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Visual cost of energy facilities: A comprehensive model and case study of offshore wind farms

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HIGHLIGHTS

- Landscape and visual effects can be predicted from preliminary planning stages.
- Visual effects are analysed by Visual Impact Maps and the Visual Cost of Energy.
- Visual Impact Maps can be included into optimisation techniques.
- Visual Cost of Energy identifies when affections in visual resources is acceptable.
- Visual Cost of Energy helps to conciliate Landscape and Visual Impact Assessment.

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ABSTRACT

The visual impact assessment of large facilities can be improved thanks to Visual Impact Maps (VIMs). A VIM can be a valuable predictor (numerical and graphical) of visual effects. VIMs are conceived to help with the analysis of the Landscape professional. Even before the design stage, VIMs provide important data that complement the set of starting technical or environmental criteria, such as wind resource, land use or flood maps. Additionally, they provide a numerical model for the Visual Cost Of Energy (VCOE). A set of visual indicators and a set of visual inventory layers properly combined result in a series of VIMs: a wide collection of information that depicts the visual effect that the development of any facility generates on the considered area. The production of VIMs can result in creation of a new computational and environmental consultation service that is available along the facility life cycle and that is useful for protection, planning, and management aims.

1. Introduction

From the very first moment of the life cycle of any facility, the professional in charge has a set of information available that helps to focus and initially address the matter; information like geological, flood, landslides, land uses, wind resource or administrative regulatory maps. All these maps are of general purpose and exist independently of any facility to be erected, designed or conceived.

Landscape maps belong to this set of essential information. Equivalent maps for Visual Impact do not exist. We present the possibility of addressing its creation under the name of Visual Impact Maps (VIMs). This is ambitious but feasible. Indeed, it is ambitious because by its own essence, visual impact needs the definition of some visual intrusion to be analysed, but VIMs do not consider any particular one. It is feasible

Abbreviations: CVI, Cumulative Visibility Index; D, Territorial Domain; DTM, Digital Terrain Model; EIA, Environmental Impact Assessment; GIS, Geographic Information Systems; IND, Function Indicator; L, Collection Of Visual Inventory Layers; LIA, Landscape Impact Assessment; LCOE, Levelized Cost Of Energy; MVE, Magnitude Of The Visual Effect; SPM2, Spanish Method 2; TVIM, Table Of Visual Impact Map; VCOE, Visual Cost Of Energy; VI, Visual Inventory; VIA, Visual Impact Assessment; VIM, Visual Impact Map; V-Indicator, Visual Indicator; VQA, Visual Quality Assessment; VS, Viewshed; VSC, Viewshed Collection; WF, Wind Farm; WT, Wind Turbine.

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because, currently, the power of computation methods let the researcher to create hypotheses and models to simulate scenarios that some years before were unimaginable.

The idea of VIMs is strongly related to Visual Impact Assessment (VIA). VIMs are GIS-based and VIA-indicators based. The aim of the method is serving to planners, designers, managers and landscape professionals; VIMs do not intend to be an alternative for carrying out standard VIA, Landscape Impact Assessment (LIA) or Visual Quality Assessment (VQA) for Wind Farms (WFs) or other facilities.

Some previous attempts to create VIA regional models to be queried for planning, siting or designing were made by Rodrigues, Montañes and Fueyo (2010) and Möller (2006). Both of them are based on the existence of an inventory of facilities; however, our research does not aim this purpose; it has been created to be included in multicriteria optimisation methods, particularly oriented to find an optimal layout of WFs.

VIMs were born as an answer to one of the conditions formulated in a study of multicriteria optimisation: Manchado, Gomez-Jauregui, Lizcano, Iglesias, Galvez & Otero (2019) apply a model to the repowering of a WF. They describe the term visual cost as a function of cost, this is, a function to be minimised. The term cost is not expressed in terms of money but as a set of visual effect indicators. That paper provides the need of expressing the visual cost as a vector of functions of visual indicators but does not give a procedure to obtain it.

In the same year, and independently, Pınarbaşı, Galparsoro, Depellegrin, Bald, Pérez-Morán and Borja (2019) communicate a model for the approach of offshore WF feasibility ecosystem-based marine spatial planning using Bayesian Belief Networks (BBN); they use a monetary function of cost called LCOE (Levelized Cost of Energy) which, in this case, is expressed in terms of €/Kwh. That paper also includes a Cumulative Visibility Index (CVI) that identifies areas of the sea space with the highest visibility. This CVI does not offer an expression for Manchado's VCOE neither.

VIM series can become a new field of research and of application. Indeed, many energy companies develop optimisation multicriteria systems (Tang, 2021) to obtain the layout of their WFs. If the set of the multicriteria optimisation input data does not contain a function able to describe visual effects spread all along the whole study area, then it will not be possible to consider these visual effects during the multicriteria optimisation stage. It would be much better if visibility effects were present at this stage, in which very relevant layout decisions are made (together with others, probably). Providing VIMs can therefore make it possible to include them among the set of constraint functions to be minimised. This is definitely good for the essential aims intended by visual impact and in general by landscape as a field of study and of environmental care. Finally, and very important, using VIMs does not reduce at all the need of performing the classical detailed VIA analysis, once the multicriteria optimisation step has finished and the facility is completely designed: VIM is not VIA.

Thus, the original aim of this paper is giving a solution to the vector of visual cost formulated in Manchado et al. (2019). However, the study has gone beyond, and has revealed a real framework of research and applications that we present under the name of VIMs. This paper is arranged as follows. Section 2, under the title of background, should be understood as a multiapproach extension of this introduction carried out in current Section 1: it starts illustrating the frontiers between what a VIM is and what is not; also, in Section 2, a review of extant literature on visual indicators is offered and includes the definition of Visualscape. Section 3 describes the methodology of VIMs. Section 4 presents a case study. Section 5 depicts the obtained VIM series and uses it to describe the concept of visual cost of energy (VCOE); Section 6 contains a discussion of the key aspects of our work. Finally, Section 7 offers the conclusions and suggests future research lines.

2. Background

In Sections 2.1 and 2.2, we describe the most relevant features of VIA and VIMs. Then, in Section 2.3, a concise review of visual indicators is provided, together with a referenced detail of those that we used in the case study. This Section 2 concludes with the definition of Visualscape in Section 2.4.

2.1. VIA, LIA and VQA

VIA originated as a part of landscape evaluations (Palmer, 1983). Though VIA and LIA are not synonymous, they are strongly related. Guidelines from The James Hutton Institute (The James Hutton Institute, n.d.) or LI-IEMA (2013) are good examples for establishing the mutual VIA–LIA relationship.

According to Gobster, Ribe and Palmer (2019), "*Visual Impact and Visual Quality Assessments (VIA, VQA) are closely aligned; VIAs tend to be more project-oriented and attentive to particular landscape changes produced by development proposals; while VQAs tend to focus on large-area, long-term planning, usually for public landscapes such as national forests and parks*".

Some well-known and consolidated recommendations to conduct a VIA are references (National Research Council, 2007; Vissering, Sinclair & Margolis, 2011; Scottish Natural Heritage, 2017). Practically all of these are totally or partially Geographic Information System (GIS)-based and use all or some of the following basic elements: (i) a visual inventory, (ii) viewsheds, (iii) key observation points (Otero, Bruschi, Cendrero, Galvez, Lazaro & Togores, 2004; Palmer, 2019), and (iv) visibility or VIA indicators. This work is aimed at readers familiar with these concepts; otherwise, referencing the studies cited in this paragraph is strongly recommended.

2.2. What are VIMs (and what are not)?

VIMs are for multicriteria optimisation, not for assessment. VIMs are not VIA, nor LIA nor VQA. Undoubtedly, VIMs are strongly related to VIA and, in fact, we can consider them a VIA's branch, in which the visual intrusion is spatially spread throughout the study area. More precisely, any point of the study area is considered to support a visual intrusion. Thus, once elaborated, VIMs support queries about the visual implications of a facility that is placed wherever in the study area; and this answer is produced instantaneously (in computational terms).

In other words, VIMs are not VIA because they are not done considering any particular assessment. Conversely, they can contribute to perform any particular assessment. In the next sections we will develop these ideas.

VIM is a predictor system. It processes the visual inventory, viewsheds, key observation points, indicators, and other elements, and provides information about the degree of visual effects, not only before the facility appears but also before the project has commenced. The VIM consists of a series of maps and tables, and each map and table considers that any point P(x,y) in the study area is potentially a location at which infrastructure can be erected. The VIM quantifies the overall visual effects that such infrastructure, placed at any point P(x,y), brings about in each and every element of the visual inventory.

A VIM series is mainly conceived for a regional (and possibly national) scale and provides real time answers to four basic questions (which will be answered in Section 5); the two former refer to raw values of VIMs, the two latter refer to postprocessed values of raw VIMs:

- What will be the visual effects of siting an energy facility at any point P? *[question1]*.
- Why is setting an energy facility at any point P_1 better than doing it at any other P_2? *[question2]*.
- What function measures the visual cost of erecting a facility at any point P? *[question3]*.

