	28 000 [b c]
Hydro (Large hydroelectric dams (non-multipurpose reservoirs))	-	Unknown [d]	(Trainor,2016)	16 900

a. Results rounded up to one thousand.

b. Conversion of installed capacity to energy with the use of corresponding CF's of Table 2

c. CSP land use does not present significant difference in the report of Ong et al. [65].

d. Data set consists of 50 randomly selected hydroelectric reservoirs from the USA (Trainor,2016). The scale of the estimate was verified by own calculations based on data sets of 9.7 GW of installed capacity from Spanish and Greek hydroelectric reservoirs.

2.3.2 Hydroelectric energy land use

Land use of hydroelectric projects is measured through the land area that is used by hydroelectric reservoirs. In reality, land is also used by the dam, the power plant and other appurtenant structures, but the reservoir area is larger by several orders of magnitude, rendering these additional land-uses negligible[3]. Hydroelectric land use, as measured through the reservoir area, can be considered an adequate metric of landscape impact for the following reasons: (a) The major landscape transformation of hydroelectric projects is, in fact, the inundation of sections of river valleys, for the creation of artificial lakes and (b) as described in detail in the next subsection, negative visual impact from reservoirs and hydroelectric facilities has not been reported in literature. Therefore, in contrast to wind and solar energy, the landscape impact of hydroelectric projects can be fully quantified through its direct land use, i.e. the reservoir area.

However, a generic estimate of hydroelectric land use was harder to reach in comparison to solar and wind energy as there was no consensus in literature. This prevented a quick and definitive conclusion and instead generated the requirement for in-depth analysis of published research and supplementary own calculations. All estimates of hydroelectric land use based on national or global data that were compiled from literature are presented in table 4. The estimates present a wide range, the lowest and highest being 2000 m^2/GWh and 768 234 m^2/GWh. For comparison, the range defined by these estimates is 766 234 m^2/GWh, while the corresponding ranges for solar and wind energy land use, are 35 000 and 221 807 m^2/GWh, respectively.

Investigation of the discrepancy

A level of variability is generally justified in estimates of land use from hydroelectric projects since the average surface area of hydroelectric reservoirs is dependent both on the average terrain topography of

[3] This is verified by calculations of land use of hydroelectric infrastructure in section 2.3.2.3.

the area examined and on the exact locations selected for the projects, within this area. Thus, variability is to be expected, especially when comparing studies that analyzed data from various different countries or regions. However, the following observations made during the review of literature, indicated that the discrepancy of estimates of hydroelectric land use might be caused or exaggerated by additional factors. In summary, these observations were (a) the lack of correlation of estimates to topographical relief, i.e. flat countries having smaller ratios of average reservoir area to energy generation and more mountainous countries having larger ratios, and (b) several irregularities in the data selection processes of relevant studies and especially in older literature.

In more detail, the first possible explanation that was examined in the investigation of this discrepancy was the aforementioned sensitivity of hydroelectric land use to terrain topography. However, no correlation of average reservoir surface with the countries' terrain was identified in the compiled estimates. Indicatively, even two studies on the extremes of the range of the estimates (IINAS – 3500 m^2/GWh [105] and Pimentel et al. 750 000 m^2/GWh [107]) had used data from countries with similar and, in fact, close to average terrain; in particular, their ruggedness indexes were calculated 0.6 (Germany) and 1.1 (USA), respectively, in the analysis of Nunn and Puga [87] (Figure 1). Furthermore, even two studies that utilized data from the same country reached conclusions on average reservoir area that differ greatly; Pimentel et al. estimated 750 000 m^2/GWh [107] and Trainor et al. 16 900 m^2/GWh [28] for hydroelectric land use in the USA. Unexpectantly, their difference, 733 100 m^2/ GWh, is almost as large as the total range of estimates of Table 4, i.e. 748 000 m^2/GWh.

The second possible explanation that was investigated, was the presence of estimates that overestimated or underestimated hydroelectric land use. To explore this scenario the studies of Table 4 were examined in detail, placing emphasis on the data that were used in each case. Unfortunately, accessibility to utilized datasets used was limited in the more recent of the studies [28,104,105]. These studies presented generic estimates without reference to particular datasets. The older studies of Gagnon and van de Vate, Goodland, and Ledec and Quintero [84,108,109] were more descriptive over data selection but important irregularities were identified when they were analyzed in depth. In particular, the datasets used, which were largely common between the three studies, were found to be partial to reservoirs with bad environmental design. In the studies of Ledec and Quintero and Goodland [108,109], 96% and 94% of the projects analyzed respectively originate from countries with developing economies and additionally Ledec and Quintero included some particularly small projects whose average reservoir area is larger by two orders of magnitude from the largest recorded estimate of hydroelectric land use (or by four orders of magnitude from the smallest recorded estimate). This is justified by the fact that the aim of these studies was the analysis of extreme environmental impacts of hydroelectric projects, rather than the estimation of an average of hydroelectric land use. Furthermore, several of the reservoirs used in the calculations are not exclusively hydroelectric but are multipurpose reservoirs, which is expected to contribute to overestimations. It has to be noted that Goodland, in contrast to Ledec et al., does not claim to have reached an estimate of global average of hydroelectric land use, with the use of these data. The study of Gagnon and van de Vate [84], referenced several other data sources in addition to Goodland [108] but unfortunately the majority of the cited studies could not be accessed. On the basis of the preceding arguments as well as the further in-depth analysis of Appendix A on the three aforementioned studies, their results were not considered suitable for inclusion in the calculation of a generic estimate of hydroelectric land use.

Table 4. Estimates of Hydroelectric land use from literature (in which national data or compilations of global data were used)

Geographic origin of data set	Dataset details	Land use per unit energy generation (m^2/GWh)	Source
N/a	Generic estimate by authors	10 000	[104]
Germany	Na	3500	[105] as cited in [104]
USA	47 hydroelectric dams randomly selected from the National Hydrography Dataset	16 900	[28]
China	Representing 22.1 GW of installed capacity	24 000	[110] as cited in [84]
Switzerland	Representing 11.8 GW of installed capacity	2000	[85] as cited in [84]
N/a	Personal communication of Ledec and Quintero with J. Goldemberg	185 117	[109]
USA	Based on a random sample of 50 hydropower reservoirs in the USA	750 000	[107]
Asia & Africa & Latin America	189 projects: Many small dams in Africa [a]	86 872	[108] as cited in [84]
Various	Estimated using data from the World Bank (Goodland,1995), which is based upon a survey of nearly 200 plants.	98 729-768 234[b]	[108] as cited in [111]
Varioys	Calculated using the sum of installed capacity and reservoir area of all referenced projects	34 181[c]	[108]

a. Original data of Williams and Porter[111] was in m^2/MW and was converted to m^2/GWh with the CF of Table 2.

b. Weighted average (in terms of installed capacity) of the three cited figures

c. The CF of Table 2 was used for conversion from m^2/MW to m^2/GWh.

Challenges in calculating hydroelectric land use

The irregularities found in the older studies that were referenced previous subsection [84,108,109], demonstrated the need to access and thoroughly examine the data sets used in each study of hydroelectric land use. However, since detailed data sets were actually not found in the remaining studies [28,104,105,107], we concluded that it was necessary to perform own verifying calculations. During this process, we identified some inherent challenges in the estimation of hydroelectric land use [112], which might be partially responsible for the difficulty of the academia in reaching a consensus on hydroelectric land use. In the case of solar and wind energy projects, calculation of land use is less complex than hydroelectric projects as it only depends on two variables: (a) the size of area used by the projects and (b) their energy generation or installed capacity. For hydroelectric reservoirs, other than the surface area of the reservoir and the energy generation or installed capacity of the hydroelectric power plant, the same calculation additionally requires:

- Identification and separation of single-purpose hydroelectric reservoirs and multipurpose hydroelectric reservoirs: It is common for hydroelectric projects to be combined with other water uses as part of multi-purpose reservoirs [98,113]. In particular, according to data from the International Commission on Large Dams, out of the 5786 hydroelectric dams globally 3932 are multi-purpose dams [114]. However, to avoid overestimating hydroelectric land use, reservoirs with additional uses that affect the volume of water storage, such as water supply, irrigation, industrial use and flood control, should not be included in the calculations.
- Understanding of the multiple (in some cases) components of hydroelectric complexes: The structure of a hydroelectric complex is not always binary, consisting of a single reservoir and a single power station. On the contrary, it can be a very complicated system consisting of several reservoirs and power stations, in distance [115]. Tracking the multiple components of a hydroelectric complex can be challenging, due to their spatial dispersion and their differentiation in size. Their omission of a single component however, can alter results significantly. For example, if a pumped storage reservoir upstream or an additional power station downstream of the main dam is omitted, this will lead to miscalculation of the installed capacity and thus of the land-use of the project (per installed capacity). Especially in extensive calculations, which include multiple hydroelectric projects, avoiding such omissions can be challenging.

