D1.2 Holistic impact assessment metrics for on and offshore wind

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Description	In this deliverable, we developed the metrics library for holistic assessment. We reviewed scientific papers, reports, and environmental impact assessments of both onshore and offshore projects to identify gaps in methodological and indicator availability in wind energy impact assessments. With the preliminary results from our ongoing interdisciplinary dialogues (T3.4) and dedicated stakeholder workshops (T4.1), we are co-producing new metrics for the socio-environmental impact assessment (MS1.2; D1.2). We established a new framework for holistic assessment.

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JustWind4All aims to support the acceleration of wind energy through just and effective governance. We develop knowledge, practical guidelines, instruments, strategies, and training for just and effective decision-making in onshore and offshore wind energy governance. In work package 1, we implement an approach to the holistic assessment of wind energy impacts based on socio-ecosystem metabolism.

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EXECUTIVE SUMMARY

In this Deliverable 1.2 of the JUSTWIND4ALL project, we describe the work undertaken in Work Package 1 (Holistic Assessment) to define a library of metrics for wind energy that informs decision-making, making the implementation of wind power smoother. The library presented here is the result of a coproduction process that has taken into account not only the amount of information we wanted to cover in our holistic assessment but also this intended use of the library. We conducted literature reviews, participatory workshops, and case studies to identify the information gaps that a holistic metrics library needs to address. In defining the metrics, we prioritized their usefulness in addressing those gaps. The objective of this work is to ***provide a framework for the development of metrics*** that is useful for decision-making and that can show a broader perspective to wind power development

Barriers to the implementation and information gaps

The main barriers found are summarized as:

- General issues include insufficient understanding of integrated impacts on wildlife and local activities, inadequate strategic planning, administrative delays, and low awareness and participation. Addressing these barriers **requires the development of new metrics** to raise awareness, integrate environmental considerations, and enhance participation.
- A vast amount of data is generated on wind power, but these studies are often **clustered and disconnected from one another**. The lack of integrated assessments is particularly pronounced in the case of emerging technologies, such as floating wind or airborne wind energy.
- Despite the need to assess social and environmental parameters to reduce barriers, most research funding is still focusing **on techno-economic parameters**.
- A life cycle approach is desirable to understand the cumulative flows of materials and energy, as well as their related impacts. However, Life cycle analyses (LCA) do not provide information about how important those flows are to maintain the normal functioning of society and are too general to be informative about actual local environmental **impacts**.

The WindSES framework

In this section, we present a framework for developing holistic assessments that inform decision-making regarding the implementation of wind power in the energy transition. To avoid creating disjointed metrics and to prevent redundancy with existing work, we base the framework on the conceptualization of the socio-ecosystem (SES) as a holarchy. Holarchies consist of a network of nodes structured as nested functions, which are highly interconnected through flows of energy, materials, money, and information. This framework is based on a description of the socio-ecosystem, where changes in one relationship (energy use) affect the overall dynamics of both the ecosystem and the organization.

We utilized an **adaptation of the ENBIOS framework, which links LCA and MuSIASEM**; it inherits the sustainability assessment, which encompasses four checks for: i) techno-economic viability (including ii) openness), iii) environmental feasibility, and iv) social desirability, connecting metrics from social and ecological analytical levels.

We defined five analytical levels in our SES model. **Level n-4** is structural and encompasses actual parks and their respective sites. At this level, metrics must be specific to the site, and LCA is not useful for understanding the impact. **Level n-3** pertains to the energy technology level, where decisions are made about whether to prioritize certain technologies, for example. At **level n-2**, we differentiate between decarbonized renewables and non-renewables. This level enables decisions to be informed by climate models, allowing us to understand the consequences of climate change, among other factors. **Level n-1** relates to the total energy supply, which connects with demand to explore the viability of the energy system. Finally, **level n** represents the entire energy sector and its connections with other sectors, enabling us to illustrate the linkages that wind energy has with other activities.