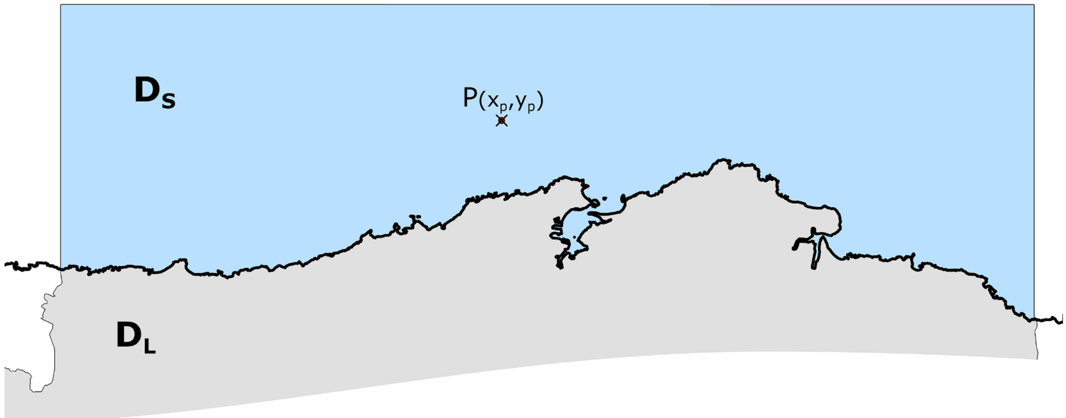

Fig. 1. Territorial domain under study, divided into one land subdomain (D_L) and one marine subdomain (D_S). When P (x_p, y_p) varies all along D_S, a new VIM_j^i is generated.

- What function measures the cumulative visual cost of erecting several facilities in any site of the study area? *[question4]*.

Finally, VIMs is a set of cartographical layouts and numerical tables that can be expressed in terms of different visual indicators, and not a single map or a single indicator report. Such a set results from crossing two essential sources: the set of *r* visual inventory layers in the study area $L = \{L_1, L_2, \ldots, L_r\}$ and a set of *s* selected visual indicators $VI = \{VI_1, VI_2, \ldots, VI_s\}$. Such combinations give rise to a collection of $r \times s$ VIM elements denoted as VIM_j^i; $i \in (1, 2, \ldots, r)$, $j \in (1, 2, \ldots, s)$. Obviously, a VIM_j^i is not a viewshed either because it does provide further information about simple intervisibility. In fact, each VIM_j^i concentrates and maintains in each of its points, the value of a visual effect indicator that extends to a whole layer of the visual inventory.

2.3. V-indicators. SPM2 and MVE

VIA methodologies use either visibility indicators or visual impact indicators. Henceforth, we will refer to them as V-indicators, avoiding differentiation between them, as this is not necessary in this case. V-indicators are usually applied to the visual inventory layers of the region under study, according to replicable methodologies developed by different authors. Being VIMs methodology V-indicators based, we suggest to read (Manchado et al., 2019, section 1.2), in which a detailed review of V-indicators is carried out.

The so-called Spanish Method, SPM, (Hurtado et al., 2004) proposed five indices, *a, b, c, d,* and e, with values ranging from 0 to 1. Lately, the Spanish Method 2, SPM2, (Manchado, Gomez-Jauregui & Otero, 2015) incorporated certain improvements to guarantee a more uniform and replicable methodology. Herein, we work with the five V-indicators of SPM2 (also called *a, b, c, d,* and *e)* which are applicable to any layer of the visual inventory. A detailed description and formulation of these five indicators is found in (Manchado et al., 2015, section 3). The indicators are implemented in a computer application called MOYSES (Manchado et al., 2013), available in the cloud (contact the authors).

SPM2 combines the visual impact expressed as 'visibility from' (V-indicator *a*), 'visibility towards' (V-indicator *b*), 'visibility angle' (V-indicator *ang of c*), 'number of WTs' (V-indicator *n* of *c)*, 'distance decay' (V-indicator *d*) and 'affected population' (V-indicator *e*). Without diminishing the value of other alternatives, SPM2 encompasses the visual impact elements most commonly used and discussed in scientific literature.

For its part, V-indicators of MVE (Otero et al., 2012) have these expressions (5)–(7):

- Visually Affected Area:

$$VAA = \frac{(Total\ number\ of\ seen\ pixels\ in\ the\ area\ of\ study)}{(Total\ number\ of\ pixels\ in\ the\ area\ of\ study)} \tag{5}$$

- Visually Affected Roads:

$$VAR = \frac{(Total\ number\ of\ seen\ pixels\ in\ the\ layer\ of\ roads)}{(Total\ number\ of\ road\ pixels\ in\ the\ area\ of\ study)} \tag{6}$$

- Visually Affected Population:

$$VAP = \frac{\begin{matrix}(Total\ number\ of\ inhabitants\ in\ the\ seen\ pixels\\ of\ the\ layer\ of\ population\ density)\end{matrix}}{(Total\ number\ of\ inhabitants\ in\ the\ area\ of\ study)} \tag{7}$$

2.4. Visualscapes

According to Llobera (2003): "*a visualscape is defined as the spatial representation of any visual property generated by, or associated with, a spatial configuration. Spatial representation refers to the way in which a visual property at a location is stored and represented*"… "*Visual property refers to the measure of any visual characteristic associated to a location in the sample space*" and "*spatial configuration…*" is a way to control "*… the scope, scale*", and intent of the visual analysis. "*Any spatial configuration creates its own visual structure.*"

In the field of VIA, a viewshed, a visibility map, or a cumulative impact map are visualscapes. A VIM also possesses the nature of Llobera's visualscape.

3. Methodology. VIM series: concept, elements and calculation method

3.1. Definition of a VIM_j^i

Let us consider a territorial domain D and a property spread over it. The representation of this property on D is a visualscape (Llobera, 2003). D may be any territorial area, and the property is any feature of the territory (physical, biotic, social, legal, etc.). The representation of this property may be numeric or graphic (raster or vector form).

Let us imagine (see Fig. 1) a territorial domain D divided into two complementary zones: the land subdomain D_L and sea subdomain D_S. Let us also consider a point P (x_p,y_p) belonging to D_S. Let us suppose that we erect a WT at P (WT_p). The visual effect of WT_P on the elements of a layer L_i of the visual inventory $L = \{L_1, L_2, \ldots, L_r\}$ can be expressed through a V-indicator of the collection $VI = \{VI_1, VI_2, \ldots, VI_s\}$ (see Section 2.3).