Gagnon et al. highlighted cases in which these challenges were not fully addressed, in their literature review [98], and furthermore, in this article, the studies of Ledec and Quintero and Goodland [108,109] are highlighted for similar omissions (see Appendix A). To avoid biased estimates, if studies did not clarify whether they dealt with these challenges or if their data sets could not be accessed to be inspected (e.g. [107,109,110]) they were considered potentially prone to not having addressed them and where thus not included in the generic estimation of hydroelectric land use.

Conclusion on hydroelectric land use

In recent analyses, Trainor [28], Fritsche [104] and IINAS (as cited in [104]), estimate hydroelectric land use in the range of 3000-16 900 m^2/GWh. Out of them, the study of Trainor et al., which is based on a random sample of 47 hydroelectric projects in the USA, was found to suit the secondary screening criteria of section 2.2.2 and the additional considerations over hydroelectric land-use calculations the best, for the following reasons: (i) all projects used wwere single-purpose hydroelectric projects (Trainor, personal communication, Mar 27, 2019) randomly compiled in a national scale, (ii) data originated from USA that has moderate terrain topography (Figure 1), (iii) data were presented in terms of energy generation, (iv) based on realized energy generation data and finally, (v) USA has developed economy status. Thus, 16 900 m^2/GWh was selected as the estimate with the best generic applicability regarding land use of hydroelectric reservoirs. The older estimate of Pimentel et al. [107] (Table 4) that was also based on a random sample of 50 hydroelectric reservoirs from the USA, was not utilized since the authors did not clarify whether these were multipurpose reservoirs or not (personal communication efforts proved unsuccessful). As a result, based on the arguments for the previous subsection it was not considered suitable. Despite the consensus in these more recent studies, the data set that supports the estimate of Trainor is not very extensive and both Fritsche [104] and IINAS (as cited in [104]) did not provide detailed data-sets. Therefore, some additional calculations were carried out for the verification of the estimate. The projects used for verifying calculations were (a) Spanish hydroelectric dams of installed capacity larger than 100 MW [116,117] and (b) the complete list of Greek hydroelectric dams. Greece is a country with relatively high terrain ruggedness, and therefore Greek hydroelectric reservoirs were expected to require smaller land use than the global average. Nonetheless, they were included as a secondary verification, because of the accessibility and the in-depth knowledge of the relevant datasets to the authors. The results are presented in Table 5 and are close to the estimate of Trainor et al.

Table 5. Spanish and Greek hydroelectric reservoir land use data.

Data set examined	Land use per unit installed capacity (m^2/MW)	Installed capacity of projects (GW)	Data source	Land use per unit energy generation (m^2/GWh)[a]
Greek hydroelectric dams	44 291	1.1[b]	[118]	14 000
Spanish hydroelectric dams	41 304	8.6[c]	[116,117] [d]	13 000

a. Includes reservoir area and an additional 200 m^2/GWh for appurtenant structures (in accordance to the calculation of average land-use of appurtenant structures). Estimates rounded up to one thousand.

b. Total hydroelectric capacity examined was 3.3 GW, 1.1 GW of which was from single-purpose hydroelectric reservoirs.

c. Total hydroelectric capacity examined was 11 GW, 8.6 GW of which was from single-purpose hydroelectric reservoirs.

d. García Marín and Espejo Marín as source for installed capacity and SNCZI as source of reservoir area.

Other than the reservoir area, additional land uses of hydroelectric projects were also calculated to investigate their contribution to total land use, since relevant data were not found in literature. In particular, the sum of the area of the main dam, auxiliary dams (when present), modified slopes, power stations, visible pipelines and other auxiliary structures was measured, for Greek single-purpose hydroelectric reservoirs, using Google Earth. The average land required for these uses was calculated at 200 m^2/GWh, which is an insignificant amount in the scale of the calculation of hydroelectric land use (Figure 2).

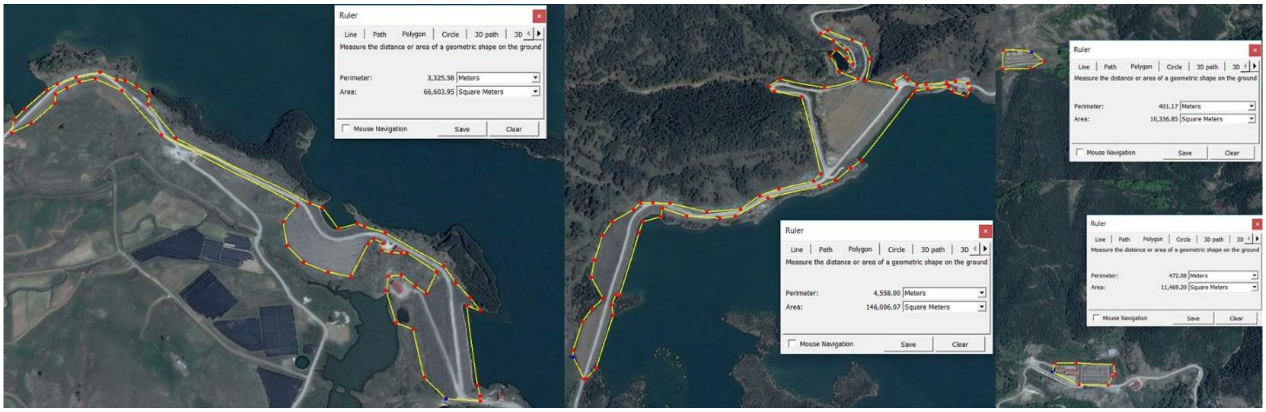


Figure 2. Example of measurements of land use from appurtenant structures and adjacent engineering works in a hydroelectric project. The project presented, Piges Aoou dam, had the most extensive non-reservoir land use out of the Greek hydroelectric dams, consisting of the power station, main dam, auxiliary dams and other appurtenant structures.

2.4 Visibility

Other than the direct impact on landscapes, which is measured by land-use, landscape impacts are also generated due to the visibility of renewable energy projects. This so-called visual impact, although more subjective, can extend several kilometers away from the project's locations. Visual impacts of RE developments have been extensively analyzed in scientific literature [27,29,42,49,95] and in institutional environmental impact assessment guidelines, which include measures to quantify and reduce these impacts, primarily for wind energy projects [50,119,120].

Hence, several methods have been developed to estimate and quantify visual impact, ranging from photomontage and digital representation to GIS-based viewshed analyses [121–125]. Since the aims of this section are the review and elicitation of generic estimates on the visual impact of different RE technologies, priority was given to methods of estimating visual impact that have been applied widely in national or regional scale, with similar or comparable technical assumptions. The methodology that fulfilled these criteria the best was the so called "viewshed analysis" and in particular, the calculation of "zone of theoretical visibility" (ZTV) [126] or "zone of visual impact/influence"[127], as it is also called. ZTV is calculated with GIS technology in the form of a binary map presenting the areas from which an object, e.g. a wind turbine, is visible and the areas from which it is not. Even though this method describes deterministically a phenomenon which is not deterministic [128], i.e. the discernibility of an object changes according to weather conditions, time of the day, eyesight of viewer etc., it was preferred in relation to other methods for the following two reasons: (a) It is the only technique that has been applied, in several cases, on estimations of landscape impact on a large scale, national or regional, and (b) it is a method of spatial quantification of visual impact, in which visibility is determined by the examination of terrain morphology, without the incorporation of indexes of impact-perception. This is in contrast to several other common methods of evaluating visual impact, such as the Quechee Test [129], multicriteria analyses [130,131], visualization and image analysis techniques [132,133], the Spanish method [122], etc. that intertwine spatial analysis with perception analysis. Even though the combination of spatial and perceptual analysis renders such methodologies more complete, it also renders them more complex and more difficult to scale up, to analyze visual impact on large scale. Furthermore, since perception on landscape impact of RE technologies is analyzed separately in the next section, the analysis of visibility in this section is primarily focused on its spatial aspect.

All types of viewshed and ZTV analyses are described by a common calculation methodology; a digital elevation model of the area of interest is used, in which the locations of the objects that cause visual impact are pinpointed and their visibility is calculated radially with a line-of-sight test. When examined more thoroughly though, different analyses present variation on the setup of several parameters that potentially affect the size of the ZTV calculated. The majority of published studies analyzed, presented at least a few differences in the setup of these parameters, however most of them were considered minor and were not analyzed in depth. An exception to this was the maximum distance of visibility of wind turbines. Maximum distance of visibility was considered a major differentiating parameter among studies on visibility of wind energy projects as it was found to range from 10 km to 35 km, which was expected to have a significant effect on the size of the generated ZTVs. Other than the maximum distance of visibility, which is analyzed in depth in the next paragraph, examples of minor differences between the various ZTV analyses that were not analyzed further are: the adjustment of elevation according to land-use height, which was only taken into account in a few studies [34], the inclusion of visibility of wind turbines from regions sharing borders with the area examined [31], observer height and observed object height [33].

Maximum distance of visibility or visual threshold[4] defines the spatial extends of the area that is investigated for visibility. Thus, it is arguably the parameter that affects the results of a ZTV calculation of the most. In literature, the maximum distance of visibility of a wind turbine in clear weather conditions from an "unaided eye" is reported as long as 58 [93] or 42 km (for offshore wind turbines)[134]. In ZTV analyses however, the distance used is usually shorter, but varies greatly from study to study. The distance in which visual nuisance is considered significant but not dominant, ranges from 3 to 40 km in literature. For example Bishop [67] describes that "visual impact remains `in the eye of the beholder' but may well become minimal beyond 5 km to 7 km". Similarly, the Thomas Matrix and Sinclair Matrix, as cited by Sullivan et al. [93], present distances of 3-4 km and 7.5-12 km, respectively, as distances of moderate impact but potentially intrusive. Betakova et al. propose visual thresholds of the same scale, 10 km for landscapes with "high aesthetic values" and 5 km in "less-attractive landscapes" [135]. This correlation of visual impact perception with the quality of the examined landscape, has also been supported in other studies, e.g. by Molnarova et al. [136]. Sullivan et al. estimate the distance of major perceived contrast at 16 km, [93] and the general trend in more recent studies, is the promotion of larger distances for the calculation of ZTV for average-sized wind turbines, like 48 km by Sullivan et al. [93], 20 km by Bishop [67] and 16 to 40 km by Vissering et al. [95]. Moreover, in the recent version of guidelines from SNH, which are considered to be among the most reliable in the scientific field of visual-impact analysis [137] and have been applied extensively[32,33], the use of a 35 km threshold is suggested for ZTV analyses of modern wind turbines, with heights of 101-130 m [138].

As can be observed in Table 6, the maximum visibility threshold in the compiled large-scale ZTV studies ranges between 10 and 35 km. To mitigate the fluctuation that is expected in the results of ZTV analyses based on this variation of the visibility threshold and allow for a more fair comparison of the compiled studies, we also included a simplified homogenization of the results. The homogenized estimates are presented in Figures 3 and 4, which explore the spatial evolution of ZTV in relation to installed capacity and energy generation. The homogenization was made by scaling the ZTV of each cited study with a weight based on the ratio of the visual threshold used in each study to the average visual threshold of all studies [5] that was 20.83 km.

[4] It is also referenced in literature as discernibility range [34].
[5] Except the study of Rodrigues et al. [34], who did not use a universal visual threshold, but calculated a unique visual threshold for each renewable energy facility examined.

It is noteworthy that Table 6 includes ZTV analyses exclusively from wind energy projects. This is due to the fact that large-scale visibility analyses have only been carried out for wind energy; with one exception, the ZTV analysis of Rodrigues et al. [34] that also included solar energy developments. This lack of research interest for solar and hydroelectric energy, is to be expected based on the initial observations of section 1.3 and the differences of the examined technologies in regard to perception of landscape impact, which are analyzed in detail in the next section and the discussion. However, differences in terms of topographical extents of visibility are also present and are noticeable in the analysis of literature on visual impact. In particular:

- Solar energy developments are more easily concealed within terrain forms, and as a result they generate much smaller visual impact than wind turbines. The height of PV panels is usually less than 5 m whereas the height of wind turbines, with current technology, ranges from 125 to 247 m [139] (heights of models V90-2.0 MW IEC S and V162-5.6 MW DIBt S of Vestas, respectively). The spatial differences of visual impacts from solar and wind energy are also demonstrated by Rodrigues et al. [34], who estimated that the visually affected area from wind energy approximately 3.6 times larger than the visually affected area from solar energy, in two scenarios of similar energy generation from wind and solar energy in Spain (50 TWh/year from wind energy and 53 TWh/year from solar energy). Furthermore, a study by Sullivan et al. [93] on the visual threshold of solar energy projects it was estimated to range between 24 and 35 km. This illustrates that were there not for the small height of solar panels, they would probably produce comparable visual impact to wind energy projects.
- Even though reservoirs are definitely the cause of major direct-transformation to landscapes [140], hydroelectric dams have attracted very limited research interest regarding the visual aspect of their impact to landscapes [60]. From a spatial standpoint, this is justified by the fact that hydroelectric facilities and reservoirs are usually concealed in valley terrain. Even though large-scale ZTV analyses have not been carried out for hydroelectric projects, this is excellently demonstrated in the study by Dehkordi and Nakagoshi [141], where it is shown that the ZTV of the infrastructure and reservoir of Haizuka dam, in Japan, is confined within the borders defined by the ridges of the valley where the project is constructed. Similar arguments have also been formed by Cohen et. al. [60]. Visual impact from reservoirs has also been analyzed by Christofides et al. [142] and Sargentis et al. [143] but on another context; i.e. investigating the aesthetics of a reservoir depending on water level with the aim of optimizing the view from touristic facilities —which were developed because of the reservoir—rather than calculating a visually affected area.

Table 6. Data and results from national and regional-scale visibility analyses of wind energy projects.

Name of country/region	Installed capacity (MW)	Zone of theoretical visibility (km^2)	Visibility threshold (km)	Source	ZTV per unit energy generation (km^2/GWh)
Spain	23 066	85 736	35[a]	[34]	1.71
Netherlands	2206	7121	10	[35]	1.69
Poland (Kuyavia-Pomerania)	282	11 033	30	[32]	20.30

Denmark (North Jutland)	513	7616	30	[31]	7.37
Spain (Andalucia)	2992	87 555	15	[82]	1.18
Scotland	4776	78 809	30	[33]	3.24
Greece (South Aegean)	95	1453	10	[83]	7.94

a. Rodrigues et al. [34] did not use a fixed number but an equation for the calculation of the visibility threshold of turbines according to their height. The equation was used here for a V63 – Vestas wind turbine (91.8 m total height; https://en.wind-turbine-models.com/turbines/821-vestas-v63), which was considered representative of the average wind turbine in Spain.

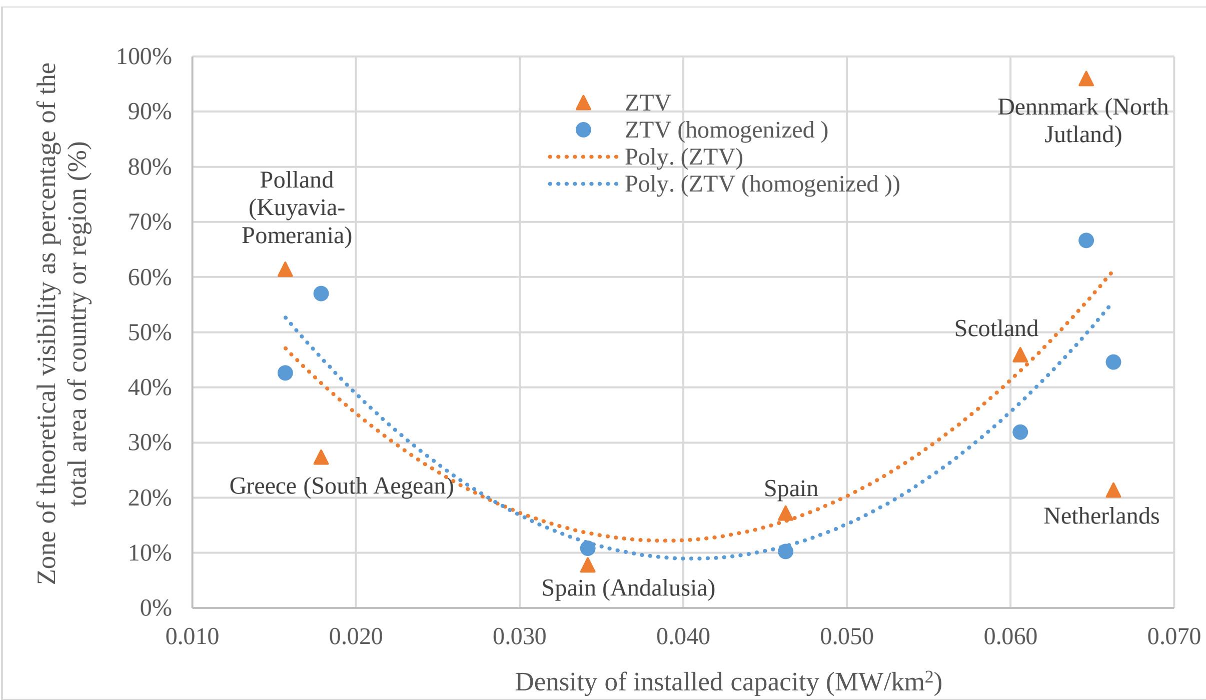


Figure 3. Area of countries/regions from which wind turbines are theoretically visible vs. density of installed capacity. Sources of visibility data are presented in Table 6. A homogenized version of the results, based on the average visual threshold used in the studies, is also plotted as a meta-analysis of the visibility threshold.