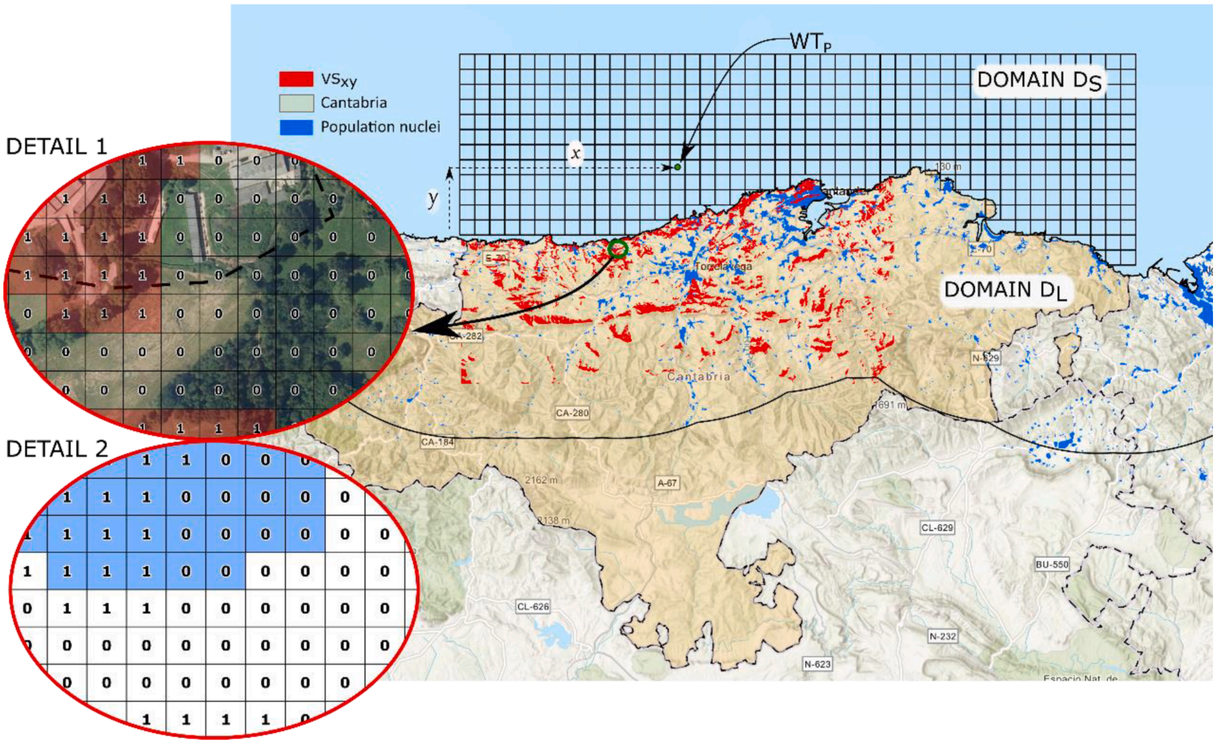

Fig. 2. Viewshed VS_{xy} over D_L. The domain D_S appears discretised in cells. A Wind Tower WT_P placed in cell P(x,y) gives rise to viewshed VS_{xy} (shown in red along the domain D_L). A magnified view of VS_{xy} along with the DTM (Digital Terrain Model) of the area in background is shown in DETAIL 1, at the left of the picture. Each cell saves its visibility value (0 or 1). Along with layer L_i (DETAIL 2), VS_{xy} reveals how many cells of this layer are seen from WT_P (cells in blue and having a value 1 in VS_{xy}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Let us select one V-indicator called VI_j (for example, V_{AA}, shown at the end of Section 2.3) and consider that the visual intrusion elicited by WT_P over a layer L_i of the visual inventory, expressed by means of the V-indicator VI_j, is denoted as IND_P. Then, $IND_P = f(x_p, y_p)$. When $P(x_p, y_p)$ covers the whole domain D_S, the variable IND_P generates a surface $f_j^i(x, y)$ in D_S. This resulting surface is denoted as VIM_j^i. Subindex j refers to one V-indicator, and superindex i refers to one layer of the visual inventory. For each WT_P model, there is a new series VIM_j^i. Thus, there exist three input data sets (the three former) and three settings (the three latter):

- Domain D_S, in which VIM_j^i is defined.
- Domain D_L, where the layers of the visual inventory exist.
- A set of layers of the visual inventory $L = \{L_1, L_2, \ldots, L_r\}$.
- A set of V-indicators $VI = \{VI_1, VI_2, \ldots, VI_s\}$.
- The height of the WT.
- The observer's height.

3.2. Computing a VIM_j^i

The VIM_j^i computation is carried out in two steps:

- STEP 1. Pre-processing: Computation of the collection of viewsheds of the considered WT model for the cells of D_S.
- STEP 2. Computation of the series of $VIM = \{VIM_j^i\}, _{j=1\ldots s}{}^{i=1\ldots r}$.

3.2.1. Collection of the viewsheds

If the domain D_S holds K cells (see Fig. 2), each one of these cells represents a possible position for a WT to be erected. We will refer to P(x, y) as the cell of the D_S with centre in (x,y). Therefore, D_S gives rise to a collection of viewsheds, one for each of their cells. We will refer to this viewshed collection as VSC; the domain for VSC is D_L. We will call VS_{xy} to the viewshed generated by WT_P; in other words, each point P(x,y) of D_s originates in D_L one element VS_{xy} of VSC.

Each VS_{xy} maintains its visibility status for each one of the cells of D_L (0: non-visible, 1: visible) when it is seen from the top of WT_P. The method for performing this computation is well-known; see, for example, MOYSES (Manchado et al., 2013) and references (Llobera, 2003; Fisher, 1991). For a specific model of the WT, the collection VSC is invariant.

3.2.2. Computation algorithm

Once the collection of viewsheds VSC is computed, this algorithm can be used for each VIM_j^i:

Input Data: D_S, D_L, VSC = $\{VS_{xy}, P(x,y) \in D_S\}$, V-indicator = VI_j, Layer = L_i
Output: VIM_j^i
Procedure:

1. Load the collection VSC.
2. For each cell P(x,y) of the D_S:
2.1. Obtain the viewshed VS_{xy} (corresponding to a WT_P placed in cell P) from VSC.
2.2. Compute the boolean intersection between VS_{xy} and L_i. This gives rise to the collection of cells of the L_i layer that are visible from WT_P (see Fig. 2, DETAIL 2).
2.3. Assign to the cell P(x,y) the value VI_P: this is the visual effect of WT_P over layer L_i, expressed by the V-indicator VI_j; this is $VIM_j^i(x,y) = VI_P$.
2.4. Next P(x,y)
3. End

Fig. 3 shows a simplified example of the application of the algorithm, in which D_S has 20 cells, D_L has 100 cells, the visual inventory has only one layer (regional population distribution: inhabitants by cell) and only one V-indicator V_{PD}. This situation gives rise to one $VIM_1^1(x,y)$. Iterations 1 (Fig. 3, above) and 18 (Fig. 3, below) are illustrated and commented in the figure caption. A loop performing the 20 iterations, from $D_S(1,1)$ to $D_S(2,10)$, would give rise to the VIM_1^1. More V-indicators and more visual inventory layers would create different VIM_i^j and thus the whole series of maps.

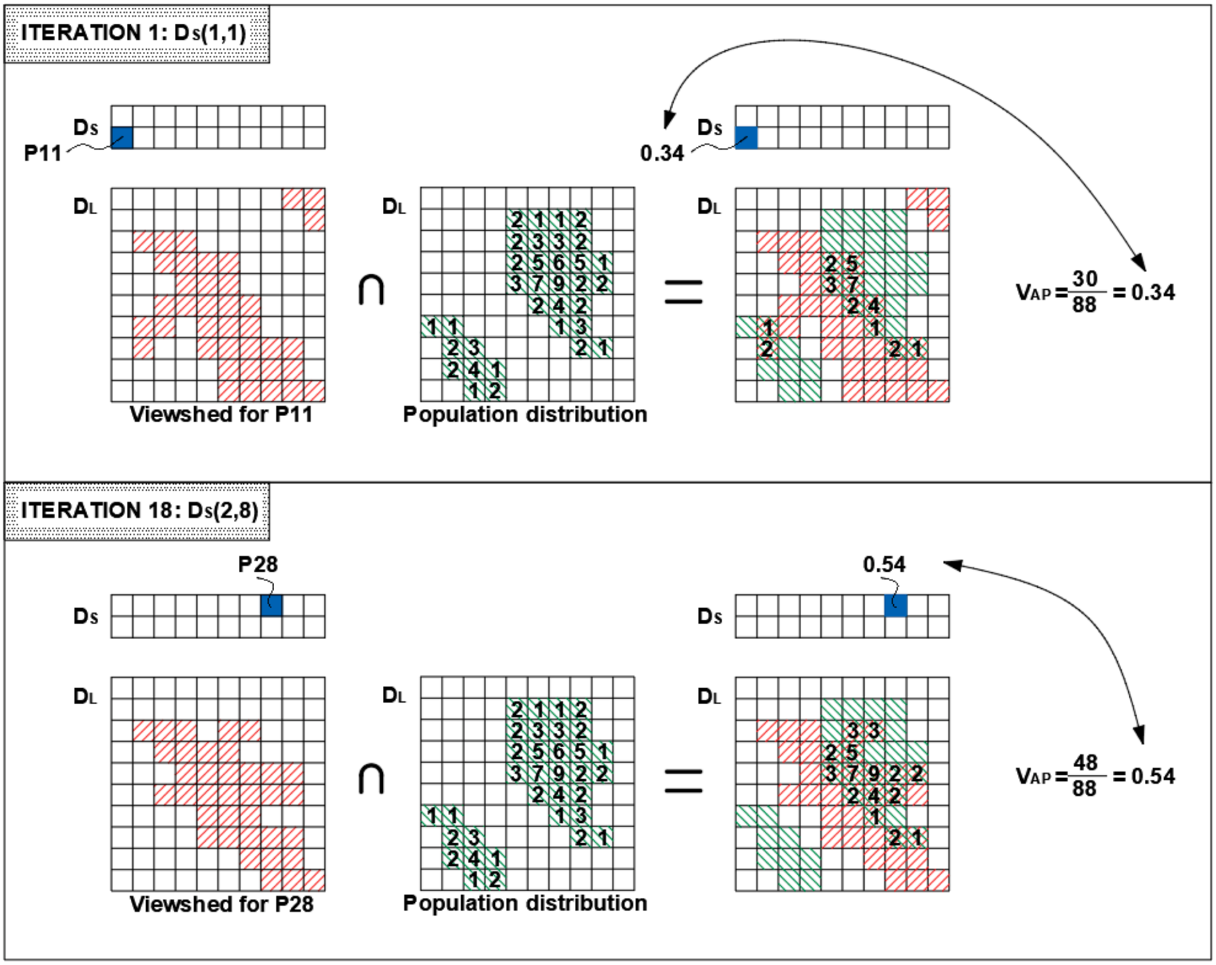

Fig. 3. (Above) Cell $P_{11} = D_S$ (1,1) has its VS_{11} associated viewshed in D_L (in red, those cells seen from P_{11}). This VS_{11} is spatially crossed (intersection) with the layer of Population Distribution. Each resulting cell has its associated population. Then indicator V_{AP} can be calculated. The sum of population in visible cells is 30, the total of population is 88. The result, 30/88 is saved at $VIM_1^{\,1}(1,1)$. (Below) Cell $P_{28} = D_S$ (2,8) has its VS_{28} associated viewshed in D_L (in red those cells seen from P_{28}). The layer of Population distribution remains the same and the spatial cross gives a different set of cells, which are computed again according to the expression of V_{AP}. The result is saved at $VIM_1^{\,1}(2,8)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. The VIM series

On varying the index *i* from 1 to *r* (number of visual inventory layers) and index *j* from 1 to *s* (number of V-indicators), the series $VIM_j^{\,i}(x,y)$ is obtained. From this point onward, we will refer to this result as the $VIM_{V\text{-indicator}}^{\;\;layer}$ to present the meaning of both the sub-index and super-index more explicitly.