Ultimately, generic estimates of visibility were calculated or selected utilizing the results of the examined ZTV analyses that fulfilled the secondary screening criteria developed in section 2.2.2. In detail, the distinguished studies (i) were based on regional or national data sets, (ii) analyzed data from countries with moderate terrain (Spain and UK), according to Figure 1, (iii) did not embody theoretical capacity factors in the calculations, (iv) did not produce theoretical estimates[6] but utilized original data from realized projects

[6] It has to be noted that the two estimates of Rodrigues et al. for. for wind and solar energy, refer to hypothetical scenarios of energy generation. These scenarios were considered realistic however, based on their proximity to actual energy generation in Spain and the incorporation of parameters related to energy efficiency, terrain and protected areas in their generation.

and (v) analyzed data from countries with developed economies. For wind energy, the three studies of Table 6 that fulfilled the aforementioned criteria were averaged. These studies utilized data from Spain [34], Scotland [33][7] and the region of Andalusia [82][8] and their average was 2.01 km^2/GWh. For solar energy, the generic estimate produced was 0.45 km^2/GWh, based on the only available large-scale ZTV study of Rodrigues et al. [34]. Finally, for hydroelectric energy no large-scale ZTV analysis or other type of visibility analysis was found in literature.

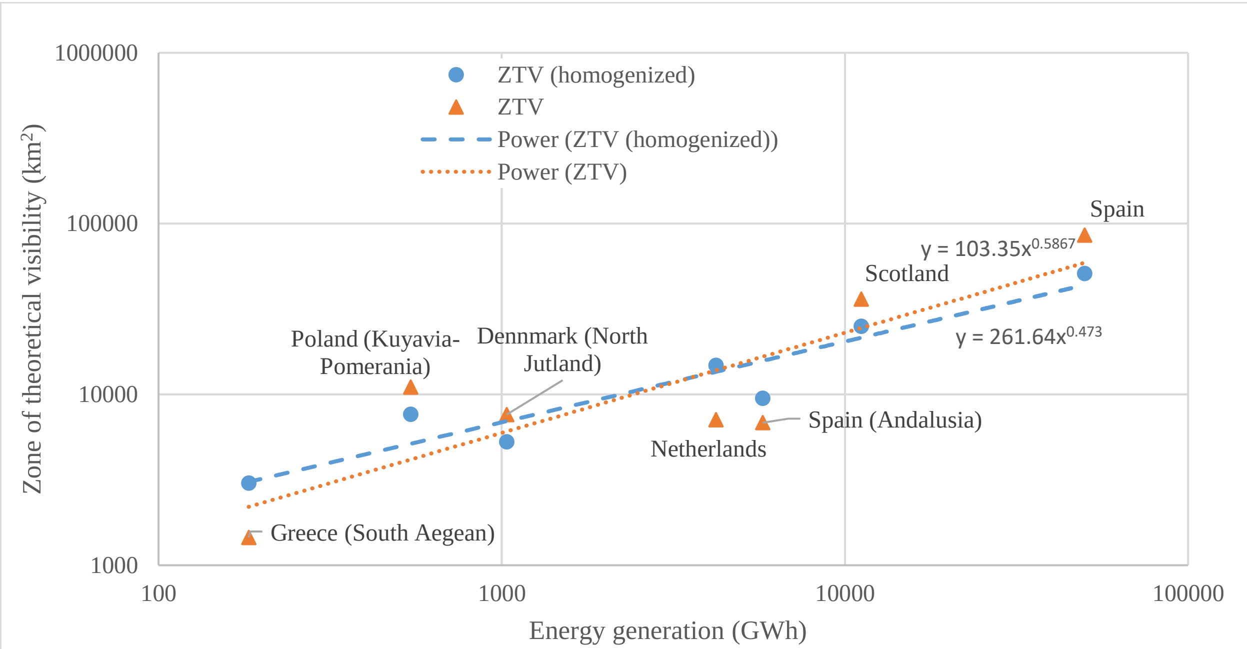


Figure 4. Zone of theoretical visibility of wind turbines vs. energy generation. Sources of visibility data are presented in Table 6. A homogenized version of the results, based on the average visual threshold used in the studies, is also plotted as a meta-analysis of the visibility threshold.

2.5 Public perception

The greatest difficulty in quantifying the impact of RE on landscapes is the innate subjectivity of analyses related to aesthetics. This is excellently demonstrated by the following discrepancy: On the one hand, part of the public views wind turbines as beautiful new elements in landscapes and perceives them as symbols of human progress and sustainability [7,45,68]. On the other, wind turbines are also viewed as disturbing structures, unrelated to the historical and natural characteristics of landscapes, and perceived as elements of industrialization [16,45,125,144]. Generally, this type of subjectivity is always present in the analysis of landscapes and is to be expected based on the definition of landscape by the Council of Europe [145]: "Landscape means an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors". The phrase "as perceived by people" demonstrates this subjectivity of public attitudes, as it links the understanding of landscape with one's own perception of it. Perception is neither exclusively emotional nor rational, but is defined in each person by a mixture of several factors [146], some of which are formed by emotion and others by rationale. To some, the view of a RE project

[7] Scotland is expected to have a higher ruggedness index, than UK (the study on Nunn and Puga [87] only provided the ruggedness index for the total of the UK and thus this was the index that was used) but is not expected to be higher than 2, which is the equivalent of 75% in Figure 1.

[8] There is no indication that the ruggedness index should be significantly larger than the national average of Spain which is close to the limit frequency of 75%.

might be unpleasant purely because of aesthetics and emotion [147] while to others because of a rational analysis based on personal ideologies [69].

Concepts like landscape impact-perception have in several occasions been downgraded and omitted from planning analyses [112,148,149]. In this analysis however, public perception is identified as an integral element of the discussion on landscape impact of RE; at least of equal importance with the other two metrics analyzed. Even though public perception on landscape impact is subjective and difficult to quantify, its effect on the development of RE has become quite objective and quantifiable. This has been proved by the various cases in which public perception on landscape impact determined the emergence of opposition and thus the approval, delay or cancellation of RE schemes, as presented in the introduction of the study. More generally, the overall management of public attitudes on RE has been recognized as a prerequisite for sustainable design [72] and perception on landscape-impact is one of their main determinants. Additionally, positive or negative perception on the aesthetics of RE installations is also strongly related to the spatial aspect of landscape; it determines the negative perception of visibility of RE developments and the existence of zones of visual impact [29], in addition to the indisputable direct impacts to land surface.

So far, public perception on RE projects —in general, including but not limited to perception on landscape impacts— has mostly been quantified through statistical analyses whose sample data originate from surveys. The surveys are carried out through questionnaires and interviews with people living in proximity to RE developments [13,144,150–155], experts [156,157] or stakeholders [144,153,158]. Some of the surveys are additionally accompanied with pictorial stimuli [159,160], for the participants to specifically evaluate impact on landscape. In literature, the vast majority of studies refer to wind energy and fewer to solar energy [155,157,161] and hydroelectric energy [154,155]. Visual intrusion or landscape impact are broadly recognized as one of the fundamental components of negative perception for wind energy and are also mentioned in a smaller extent for solar energy as well. In the case of hydroelectric energy negative perception is mostly attributed to other factors, such as environmental and social impacts.

To quantify public perception on landscape impact we carried out a statistical perception analysis of literature on the topic of landscape impact from RE to extract indexes of perception. Relevant literature has proliferated over the past 20 years, ensuring the availability of a sufficiently large sample of studies. The basic logic for selecting this type of analysis was that it allowed for the integration of both (a) the perception of the scientific community and (b) the perception of the general public. In particular, the perception of the general public is indirectly included, through surveys and questionnaires used in the analyzed studies. Indicatively, several of the articles examined present results from research made through questioning samples of citizens, decision makers and stakeholders affected by RE schemes [46,125,153,160,162–168] or research articles analyzing media coverage on the landscape impact of RE [58,169–171]. Thus, we believe that an elitist approach is avoided and the perception of the public is covered though a wide spectrum of opinions.

In more detail, the statistical analysis started with the collection of scientific articles from the search engines of Elsevier, Wiley and Springer online databases. We used the search strings "hydroelectric energy landscape impact", "wind energy landscape impact" and "solar energy landscape impact". For each search string the first twenty results from each data base were collected, leading to the collection of a total of 60 publications per RE technology. The publications were read through and searched with an algorithmic procedure for sentences that were statements of perception, i.e. phrases that stated that the RE technology examined has a negative or positive effect to landscapes. According to these sentences, publications were then categorized as being positive, mixed or negative towards the landscape impact of each of the three RE technologies examined (Figure 5). The exact algorithmic procedure followed and the publications analyzed are presented in Appendix B and in the supplementary material.

To present the results of the perception analysis in as simple format, we calculated an index of perception for each RE technology. This index was calculated as the percentage of publications labelled "Negative" minus the percentage of publications labelled "Positive". Publications labelled as "Mixed" include both negative and positive references and were not added to that sum, since they were considered neutralized. Results showcase that hydroelectric energy has an index of perception of -2% (meaning slightly positive perception), solar energy 15% and wind energy 37%. A second index was also extracted from the results to specifically quantify perception of negative landscape impact. It was named index of negative perception and was calculated by summing the percentages of articles that were labelled as "Mixed" or "Negative", as both of these labels required negative remarks on the landscape impact of the technology examined. In this index hydroelectric energy scored 15%, solar energy 22% and wind energy 60%.

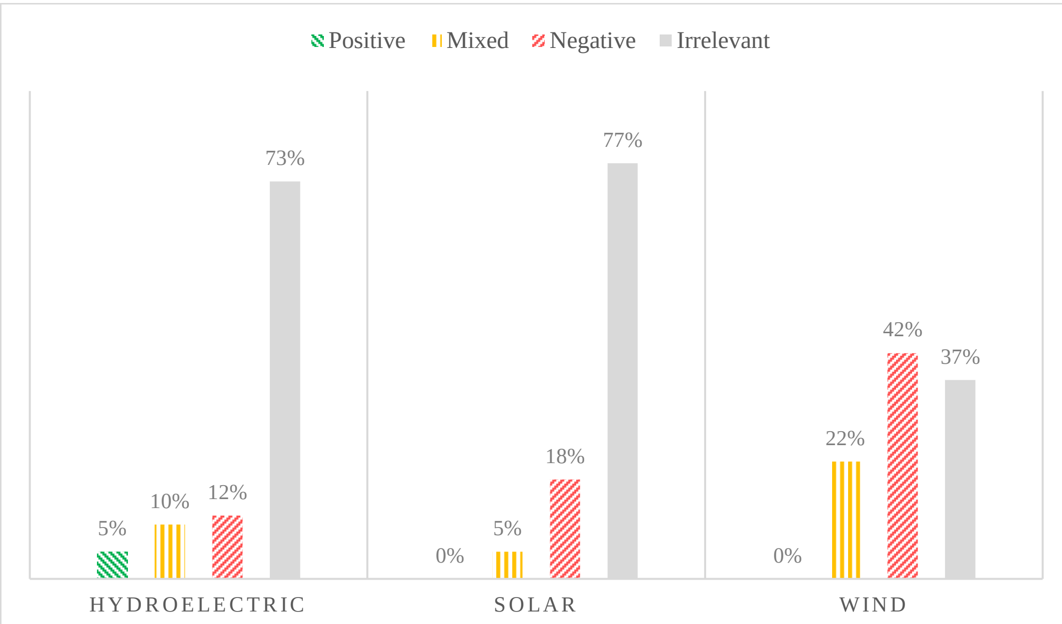


Figure 5. Percentages of articles labelled as positive, negative, mixed or irrelevant in the perception analysis of literature on the landscape impact of major renewable energy technologies (more details on the publications labelled are presented in appendix B and the supplementary material).

2.6 Generic results

Table 7 summarizes the generic estimates of land use, visibility and public perception of hydroelectric, wind and solar energy that were compiled or calculated from literature. The generic applicability of the results is based on (a) the implementation of the additional secondary screening criteria of section 2.2.2., for land use and visibility, and (b) the quantification of public perception through statistical analysis of literature.

Table 7. Generic estimates of land use, visual impact and public perception of RE in the context of landscape impact, based on literature review.

Type of RE technology	Total Land Use (m^2/GWh)	Visibility (m^2/GWh)	Index of Negative Perception in Literature* (%)
Wind (onshore)	176 000	2 014 800	60%
Solar (PV)	28 000	451 500	22%
Hydro (large)	16 900	N/A	15%

3 Discussion

Initiating the discussion over the results, we present a visualization of the results of Table 7 (in Figure 6), to allow for a better understanding of the spatial extents of landscape impacts from the examined RE technologies.

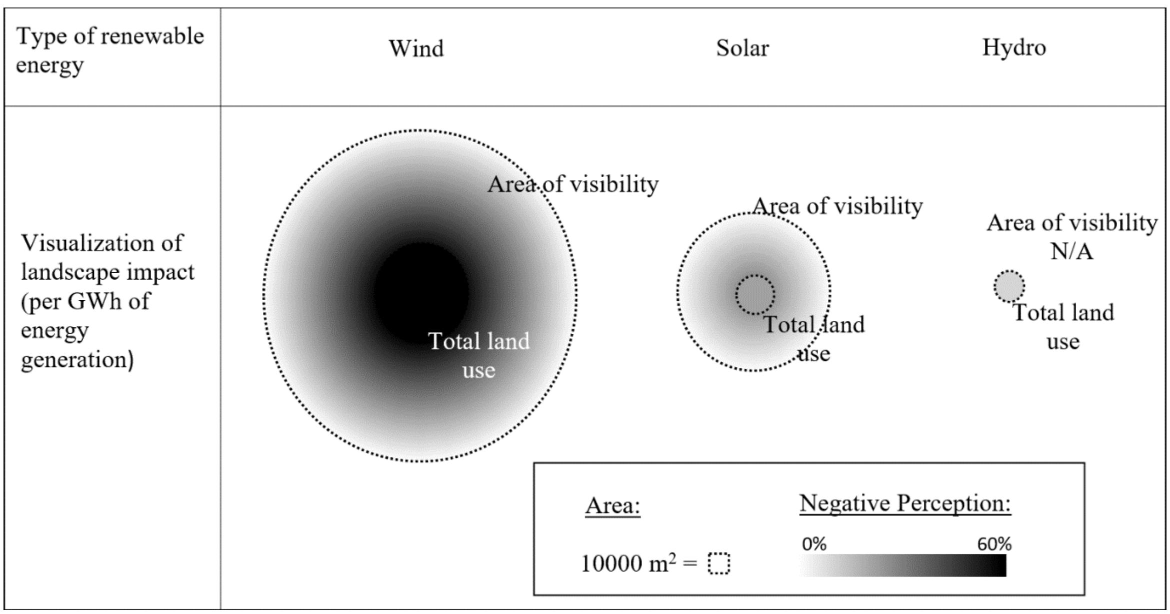


Figure 6. Visualization of results of table 7: (a) Land use is presented with a continuous fill of color. (b) Visibility is presented with a gradient fill starting from inner circle representing land use and fading radially towards the outer circle that presents the limits of visibility. This representation expresses the fact that visual impact deteriorates with distance. (c) Perception is visualized through the shade of the color used in each case, which is based on the calculated indexes of negative perception.

3.1 Solar vs. wind energy

The main criticism to both solar and wind energy concerns the industrialization of landscapes by the installation and dispersion of mechanical machines and equipment (wind turbines and solar PV panels) in extensive land areas [16,45,59,125,144,166,172,173]. However, from both a qualitative and a quantitative standpoint, wind turbines are identified as the most impactful of the two, as they introduce industrial elements in larger areas of land and are also perceived more negatively.

Wind turbines are taller than PV panels, cannot be easily hidden in terrain and are thus visible from longer distances. As a result, the area they affect visually is larger. This is demonstrated in the results of section 2.6 on visibility, where it is shown that wind energy impacts visually approximately four times larger land area than solar energy for the generation of the same amount of energy. From a landscape perspective, this differentiation is significant, but nonetheless, visibility is not the only criterion of landscape impact. Wind turbines have smaller direct land-use requirements than solar PV installations, meaning that solar installations alter landscapes more, in a land-cover level. Indicatively, direct land use was calculated at 26 000 m^2/GWh for solar energy (land use data from Ong et al. [65] and CF of Table 1) and 3600 m2/GWh for wind energy (land use data from Denholm et al. [64] and CF of Table 1). As is made evident, solar energy requires the most land area for the installation of machinery, per unit energy generation, remarkably even more than the average hydroelectric reservoir area, which was estimated at 16 900 m^2/GWh. Overall however, the great visual impact of wind energy is considered sufficient for its characterization as more impactful spatially (quantitatively), noting the exception of landscapes in which impacts on land-cover might be considered more important than visual impacts.