4. Case study: VIMS for studying offshore wind energy facilities in Cantabria (spain)

In this case study, we aim to generate VIMs for the Cantabrian coastline. Fig. 4 shows the domain under study $D = D_L + D_S$. D_S has been adjusted to the administrative limits of the regional waters and the recommended visual distance thresholds (Gobierno de Cantabria, 2014a; Gobierno de Cantabria, 2014b; Gobierno de Cantabria, 2014c). The proposed WT height was 200 m. We defined the southern limit of D_L in accordance with the regional specifications (PSEC, for its acronym in Spanish, meaning the Cantabrian Energy Sustainability Plan) (Gobierno de Cantabria, 2014a; Gobierno de Cantabria, 2014b; Gobierno de Cantabria, 2014c). The PSEC establishes a series of limits for the model being analysed and a specific distribution of impact in accordance with distance. As a result, domain D_L continues up to 35 km from the shore edge. This means that a considerable portion of three neighbouring regions must also be included in the domain, along with their visual inventory.

In accordance with these considerations, we created the subdomains D_S and D_L as digital terrain model (DTM) with a 25 m grid spacing. We obtained it via an interpolation based on the terrain scanning data of LiDAR flights, recorded as part of the National Aerial Orthophotography Plan (PNOA - *Plan Nacional de Ortofotografía aérea)* and retrieved directly from the Spanish National Geographic Institute's official database (Instituto Geográfico Nacional, 2020).

The visual inventory used comprises 24 layers from which we outline the following: population nuclei, roads, railways, beaches, vantage points along the official network of regional roads, protected natural areas, sites of cultural interest, national parks, coastal routes and trails, St. James's Way, areas of great natural beauty, historic towns, landscape units, regional population distribution, and the DTM itself.

The set of V-indicators includes those described in Section 2.3: the five indicators of SPM2 (*a*, *b*, *c*, *d*, *e*) and the three indicators of MVE (V_{AA}, V_{AR}, V_{AP}). SPM (and consequently SPM2) was created for local VIA and MVE was created for regional VIA. Additionally, MVE is included in PSEC (Gobierno de Cantabria, 2014a; Gobierno de Cantabria, 2014b; Gobierno de Cantabria, 2014c), that suggests its use. MVE and SPM2 have coincidences in some of their V-indicators but each method has been developed independently according to its original definition. In any case, together, MVE and SPM2 can characterise the main visual

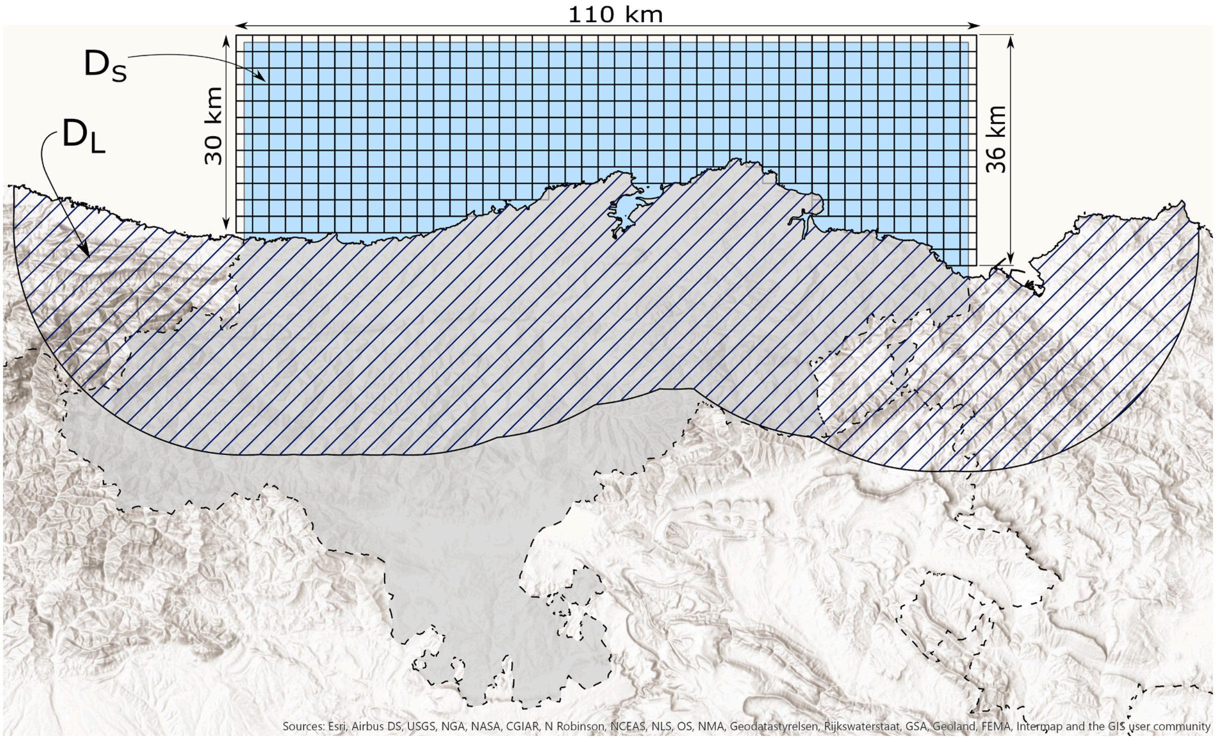

Fig. 4. Territorial domain under study. D_L extends 35 km inland from the coastline. In grey, the area located within the Cantabria region is marked. In white, the areas located within neighbouring regions are marked.

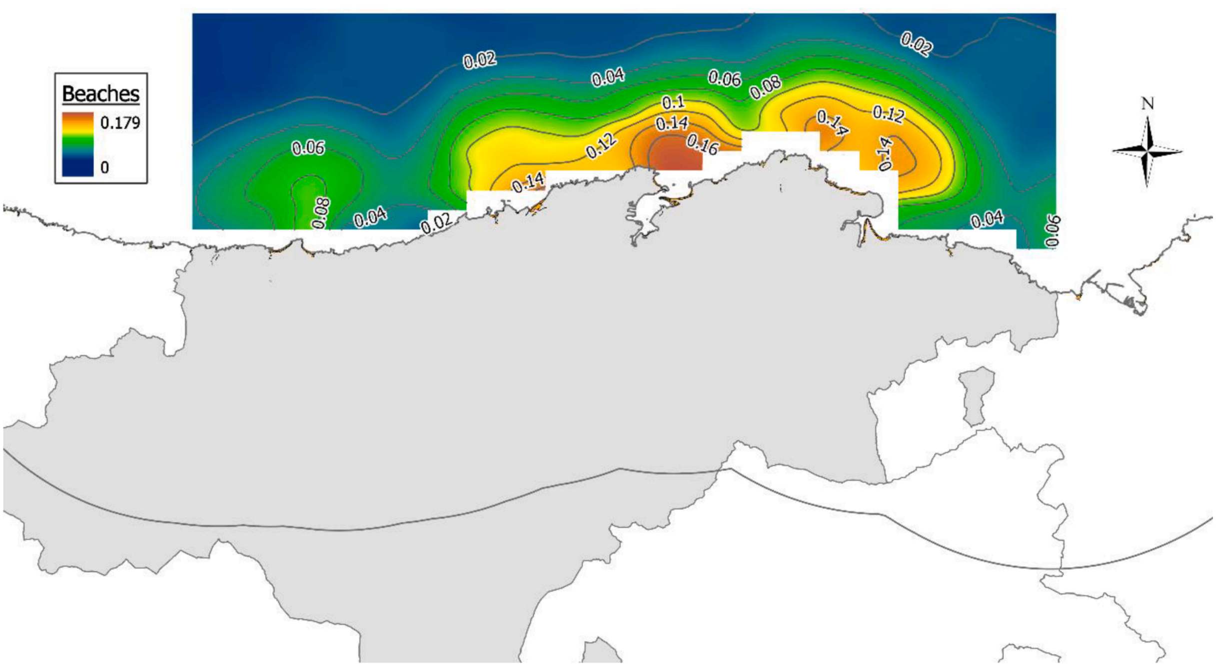

Fig. 5. VIM for V-indicator d and beaches. Contour lines identify higher visual impacts at the centre of the Cantabria region.

features of the intrusion. Not all the 8 V-indicators are applicable to the 24 layers (for example, V_{AR} applies over layers of lines and not over areas); thus, the total number of elements of the series VIM is not the product 8 × 24, but a total of 296 maps (and their corresponding tables). Section 6.5 provides an additional explanation for this.

5. Results: VIM of offshore WFs in Cantabria

Any one of the 296 $VIM_{V\text{-indicator}}^{layer}$ surfaces is illustrative enough to show what a standard VIM looks like, which is described below in Section 5.1. Section 5.2 shows the numerical expression of the $VIM_{V\text{-indicator}}^{layer}$, which we denote as $TVIM_{V\text{-indicator}}^{layer}$ (TVIM refers to table of the Visual Impact Map). This leads to the notion of VCOE. Section 5.3 explains how the TVIMs are applicable for comparing the

Table 1
An excerpt of the numerical structure $TVIM_d^{BEACHES}(x,y)$. If, for instance, WT is erected on P (405665, 4808743), the visual effect on the beaches of Cantabria would reach a value of 0.0286 (out of a maximum of 1.0).

		Y(m)						
X(m)		…	4808693	4808718	4808743	4808768	4808793	…
	…	…	…	…	…	…	…	…
	405615	…	0.0285	0.0286	0.0287	0.0288	0.0289	…
	405640	…	0.0284	0.0286	0.0287	0.0288	0.0289	…
	405665	…	0.0284	0.0285	0.0286	0.0287	0.0288	…
	405690	…	0.0283	0.0284	0.0285	0.0286	0.0288	…
	405715	…	0.0282	0.0283	0.0285	0.0286	0.0287	…
	…	…	…	…	…	…	…	…

VCOEs of different hypotheses of placement of WTs. Finally, Sections 5.4 and 5.5 show the functions $VCOE_{WT}$ and $VCOE_{WF}$, oriented to multi-criteria optimisation models.

5.1. Comprehensive library VIM. Graphical and numerical expressions

Fig. 5 shows a VIM 3D surface in the plan view, suitable to show the absolute degree of the visual effect. The surface $VIM_d^{BEACHES}$ presents “passes and creeks”: sites that locally minimise the value of the considered indicator. The maximum value in the area is 0.179 (in the range [0, 1]). Another VIMs, following the representation of Fig. 5, can be found in Figs. S4–S17 in the supporting information.

5.2. Visual cost of Energy (VCOE)

Table 1 shows $TVIM_d^{BEACHES}$ (x,y), whose cells store the value of the visual impact over the beaches of the study area (the region of Cantabria), expressed by means of the indicator *d* of SPM2. In general terms, each $VIM_{V\text{-}indicator}^{layer}$ (x,y) has one associated $TVIM_{V\text{-}indicator}^{layer}$ (x,y). The collection of 296 TVIMs numerically maintains the visual effect of a WT 200 m high when it is placed in any cell of the domain D_S, for each layer of the visual inventory and expressed according to each of the 8 indicators that we proposed earlier. We call this set of tables the VCOE.

Hence, the VCOE is a set of tables $TVIM_{indicator}^{layer}$ (x,y); this is the set of raw data that describe, with a maximum level of detail, the visual implications that the erection of one offshore WF can have in the

Table 2
An excerpt of $TVIM_{WTP1}$, summary of tables TVIM for WT_{P1}. Rows show the set of used indicators; columns show the layers of the visual inventory. Each cell of the table represents the value of an indicator measuring the visual effect of WT_{P1} over a layer of the visual inventory. Cells with null values are obtained when the indicator is not applicable to the layer.

WT_{P1} Coordinates	X =	405665 m	Y =	4808733 m

	Visual Inventory Layer						
V-indicator	Population Nuclei	Areas of Outstanding Landscape	Natural Parks	Roads	Coastal Trails	Beaches	**VCOE** $_{WTP2}$
V_{AA} of MVE	0.0267	0.0101	0.0358	-	-	0.0428	**0.0288**
V_{AR} of MVE	-	-	-	0.0147	0.1486	-	**0.0816**
V_{AP} of MVE	0.0109	-	-	-	-	-	**0.0109**
***a* of SPM2**	0.0263	0.0100	0.0365	0.0143	0.1474	0.0456	**0.0467**
***b* of SPM2**	0.0267	0.0101	0.0358	0.0147	0.1486	0.0428	**0.0464**
c of SPM2	0.0042	0.0008	0.0025	0.0029	0.0384	0.0052	**0.0090**
***d* of SPM2**	0.0163	0.0033	0.0137	0.0092	0.1031	0.0286	**0.0290**
***e* of SPM2**	1	-	-	-	-	-	**1**
MEAN VALUE FOR LAYER	**0.1587**	**0.0068**	**0.0248**	**0.0111**	**0.1172**	**0.0329**	

Table 3
An excerpt of $TVIM_{WTP2}$, summary of tables TVIM for WT_{P2}.

WT_{P2} Coordinates	X =	427395 m	Y =	4815763 m

	Visual Inventory Layer						
V-indicator	Population Nuclei	Areas of Outstanding Landscape	Natural Parks	Roads	Coastal Trails	Beaches	**VCOE** $_{WTP2}$
V_{AA} of MVE	0.0966	0.0091	0.0040	-	-	0.1467	**0.0641**
V_{AR} of MVE	-	-	-	0.0382	0.2265	-	**0.1323**
V_{AP} of MVE	0.0761	-	-	-	-	-	**0.0761**
***a* of SPM2**	0.0942	0.0089	0.0040	0.0382	0.2219	0.1417	**0.0848**
***b* of SPM2**	0.0966	0.0091	0.0040	0.0382	0.2265	0.1467	**0.0868**
c of SPM2	0.0345	0.0039	0.0009	0.0112	0.0573	0.0305	**0.0231**
***d* of SPM2**	0.0796	0.0075	0.0028	0.0228	0.1588	0.1237	**0.0659**
***e* of SPM2**	1	-	-	-	-	-	**1**
MEAN VALUE FOR LAYER	**0.2111**	**0.0076**	**0.0032**	**0.0295**	**0.1770**	**0.1173**	

Table 4
Layout definition of the WF.

WT	X (m)	Y (m)
1	427,395	4,815,763
2	428,395	4,815,763
3	429,395	4,815,763
4	430,395	4,815,763
5	431,395	4,815,763

Table 5
The table $VCOE_{WF}$. The table summarises the cumulative visual effect of a WF. Rows show the set of V-indicators; columns show the VCOE for each WT. Only an excerpt of the table is presented.

V-indicator	WIND FARM				
	$VCOE_{WTP1}$	$VCOE_{WTP2}$	$VCOE_{WTP3}$	$VCOE_{WTP4}$	$VCOE_{WTP5}$
V_{AA} of MVE	0.0641	0.0633	0.0625	0.0619	0.0618
V_{AR} of MVE	0.1323	0.1301	0.1279	0.1259	0.1239
V_{AP} of MVE	0.0761	0.0785	0.0818	0.0856	0.0895
a of SPM2	0.0848	0.0840	0.0837	0.0836	0.0837
b of SPM2	0.0868	0.0856	0.0843	0.0832	0.0825
c of SPM2	0.0208	0.0209	0.0216	0.0226	0.0241
d of SPM2	0.0659	0.0667	0.0676	0.0684	0.0694
e of SPM2	1	1	1	1	1

terrestrial domain D_L. Strictly, this collection of tables has two degrees of freedom: the V-indicator and the layer. There are two basic methods of making use of it: a direct comparison of two tables (Section 5.3) or more elaborated processes aimed at synthesising this set of tables (Sections 5.4 and 5.5).

5.3. Comparison of hypotheses: direct query to VCOE tables

Erecting WT_{P1} 200 m high at point P_1 (405665, 4808733) has a visual effect on the beaches of Cantabria that V-indicator *d* estimates as 0.0286 (see Table 1). Collecting the value of the same cell P_1 (405665, 4808733) in the 296 tables $TVIM_{V\text{-indicator}}{}^{layer}$ gives Table 2 (only an excerpt of the set of layers is presented). We call this table $TVIM_{WTP1}$. V-indicators in tables $TVIM_{WTP}$ are defined in the domain [0, 1] and cells with a null value report that the layer cannot be processed by the V-indicator. The table $TVIM_{WTP}$ is the answer given by VIMs to the question 1 in Section 2.2.