From a perceptual (qualitative) standpoint as well, wind energy is perceived more negatively than solar energy regarding landscape impact, as is demonstrated in section 2.5. Even though this difference in public perception is certainly affected by the fact that wind energy developments generate more extensive visual impacts, which is a quantitative difference and is mostly attributed to the size of wind turbines, it is also aggravated by differences in the qualitative aspect of the reported landscape impacts. In particular, wind turbines are more noticeable than solar panels due to blade movement, noise generation and night lighting requirements[125]. Solar panels on the contrary, are static, do not generate noise or significant light pollution and the only specific visual phenomenon associated with them is the generation of glare from light reflections, which however has not received as much criticism as the other phenomena discussed.

3.2 Hydroelectric vs. solar & wind energy

The reviewed metrics indicate that both qualitatively and quantitatively hydroelectric energy generates less impact to landscapes than solar and wind energy, respectively. In our perspective, the main cause for this is that hydroelectric dams are not considered responsible for landscape industrialization; at least to the same extent as solar and wind energy developments. Indicatively, criticism on industrial transformation, in the context of landscape, has not been raised as an issue of hydroelectric projects in scientific literature. This is demonstrated, in the results, by the perception index of hydroelectric energy. The index was calculated -2%, showcasing that positive perception prevails over negative, in literature. Furthermore, it is also confirmed by the fact that even though hydroelectric energy is an older technology that has been utilized more than solar and wind energy globally [39–41], visual impact from hydroelectric projects was found to have hardly been referenced in literature.

Three key features render the impact of hydroelectric projects to landscape less industrial and distinguish them from solar and wind projects. Firstly, their basic impact on landscapes is the creation of an artificial lake (reservoir), which is comparable, visually, to natural lakes [142,143,174]. A reservoir accounts for approximately 98% of hydroelectric land use, as was demonstrated in section 2.3, and even though it certainly transforms landscapes, this transformation is no perceived as industrial since it does not include machinery or human constructions. Secondly, the dam and its appurtenant facilities have the major advantage that they can be designed architecturally. In contrast to wind turbines and solar PV panels, the design of the structural parts of hydroelectric dams is not predetermined by industrial specifications. On the contrary it can be adapted to conform to the cultural and topographical attributes of an area with the implementation of architectural and landscape design (Figure 7). Finally, the area that is required for the dam and the appurtenant works of infrastructure (power station, spillway etc.) is significantly smaller compared to the are required for energy-generation-infrastructure in the other two types of RE discussed. As was estimated, around 200 m^2/GWh are required for energy-generation-infrastructure, on average, and moreover this hydroelectric infrastructure is usually concealed visually, since it is installed within ravine topography.

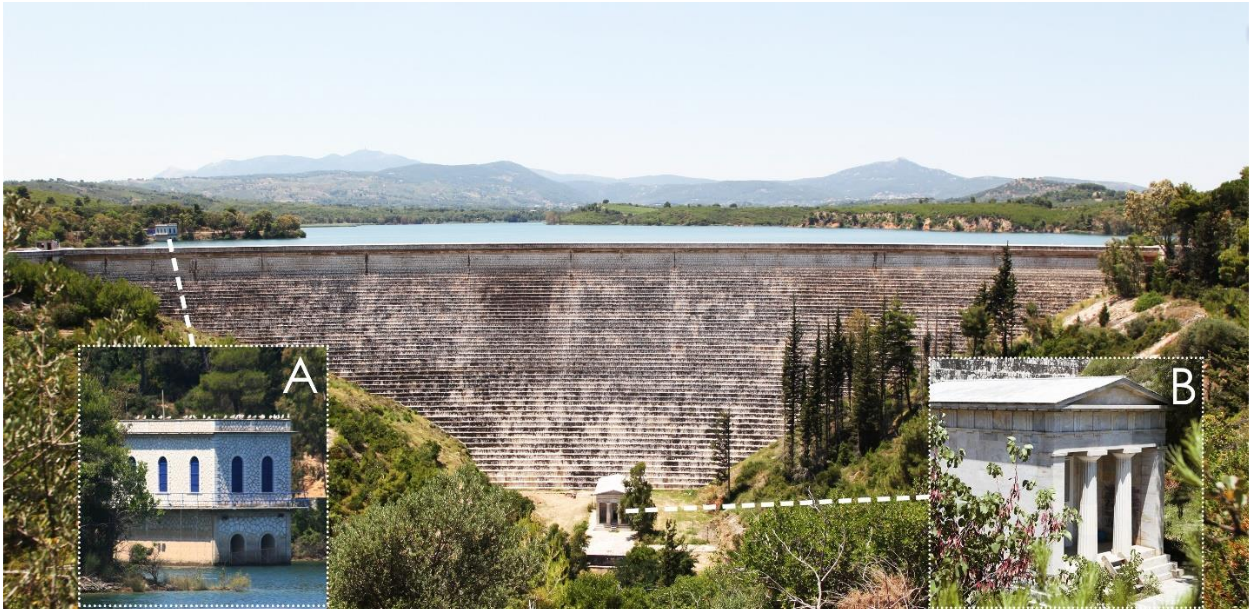


Figure 7. Example of architecturally designed dam (Marathon dam in Greece). Picture of the downstream face of the dam, which is overlaid with marble from the mine of Penteli that was also used to build the Temple of Parthenon, including pictures of architecturally designed appurtenant structures: (A) water intake tower, with similar design with the downstream face of the dam and (B) reservoir control building at the base of the dam, built to resemble the ancient temple built after the victorious battle of Marathon (480 BCE) and symbolizing the victory of modern Athens in the battle against water scarcity. The dam of Marathon is not a hydroelectric dam but is indicative of the architectural adaptability of dams and their appurtenant structures, that can, and has been utilized in hundreds of hydroelectric dams internationally. Technical information on Marathon dam can be found in Soulis et al. [175].

The landscape impact of hydroelectric dams becomes more considerable in cases of inundation of monuments of cultural or natural heritage by reservoirs [176]. Data for an estimation of a global average of reservoirs that inundated monuments, landscapes of cultural significance etc. were not found. It was observed however, that the problem is more common in countries with high density of cultural monuments and especially when governed by authoritative regimes that are less sensitive to potential public opposition to such projects. In Greece, for example, it has not been a significant issue while in Spain, mentions of at least 20 reservoirs that inundated important cultural heritage were found[9] (out of a total of 1230 reservoirs), many of which were built during the regime of Francisco Franco. The inundation of built monuments has in some cases been avoided, as such for example in the cases of Aswan dam in Egypt [177] or Hilarion dam in Greece [178], though the transportation of the monuments at risk.

3.3 The distinct role of hydroelectric dams for renewable energy landscapes

In a holistic assessment of landscape transformations from RE, hydroelectric energy stands out as the only major technology that generates transformations with potential for unanimously positive perception. Pointedly, in the perception analysis of literature in section 2.5, articles with reference to exclusively positive landscape contribution were only found for hydroelectricity (Figure 5). This can arguably be

[9] Data collected from Spanish media articles and Wikipedia: https://www.escapadarural.com, https://www.traveler.es, https://en.wikipedia.org/wiki/List_of_submerged_places_in_Spain),

attributed to the fact that the installation and dispersion of industrial machines in landscapes, which in the cases of solar and wind energy is reported as the origin of impacts, is very limited in hydroelectric energy; the major impact being the reservoir, which is comparable to natural lakes. Furthermore, various examples internationally [179,180] demonstrate that dams can create aesthetically impressive results and even landmarks. This is the case especially when their architectural potential is utilized but has also been observed in cases of standardized technical design with no additional architectural interventions. Various academic [61,170,181–184] and institutional publications, e.g. from Spain [185], Norway [186] and Scotland [187], have analyzed the positive impacts of dams and power stations to landscapes, in depth. In these publications, dams were studied for their architectural and landscape design and their contribution to creating scenic landscapes, enhancing built heritage and creating touristic attractions.