It is possible to contrast the visual effects of WT_{P1} with those of any other WT_{P2} by comparing their tables $TVIM_{WTP1}$ and $TVIM_{WTP2}$ (Table 3). In our example, a direct inspection comparison cell by cell indicates that WT_{P1} is preferable because of its lower values. The comparison of tables $TVIM_{WTP1}$ and $TVIM_{WTP2}$ is the answer given by VIMs to the question 2 in Section 2.2.

The last row of Tables 2 and 3 sum up the visual effects for each layer of the visual inventory as a mean value, this choice is discussed in Section 6.4. As a result, we can state that only 15.87% of the total area of the population nuclei of Cantabria is affected by the erection of WT_{P1}, 11.72% of the total length of coastal trails, 3.29% of the total area of beaches, and so on. Overall, these values express the alteration (we could also call this the consumption) of the visual resources of the Cantabria region, a consumption that is expressed in intrinsic terms (area or length visually affected, not its estimated monetary value).

5.4. The $VCOE_{WTP}$ for one wind tower WT_P

Some multicriteria optimisation techniques have already considered the use of the VCOE (Manchado et al., 2019) as a constraint function to be minimised. Given a point P(x,y) and a wind tower WT_P placed at P, we call $VCOE_{WTP}$ to the vector column that describes the visual effect generated over the visual inventory by the erection of WT_P. Each element of $VCOE_{WTP}$ is the mean of the values of a row of $TVIM_{WTP}$. Thus, $VCOE_{WTP}$ (x,y) is defined for each cell P(x,y) of D_S. See, for example, the last column of $TVIM_{WTP1}$ or $TVIM_{WTP2}$ (Tables 2 and 3). Again, it should be noted that $VCOE_{WTP}$ expresses the VCOE in intrinsic terms, and not as an estimated financial cost. Finally, $VCOE_{WTP}$ is the answer to question 3 in Section 2.2.

5.5. Cumulative effects of $VCOE_{WF}$ for a WF

A WF $\{WT_{P1}, WT_{P2}, \ldots, WT_{Pn}\}$ has its corresponding set of tables $\{TVIM_{WTP1}, TVIM_{WTP2}, \ldots, TVIM_{WTPn}\}$, whose last columns are the vectors $\{VCOE_{WTP1}, VCOE_{WTP2}, \ldots, VCOE_{WTPN},\}$. This last set gives rise to a numerical representation for $VCOE_{WF}$. It is remarkable in terms of its usefulness as a model of cost that can be minimised in strategies applicable to the repowering or design of WFs (Manchado et al., 2019). As an example, Table 4 defines the layout of a WF, and Table 5 shows its $VCOE_{WF}$. This table is the answer to question 4 in Section 2.2.

A complete version of Tables 1, 3, and 5 can be obtained from Tables S3 to S8 in the supporting information.

6. Discussion

We will discuss the VIM methodology from six approaches: accuracy, validation, performance, the VCOE, the VIA–LIA connection and how and why VIMs are previous and not dependent of any project.

6.1. Accuracy of the methodology: DTM and viewsheds

The VIM methodology needs using viewsheds. Precision and accuracy of V-indicators have always been a matter of our interest. Seven of the eight V-indicators chosen for this study are based on intervisibility and this is not by chance. Intervisibility is a deterministic phenomenon; it is pure geometry established between the camera and the target points. For visibility-based V-indicators, any imprecision or inaccuracy must come from the viewshed, propagated by the input data that contains the definition of each target and camera points: the DTM.

Fisher reported the inaccuracies of DTMs and their propagation to viewsheds (Fisher, 1991, 1992). We have replicated his procedure and tested the accuracy of our V-indicators for WT_{P2} (see Table 3). The DTM

Table 6
For each V-indicator there are 3 columns: VIM column refers to the value obtained from the corresponding VIM for the WT_{P2} (Section 5.3 and Table 3); Mean column corresponds with the mean of the 19 values of V-indicator from Fisher methodology; SD (standard deviation) column shows the dispersion of V-indicator for the iterations carried out in Fisher methodology.

V-indicator:	*a* of SPM2			*b* of SPM2			*c* of SPM2			*d* of SPM2		
	VIM	Mean	SD	VIM	Mean	SD	VIM	Mean	SD	VIM	Mean	SD
Areas of Outstanding Landscape	0.0089	0.0034	0.0003	0.0091	0.0066	0.0008	3.90E−03	2.26E−06	1.98E−07	0.0075	0.0056	0.0007
Sites of Cultural Interest	0.0630	0.0185	0.0022	0.0590	0.0297	0.0038	1.29E−02	1.10E−05	1.56E−06	0.0349	0.0163	0.0026
Roads	0.0382	0.0105	0.0025	0.0382	0.0169	0.0044	1.12E−02	6.74E−06	1.55E−06	0.0228	0.0100	0.0027
Coastal Trails	0.2219	0.0660	0.0097	0.2265	0.1258	0.0219	5.73E−02	4.11E−05	5.53E−06	0.1588	0.0917	0.0152
Nuclei	0.0942	0.0262	0.0053	0.0966	0.0430	0.0111	3.45E−02	1.68E−05	3.25E−06	0.0796	0.0362	0.0093
Beaches	0.1417	0.0397	0.0091	0.1467	0.0614	0.0155	3.05E−02	2.61E−05	5.73E−06	0.1237	0.0523	0.0133

Table 7
Computational cost (in time) and RAM consumption for obtaining precalculated viewsheds and the complete VIMs based on them. Each cost includes calculation and result storage.

	Total time (hours)	RAM (GB)
Precalculation of viewsheds	0.85	1
Calculation of 296 VIMs	8.41	9.4

used in this study is based on a set of LiDAR points with a known error provided by the PNOA. Thus, the error estimation was obtained by combining our own LiDAR error capture and those from comparable heights of ground LiDAR points with corresponding DTM cells. In our case, errors followed a normal distribution with mean values near 0.03 m and standard deviation of 3 m. Using the Monte Carlo methodology proposed by Fisher, we obtained 19 different DTMs, randomly varying each cell height with the previously calculated error distribution. These DTMs gave rise to their corresponding 19 viewsheds (all obtained for the same WT), which were used for computing each V-indicator 19 times. The results, summarised in Table 6, show that V-indicators reported by VIM series are higher (and therefore, more conservative) than the maximum values obtained in the case of Fisher's proposal for WT_{P2}.

6.2. Validation of VIA procedure

There are V-indicators that focus only on visibility analysis (for example, indicator V_{AA}, V_{AR}, *a* or *b*) and others that truly quantify a visual impact (like *d*, of SPM2). Our term, V-indicator, includes both types; all V-indicators used in this work are taken from studies published in the most appreciated literature in the field. We are accepting the validation and reliability of the V-indicators as they have been published in original works, cited at the end of this paper.

More in particular, Hurtado et al. (2004) does not provide an accuracy section for SPM and Otero et al. (2012) does it neither for MVE. Their indicators are purely inter-visibility based. Manchado et al. (2015, section 3.8) refers to an on-site observation experiment regarding indicator V-d of SPM2 and Manchado et al. (2013, section 11) carry out a comparison between different DTM models, revealing differences and discussing about the existing discrepancies in the peaks of the lines of sight derived from them.

6.3. Performance and computational cost

Obtaining the VIM series is a process that is moderately time-consuming and requires high computational memory. Pre-processing is required to obtain a series of viewsheds, after which the main algorithm can be applied to all the cells of the sea domain D_S. The computational cost of the calculation of a viewshed is $O(n^2)$. For the VIM procedure itself is $O(n^4)$, provided that each and every cell in D_S has to iterate over all the cells of D_L. This consumption has been optimised using interpolation and parallel computational methods. An extended description of the interpolation is offered in the supporting information that accompanies this article. Regarding the computational cost (in time), the algorithm to calculate VIMs follows three stages:

- Stage 1. Load the set of control points Nod_{ij} in a grid of 245 positions P(x,y) separated 2.5 km horizontal and 5 km vertical (see section S2 of the supporting information for more details).
- Stage 2. For each Nod_{ij}:
  o Read its associated VS_{xy} from VSC.
  o Calculate all the applicable V-indicators for each layer of L.
- Stage 3. For each cell of D_S:
  o Obtain its four closest neighbours in Nod_{ij}
  o Interpolate the values of the four neighbours Nod_{ij} for obtaining the applicable V-indicators of each VIM_j^i.

In the parallel version, this program runs once, thus, only total processing times are provided. Table 7 shows them (all are taken from the case study described in Section 4). The executions were carried out on a windows-based workstation with the following characteristics: CPU i7-10875H with 2.30 GHz and 16 cores; storage device PC711 NVMe SK Hynix 512 GB; and 64 GB of DDR4 2933 MHz RAM.