3.4 Visibility of wind energy developments

In the review of large-scale visual impact estimations for wind energy, the following two observations were made regarding the spatial evolution of visibility of projects in relation to installed capacity. Firstly, the percentage of a country or region from which wind energy installations become visible ascends to double-digits even in regions with low to medium wind energy utilization. Such examples are Kuyavia-Pomerania (Poland) [32], South Aegean (Greece) [83] and the Netherlands [35]. These regions/countries have low densities of installed capacity (smaller than 0.035 MW/km^2 except for Netherlands) but average visually affected areas of more than 20% of their respective total areas (Figure 3). In these cases, the shares of wind energy in national power generation are 5.8%, 2.6% and 4.8%, respectively in these cases. Secondly, the rate at which visual impact is generated decreases with the increase of installed capacity (Figure 4). This trend is, in our understanding, justified by the fact that visibility of multiple wind farms overlaps after a certain point of utilization of wind energy within a country or a region. Given this explanation of the phenomenon, the rate of creation of visual impact does not actually lessen, as in reality there is a saturation of wind turbine visibility, that is untraceable from ZTV analyses. So far, zones of theoretical visibility are primarily used to calculate the area from which at least one wind turbine is visible and not the density of visible turbines; exceptions to this are Möller [31] and SNH [33] that have also included graphical demonstrations of cumulative visual impact. It should be noted that this cumulative effect is also demonstrated in an analysis of the results of Rodrigues et al. [34]; in several different energy utilization scenarios they examined, the ratio of visually affected area to installed capacity declined the larger the number of wind turbines installed.

4 Conclusions

In this study, three established metrics of landscape impact of RE were reviewed: (a) land use, (b) visibility and (c) public perception. The aims of the analysis were the generic quantification of landscape impacts caused by major RE technologies, i.e. hydroelectric dams, wind turbines and solar panels, and the identification of the distinct characteristics of these impacts. Through the investigation of the selected metrics both the quantitative (spatial) and the qualitative (perceptual) aspects of RE landscape impact were addressed. The exact variables that were used to address each of the examined metrics respectively: direct and total land use, visibility analyses carried out in geographic information systems (in particular, zone-of-theoretical-visibility estimations) and indexes of perception over landscape impacts of renewable energy, extracted through the statistical analysis of literature. Subsequently, selected estimates were distinguished on the basis of their generic applicability, which was determined with the application of the following criteria: (a) use of data from areas of moderate terrain topography, since visibility and land use are highly dependent on terrain (b) utilization of large datasets originating from realized projects, (c) use of data from developed countries, (d) use of original data without embodied theoretical estimates, when possible, and (e) use of data expressed in terms of energy generation, or data that allowed for conversion to expected energy generation, thus avoiding biases associated with the energy-generation efficiency of the compared technologies (which would be present if comparisons were carried out in terms of installed capacity). Additional own calculations were only carried out for verification purposes, in the investigation of the discrepancy in estimates of hydroelectric land use.

4.1 Landscape impact typology of renewable energy

Based on the examined metrics, wind energy was identified as the most impactful to landscapes, on average, both spatially and perceptually, followed by solar and hydroelectric energy, respectively (Table 7). This conclusion provides the essence of scientific literature on landscape impact of RE in a condensed and simple format but is not an undisputable or universal truth. On the contrary, the distinct characteristics of the discussed technologies that are presented below, demonstrate that any of the examined technologies can potentially be the least impactful in particular landscapes or terrain forms and highlight the origins of this landscape impact ranking:

Wind energy

(+) Small direct land use: Smaller transformation to land surface and land cover is generated compared to hydroelectric and solar energy.

(-) Extensive total land use: Due to the requirement of dispersed installation of turbines, large land properties are used for wind energy projects. Within these areas the turbines are highly noticeable, both visually and due to periodic acoustic nuisance.

(-) Extensive visibility: Visual impacts are widely reported in literature. Wind energy developments have altered the visual scenery of countries or regions in a range of 8% to 96% of their respective total areas. These percentages have reached 27% or 61% even in cases of low wind energy utilization.

(-) Most negative public perception: Based on the statistical perception analysis of literature, wind energy is perceived as the most impactful to landscapes with reference from the academia, policy frameworks and the public. The identification of wind turbines as industrial elements as well as their increased discernibility due to size, blade movement, noise and night lights are regularly mentioned in this regard.

Solar energy

(+-) Moderate visibility: Utility scale solar panels have small height (less than 5 m) and thus solar energy developments generate smaller zones of visibility than wind energy developments. Visual landscape impacts from solar energy has been reported in literature but to a lesser extent than wind energy.

(+-) Moderately negative perception: Based on the perception analysis of literature, solar energy ranks second in terms of negative perception. Similarly to wind turbines, the main origin of negative perception for solar panels is their identification as industrial elements. In comparison to wind turbines however, solar panels are less noticeable due to the fact that they are shorter, static, they do not generate noise and they have less night-lighting requirements.

(-) Extensive land use: Significant transformation to land surface and land cover is generated due to extensive direct land use requirements.

Hydroelectric energy

(+) Neutral visibility: Visual impact from reservoirs and hydroelectric facilities has not been reported in literature. The view of reservoirs is comparable to the view of natural lakes and the hydroelectric dam and its appurtenant structures are spatially austere and usually concealed within ravine topography. Thus, the need to quantify the visibility of hydroelectric developments has not emerged.

(+-) Least negative perception: The perception analysis demonstrated that hydroelectric energy has received the least negative remarks in literature relating to landscape impact. The milder perception of landscape impacts of hydroelectric developments is mainly attributed to the fact that they have not been associated with landscape industrialization, in contrast to wind and solar energy developments. Furthermore, hydroelectric dams are the only renewable energy technology for which specialized studies that highlight their positive contribution on landscapes and architectural heritage were found.

(-) Impactful direct land use: Reservoirs generate impactful direct transformations to land surface and land cover due to inundation. This impact becomes particularly significant, in a landscape-impact context, in cases of inundation of cultural or natural heritage.

Overall, the essence of the analysis is not the competition between different technologies, but the mitigation of RE landscape impacts and associated economic and developmental ramifications and the overall enhancement of the sustainability of renewable energy. It becomes evident from the conclusions that all of the discussed technologies could be utilized for the optimal landscape integration of RE and the minimization of impacts. Indicatively: (a) Wind turbines can potentially be the least impactful in cases were protection of elements of land surface/cover is of highest priority in a landscape, since their direct land use is relatively limited. (b) Solar panels can be preferable to hydroelectric dams in areas with flat terrain due to the fact that their visibility is limited in such terrain. (C) Finally, hydroelectric dams, which, in general, can be considered the least impactful, can also be detrimental to landscapes and are not the optimal solution for every landscape. This is so both in cases like the aforementioned, i.e. extremely large reservoirs in areas with flat terrain, but also when monuments of cultural or natural value are inundated by reservoirs.

4.2 Landscape impact and NIMBYism

Early cases of landscape-impact motivated opposition against RE developments were widely attributed to the NIMBY (not in my back yard) attitude; a correlation that gradually began to be disputed [13,135,146,147,173,188,189]. The results of this study introduce practical data in the scientific debate over the emotionality or rationality of landscape-impact opposition and its relation with the NIMBY phenomenon. In particular, the results demonstrate that the quantitative (spatial) aspect of landscape impact is directly correlated to the qualitative (perceptual) one. In other words, the technologies that introduce industrial elements into larger areas and produce the most extensive visual impact are the ones that are perceived more negatively. This conclusion, in general, reinforces the view that landscape impact opposition is actually justified by differences in the impacts of the various RE technologies. In that logic, uncritical attribution of landscape-impact opposition to underlying NIMBY predispositions should be avoided. Instead the scientific and legislative discussion should be focused on a case-to-case identification and differentiation of significant and minor landscape impacts with data-driven impact evaluation.

5 Policy implications and future research

The conclusions of the study demonstrate that an optimal policy for the mitigation of landscape impacts of renewable energy would require a holistic approach that combines measures to exploit the advantages and positive aspects of each technology with measures for the mitigation of their negative impacts. So far, policy has mainly focused on the latter, primarily in the form of project-oriented visual impact analyses. We propose its expansion to a more comprehensive framework of spatial planning measures and strategies that treat landscape impact from renewable energy as cumulative problem and utilize every means available to reduce it from all possible directions. Indicative novel spatial planning directions are: (a) broad realization of the potential of hydroelectric energy for positive landscape contribution, through the implementation of directions for high quality architectural and landscape design [180]; architectural and landscape design could be implemented on new projects or as updates to existing projects, possibly in form of compensation of local communities for new and more impactful renewable energy projects. (b) specialized spatial planning of solar energy so that its potential for limited visibility can be fully utilized, e.g. with prioritization in plains or south-facing ravines. (c) prioritization of wind energy in landscapes were the protection of land cover elements is essential, based on its limited direct land-use requirements. Finally, policy makers should be up-to-date with architectural and aesthetic design improvements for wind and solar energy developments that have started to emerge, predominantly in theoretical form in literature [7,12] and online [190,191]. The utilization of such designs could contribute to the reduction of the perception of RE developments as industrial interventions in the landscape, which was identified as a major cause of landscape-impact opposition.