6.4. Broader view of the VCOE

$VCOE_{WTP}$ (Section 5.4) arose owing to a statistical treatment of the VIM series of tables $TVIM_{indicator}^{layer}$ (Section 5.2). In the same way, $VCOE_{WF}$ arose owing to a statistical treatment of the set of tables $VCOE_{WTPi}$. In this study, this statistical treatment adopted the shape of a simple arithmetic mean. Many other techniques can be applied; nevertheless, this is a subfield of this research that deserves its own space. It is known that V-indicators have been post-processed in different ways by other researchers—for example, according to the spatial difference-in-

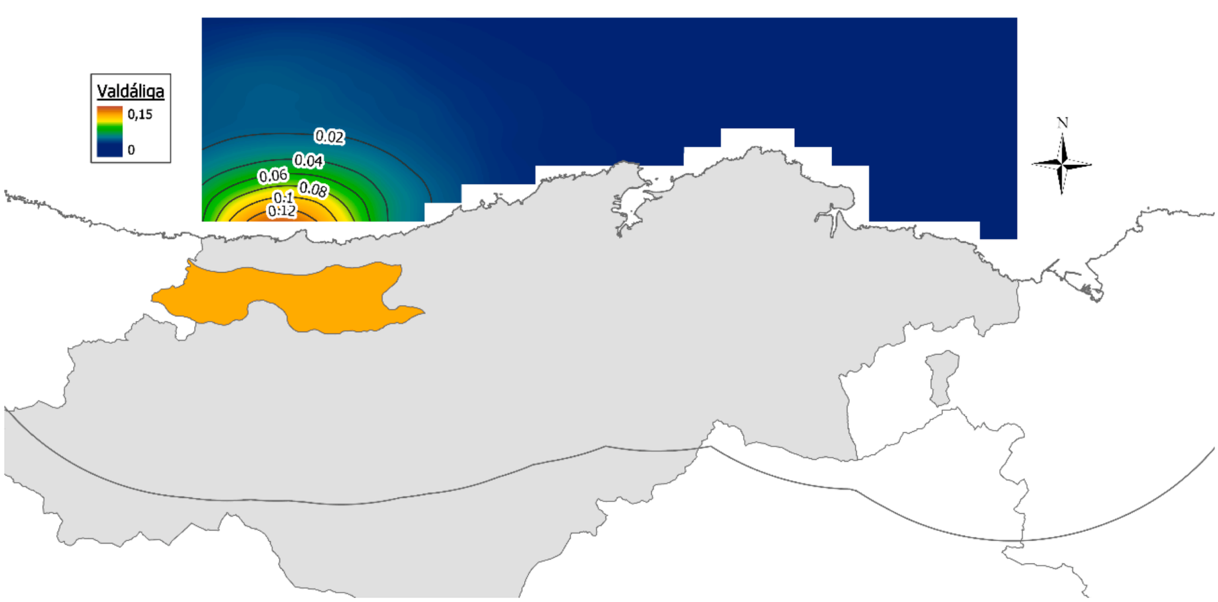

Fig. 6. VIM in 2D for V-indicator d of SPM2 and Landscape entity called Valdáliga. Contour lines identify higher visual impacts on the left.

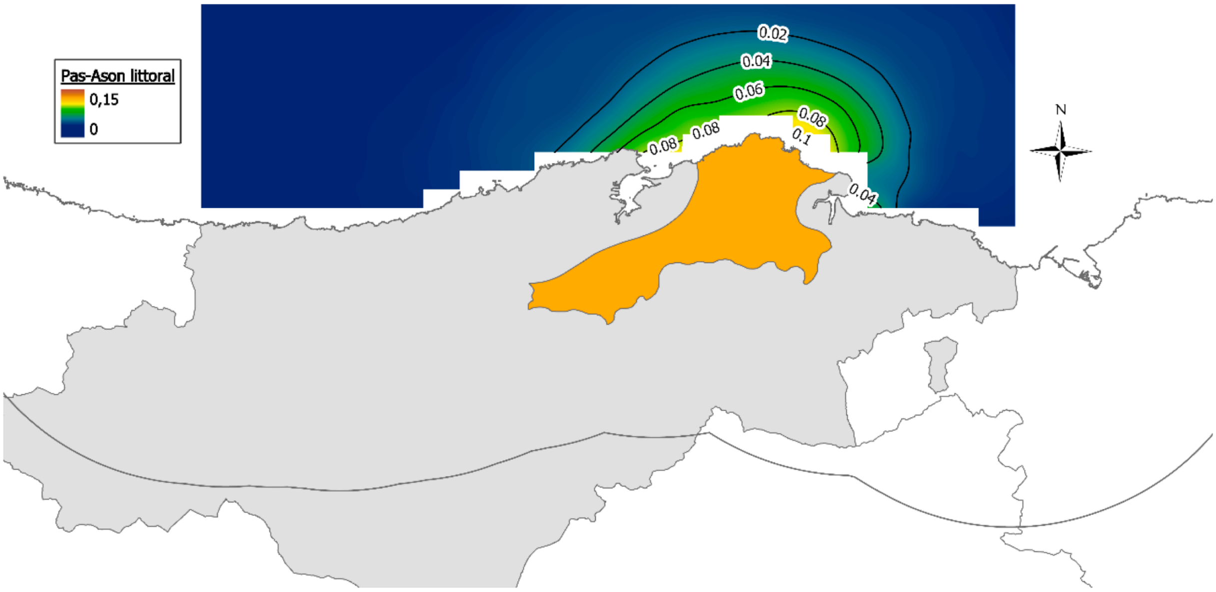

Fig. 7. VIM in 2D for V-indicator d of SPM2 and the Landscape entity called Pas and Ason littoral river. Contour lines identify higher visual impacts at the right centre.

differences approach (Sunak & Madlener, 2016), regression models (Sklenicka & Zouhar, 2019; Palmer, 2019), Willingness to Pay methodologies (Ladenburg & Dubgaard, 2007), Consumer Surplus methods (Voltaire, Loureiro, Knudsen, & Nunes, 2017), Bayesian Belief Networks, (Pınarbaşı, et al., 2019), or correlated to viewer perception (Palmer & English, 2019).

Irrespective of the method conceived to synthesise the expression of VCOE:

- VCOE (x,y) possesses a raw expression, as conveyed in Section 5.1: the collection {$TVIM_{V\text{-indicator}}^{layer}$ (x,y)}.
- The expressions of $VCOE_{WT}$ (Section 5.4) and $VCOE_{WF}$ (Section 5.5) synthesise these raw data.
- VCOE (x,y) itself does not have an economic meaning. It rather explains the potential for a natural resource to be affected by the construction of big facilities. This is expressed in intrinsic units; consequently, VCOE synthesise the degree of affection of visual resources.

6.5. Visual effects over the landscape

There is a layer of the visual inventory that needs to be described separately: the layer of landscape units, arising from official landscape catalogues. Such a layer is a tessellation of the territory, each of whose tiles delimits an area with similar and homogeneous landscape characteristics. Therefore, each landscape unit represents an official type of landscape that exists in the region (for more details, see Table S2 in the supporting information).

The VIM methodology can individually report the degree of visual effects suffered by each one of the landscape units. For example, the erection of one WT 200 m high is described in a map called VIM_d-^{VALDÁLIGA} (Fig. 6). Valdáliga is the name of one of these landscape units in the area. The reader can understand this map without additional comments, and Fig. 6 itself is sufficiently illustrative.

Additionally, Fig. 7 shows the unit "Pas-Asón", highly representative of the regional character of the landscape and particularly appreciated by population and visitors. In this $VIM_d^{PAS\text{-}ASÓN\ LITTORAL}$, it is easy to depict the line that guarantees, for example, its total preservation.

The individual study of VIM and TVIM for each landscape unit provides a method to solve the connection of VIA–LIA (which is not always easy) within a single model of analysis. Therefore, this methodology is effective and follows the official landscape designation (Cowell, 2010) in the region and, moreover, complies with official standards like those of the European Landscape Convention and its Recommendations (Council of Europe, 2000; Council of Europe, 2008) (the site for the project is the European Union).

Each landscape unit has its own VIM and TVIM; this is the reason for which the combination of 8 V-indicators and 24 layers does not lead to a total VIM series of 8 × 24 elements.

6.6. The real 3D nature of VIMs.

It could be argued that VIMs require the assumption of the height of the facility elements in order to calculate viewsheds and consequently, they would not be independent of the type of facility to be erected. The point is (see Section 3.1 and Fig. 8) that WT's height is a setting, which means that the designer can run many times the model, using different heights.

Let us consider an analogous situation happening when obtaining the wind resource model. To create it, the designer places on-site measuring towers, in several points in the area, and puts anemometers at several heights in each and every one of these measuring towers. After a suitable time, there are enough data and the wind resource model can be computed and produced. Obviously, nobody knows yet were each WT will be placed, nor its height nor its type. (This will be solved by the multicriteria optimisation process). Therefore, this method makes the wind resource model completely independent of any particular project.

The case is very similar in VIMs. The designer can (for instance) create VIM_{180}, VIM_{190}, VIM_{200}, VIM_{210} and VIM_{220} series. From these data, intermediate values VIM_{HEIGHT} (x,y) can be interpolated. Up to that point, nobody knows yet what the definitive site or height of towers will be (this will be solved by the multicriteria optimisation process): definitely a model based on VIMs does not need the definition of any project of facility.

7. Conclusions

In this study, we have described a predictor system for quantifying the visual effects of energy facilities; in particular, we have applied it to offshore WF development.

The system (see Fig. 8) requires two DTM (sea and land territories) and the layers making up the visual inventory of the area. It also involves

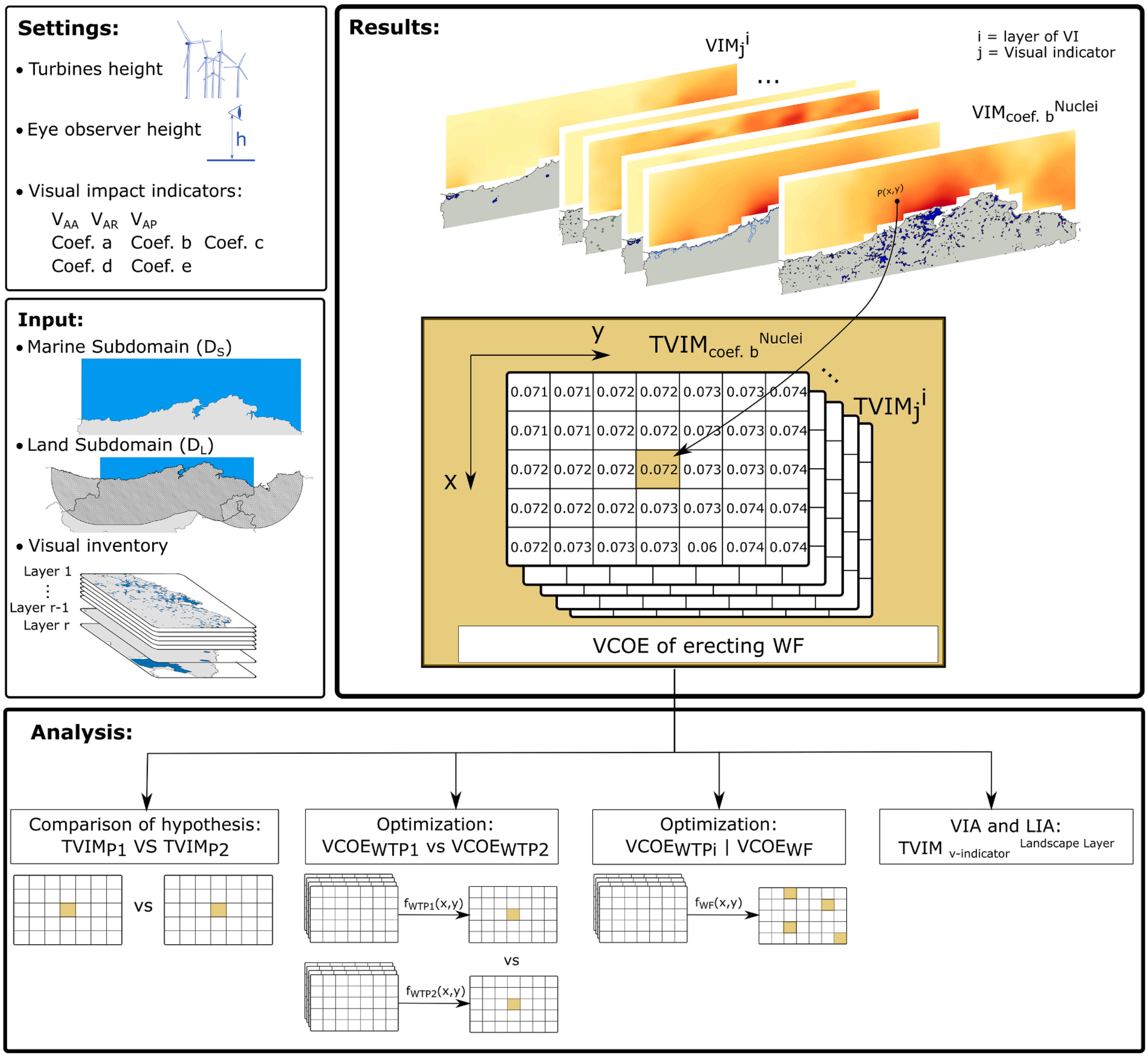

Fig. 8. Methodology schema. A VIM series and TVIMs identifying VCOE from settings and inputs given. This allows the designer to carry out a variety of analyses.

three settings: height of the WT (or any other facility), height of the standard observer, and the set of chosen V-indicators. The method gives two results: a collection of maps $VIM_{V\text{-indicator}}^{LAYER}$ (x,y) and its corresponding collection of numerical tables $TVIM_{V\text{-indicator}}^{LAYER}$ (x,y). Both maps and tables provide detailed information about the visual implications of the erection of a WT placed in whatever cell of D_S: over any of the layers of the visual inventory and all of them expressed according to any V-indicator.

TVIM (x,y) tables are the raw expression of the VCOE generated by the potential erection of a turbine in each cell of D_S. VCOE (x,y) makes it possible to directly compare the visual implications of several hypotheses for a facility. VCOE (x,y) can also be post-processed to synthesise its wide information. In this study, we have addressed the analysis of this post process to multicriteria optimisation techniques, but this is only a possibility among many others. Finally, VCOE (x,y) gives information about the visual effects suffered by each of the official landscape types existing in the area, offering a way to conciliate the often argued lack of connection between LIA and VIA.

The case study has processed 24 layers, one of which is the national landscape atlas (focused on the Cantabria region) and has considered 8 V-indicators and one model of WT. The result has been a series of 296 maps and 296 tables, stored in 13.5 GB.

This contribution can open a new branch of study for visual effects on landscape, a line of knowledge that would make it to be present all along the whole life cycle of a facility:

- Initially, developing VIMs, TVIMs and $VCOE_{WT}$. This would happen during the preliminary stage.
- Then, taking part of the set of constrain functions to be minimised in the multicriteria optimization method used for setting the layout. Multicriteria optimisation techniques happen in the design stage. Also, they can happen during the planning/siting stage (but only if this stage is solved using multicriteria methods).
- Finally, it is not bad to reaffirm that VIMs-VCOE are not for solving the definitive VIA-LIA assessment, that unavoidably must be conducted as always has been done. The big difference is that the layout to be analysed now brings inside minimised visual effects thanks to the multicriteria optimisation process. But this does not make less necessary the final and definitive assessment of visual effects. VIMs do not make assessments (VIA does them).

Regarding the future of this research, there are three main lines that are currently being pursued: i) the parallelization of the algorithms described in Section 3, ii) the inclusion of VIMs in multicriteria optimisation wind farms layout methods, and iii) the estimation of the accuracy and precision of the V-indicators.

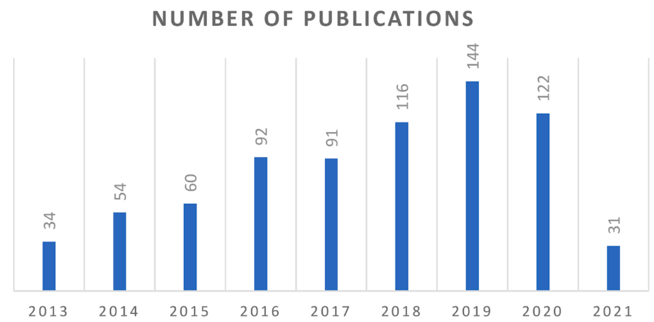

Fig. 9. A simple search in WoS of the words "optimisation wind farm layout" suggests the level of interest of this line of research.

The algorithms have been already parallelised, in a windows-based workstation and in a machine belonging to the National Network of Super-computation. The reduction of time of calculation is considerable, as expected, even getting to using DTM 1 m. cell size. The findings of this line of work are currently being object of a submission to a Computer Science journal.

Multicriteria optimisation is the real origin of VCOE, as it has been several times indicated in this paper: Manchado et al, (2019) formulated a multicriteria optimisation strategy for WFs repowering that included visual effects expressed in terms of VIA indicators. This line of research seems to be promising; in Fig. 9 we are showing the result of a simple search in Web of Science of the words "optimisation wind farm layout". Considering only the Web of Science core collection and papers, there has been an increasing interest in this kind of studies. Many of them include noise effects; there are a number of them that indicate that environmental and social impacts should be considered. (Wu, Hu, Huang, Chen, Liu & Chen, 2020; Balasubramanian, Thanikanti, Subramaniam, Sudhakar & Sichilalu, 2020). We are persuaded that the obtaining of VIMs can become a useful contribution to this regard. We think that this paper could open a field of study and interest.

The considerations made in Section 6.2, regarding the hypothesis that the inaccuracy in V-indicators appears as propagated from the DTM to viewsheds, seem also reasonable and founded. But we have much to work on this important section.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104314.

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