In regard to future research, two basic directions are proposed. Firstly, the review of literature demonstrated that further specialized research is required over particular aspects of the reviewed metrics: (a) Hydroelectric land use should be calculated in more detail and in a global context; it is noteworthy that the data sets required for this have been available for several decades. (b) National-scale visibility analyses of wind energy should be further supported and expanded to more countries. Such analyses are still scarce, even though their results have had a significant contribution in the assessment and quantification of landscape impacts of renewable energy in a large scale. (c) National scale visibility analyses should also be performed for solar energy; such studies have been carried out yet, with the exception of the study of Rodrigues et al.[34], which is however not based on data from realized projects but on a hypothetical scenario of solar energy generation. (d) Visibility saturation should be further incorporated in large-scale visibility analyses that so far only quantify the area from which at least one turbine, panel etc. is visible. Overall, further research in the aforementioned directions would be enlightening for the verification and improvement of the estimates of this study and for future large-scale impact assessments.

The second set of further research directions is introduced as a result of the proposed holistic approach for the mitigation of landscape impact from RE. Initially, efforts to improve the aesthetic design of wind turbines and solar panels should be further supported [12]. This is considered essential for the reduction of negative perception on renewable developments, which has so far been largely associated with RE equipment being perceived as industrial machinery. Alternative and customizable designs can improve the integration of renewable energy projects to landscapes and allow for their better adaptation and adjustment to locally preferred architectural styles and to site-specific natural landscape attributes. Furthermore, technical research on architectural and landscape interventions on hydroelectric projects should also be supported, so that their potential for positive landscape contribution is fully and optimally utilized. So far, the majority of dams follow standardized designs, formed solely by technical requirements and with no additional architectural and landscape design. Finally, fully utilizing the conceivability of solar energy developments through specialized landscape planning techniques, e.g. peripheral planting, should also be considered.

Appendix A – Analysis of older estimates of hydroelectric land use

In this Appendix, further details on the older studies that estimated hydroelectric land use are provided, with emphasis on the data selection processes and their overall the characteristics that hindered the generic applicability of the generated estimates.

Gagnon and van de Vate [84] thoroughly researched the subject of hydroelectric land use in the context of estimating the greenhouse gas emissions produced by reservoirs. The data analyzed by Gagnon and van de Vate are extensive, and produce a weighted average of 91 448 m^2/GWh. However, the national-scale studies they cite, in which data from China [110], Switzerland [85] and Finland [192] are analyzed, could not be found and accessed for a more in depth-analysis of the data sets that were used in each case. The study of Dones and Gantner, even though it is apparently based on a large percentage of Switzerland's installed capacity, would be unsuitable for the discussion on generic hydroelectric land use, since Switzerland has exceptionally mountainous topography. Similarly, the study of Väisänen et al. would again be unsuitable, this time due to flat topography, since Finland is slightly outside the ruggedness limits set for this analysis in Figure 1. On the other hand, the study of Ziqiang et al. would be useful if more information on data sets used could be found, since it includes the analysis of data from a significant percentage of the installed capacity of China, at the time (1996) and China has a ruggedness index close to the global average.

Ledec et al. [109] conclude on 600 000 m^2/MW as a global average land use of large hydroelectric dams, based on personal communication with J. Goldemberg. Other than this personal communication, the report includes data from 49 hydroelectric reservoirs whose weighted average, in terms of installed capacity, is 546 958 m^2/MW, that is, in line with their global estimate. However, based on their selection of data the estimate of Ledec et al. should be more accurately described as an estimate of land use of reservoirs with extreme environmental and social impacts from developing countries, rather than an estimate of global average hydroelectric land use. Even though the projects included in the analysis originate from various countries globally, it is noticed that 47 out of the 49 projects are projects from developing countries and least-developed countries, according to the United Nations categorization [193]. No further justification is provided on why these particular projects could be used to reach conclusions on a global average. Secondly, even though most data refer to hydroelectric projects with installed capacities over 100 MW, the only projects included whose capacities are smaller than 150 MW have some of the largest ratios of inundated land to installed capacity found in literature. In particular, these are five small projects from countries with developing economies with installed capacities of 34, 30, 30, 29 and 16 MW. These projects average 16 527 300 m^2/MW or 53 568 400 m^2/GWh for reservoir land-use, which is even larger than the most pessimistic estimates of average hydroelectric land use by two orders of magnitude (or by four order of magnitude from the smallest estimates). Additionally, as stated in the report, it "includes a few multipurpose projects for which hydroelectric power was less important than other objectives", which certainly contributes to overestimating the reservoir area. Furthermore some of the listed projects were presented erroneous installed capacities or have since been upgraded with larger installed capacities, such the Pak Mun and Akosombo dams.

The study of Goodland on the environmental sustainability of hydro projects [108] has been cited in several occasions, when discussing hydroelectric land use [84,109,111]. Many of the projects presented in this study are the same with those presented in the dataset of Ledec et al. [109], with the difference that the few small projects with extreme land use that Ledec et al. have included in their data are not included in the study of Goodland. Similar to Ledec et al., land use data originate mainly from developing and least-developed countries (69 out of the 73 projects). Goodland himself however, makes no claim that the data set he compiled in his study is representative of the global average of hydroelectric land use and comments that "corrections or additions… would be most welcome". He also comments on the purposes of the reservoirs presented that the "most are hydropower, rather than irrigation or flood control reservoirs", but evidently not all, incorporating additional bias to the use of his estimations as a generic estimate of hydroelectric land use.

Appendix B – Detailed methodology and results of the perception analysis of section 2.5

The exact algorithmic procedure followed to label publications over their perception on landscape impact of RE technologies comprised of the following steps:

1. The abstract and keywords were read to determine if landscape impact of RE was the main point of focus or one of the main points of focus of the article. If it was not the article was labelled "Irrelevant" and did not proceed to the next steps[10].
2. The introduction, conclusions and discussion of the article were read.
3. If at least one sentence was found, by the authors or by reference to others, in which it was evident that landscape impact was considered a problem of the RE technology examined, the article was marked for having at least one negative reference.
4. If at least one sentence was found, by the authors or by reference to others, in which it was evident that the RE mentioned was considered to have a positive contribution to the landscape the article was marked for having at least one positive reference.
5. If either a positive or negative or both types of references had not already been found, the whole article was then searched for the words: landscape, visual, aesthetic and tourism. Sentences containing any of these words were read to ensure that no relevant parts of the text had been omitted.
6. Based on the sentences found and analyzed in this second search the article was marked accordingly, as having at least one positive or negative reference.
7. If only one of the two types of references had not yet been found, the article was searched with some additional keywords to ensure that the other type of reference did not exist in the text.
8. If only a positive reference had been found, the article was searched for the words: negative, problem and impact.
9. If only a negative reference had been found the article was searched for the words: improve, enhance and heritage.
10. According to the sentences found and analyzed in this third search the article was marked as having at least one positive or negative reference.
11. If the article was marked for having both one negative and one positive reference after all of the previous steps, then the article was labelled as being of "Mixed" perception. Otherwise, if the article was marked for having exclusively negative of positive references, it would be labelled accordingly as being of "Negative" or "Positive" perception.[11]

The results of these analyses are presented in Table 8 and the sentences used to label the articles are recorded and are provided in tables as supplementary material.

Table 8 Publications that were analyzed in the perception analysis of literature grouped by perception label. Publications labelled as "Irrelevant" are not cited in this table but are reerenced in the supplementary material and their percentage is reported alongside the general statistics of the analysis in Figure 5.

Publisher	Type of RE	Positive	Negative	Mixed
ELSEVIER	Hydro	[183] [168]	[2]	[167] [170]
	Wind		[125] [153]	[58] [7]

[10] Articles labelled irrelevant are those that included the keywords that were searched but in any context that was irrelevant to landscape impact analysis; In addition, articles that were not specifically addressed on landscape impact but just included relevant comments by the author, without further justification, were classified in this category too.

			[11] [2] [165]	[169] [194] [195] [196] [160] [197]
	Solar		[7] [2] [169] [198]	[58]
WILEY	Hydro	[199]	[200]	
	Wind		[189] [144] [201] [202] [16] [164] [171]	[146] [203]
	Solar	[14]		
SPRINGER	Hydro	[184]	[204] [205] [206]	[61] [174] [207]
	Wind		[208] [163] [209] [210] [211] [207] [212] [38] [213] [42]	[162] [214] [215] [46]
	Solar		[172] [212] [42] [207] [216]	[59] [166]

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Abbreviations:

The following abbreviations are used in this manuscript:

RE Renewable energy

PV Photovoltaic

GIS Geographic information system

ZTV Zone of theoretical visibility

CF Capacity factor

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