These five levels are **associated with three ecological levels**. Level E refers to the site where the park is located. Level e+1 represents the surrounding socio-ecosystem, where onsite impacts are observed. Level e+2 encompasses the global Earth system, which includes changes in the atmosphere and global cycles of materials, as well as other impacts.

The metrics

In WindSES, the metrics are designed for a holistic assessment of wind energy sustainability, distinguishing between structural (at the wind park level) and functional (at the societal sector level) perspectives. They are structured around feasibility and viability checks. The library integrates LCA metrics for cumulative impacts. However, LCA metrics are contextualized at the level where the information can be better understood or be more useful for decision-making.

The **viability metrics** assess the extent to which the wind-related energy configurations being evaluated meet two constraints: i) they must be achievable, given their demand for technology and manufactured products (such as steel) in relation to the economy's capacity to produce them; and ii) they must be capable of providing energy in the type and amount needed to satisfy the demand. However, when the energy scenarios to be analyzed are calculated from an optimization model that compels a supply to meet demand, the second requirement is already fulfilled.

The **feasibility metrics** evaluate the extent to which wind-related energy configurations meet the following constraints: i) the total demand for resources throughout the life cycle can be fulfilled with Earth's reserves, ii) the impact on ecosystems remains within established limits, and iii) the contribution to global change is kept within acceptable limits. This global change is typically represented in energy modeling solely in terms of CO_2 emissions, thereby allowing the models to "fit" the emissions cap that has been set. We include additional metrics to explore further the pros and cons of sites, technologies, and technological mixes.

Pilot Study

We present a pilot study for the Catalunya region in Spain, where we showed the potential of the library by assessing the distribution of two impacts with different social perceptions: contributions to global warming and land occupation from all parks installed in Catalunya. We demonstrated that on-site contributions to some impacts are minimal, whereas, for other impacts, they are substantial. Additionally, the regional distribution of burdens and demands is also important and distinct from one another. In this context, a new park can be viewed as a hindrance rather than a beneficial energy transition strategy.

In the pilot study of the Tramuntana project, we demonstrate the potential interconnections of the framework at the n-4 level (park) and its connection with other analytical levels. Conducting all modeling within a single, holistic framework is challenging due to the detailed resolution required and the need for alternative methods for specific aspects, such as food web dynamics. However, the holistic method facilitates preliminary screening and expedites the tendering process. This analysis also reveals overlooked feedback loops, such as the impact of the wake effect on CO_2 sequestration.

1 INTRODUCTION

As a *"wicked problem"* (Schwab & Combariza Diaz, 2023), the energy transition presents us with challenges such as a multifaceted nature, the inclusion of conflicting values, the interconnectedness between energy and the rest of society, the uniqueness of instances, the complexity and the uncertainty involved. It can also be considered a superwicked problem (Levin et al., 2012), adding to those above, issues of pressing timings, self-causation, no central authority and irrational prioritization.

Wind power is defined as a key technology for this complex energy transition. The European Green Deal aims to increase wind capacity from 278 GW to 425 GW by 2030, targeting net-zero emissions by 2050, with an expected 50 % contribution to EU's electricity mix (European Commission, 2023). Despite policy relevance and wide social support in national surveys, wind power is every time more often met with local opposition and long permitting times (Devine-Wright, 2011). Misinformation and preconceived ideas are part of the reasons argued for this lack of local support (Winter et al., 2024). In contrast, government agencies often are not able to distinguish between socially and environmentally responsible projects and the rest, due to lack of resources and metrics that can help.

Studies about the social and environmental impacts of wind energy do exist, most extensively in the literature of life cycle assessment (LCA). LCA is a methodological framework, typically defined as holistic, that has been largely used to evaluate the environmental performance of product systems. In the wind sector, it has been used to understand the impacts alongside the value chain of turbines and parks (Arvesen & Hertwich, 2012; Mello et al., 2020; Mendecka & Lombardi, 2019; Price & Kendall, 2012). LCA has its advantages as methodological framework for wind energy development, most notably its bottom-up modelling setting and its comparable impact assessment methods. However, it presents two methodological issues for the holistic assessment of wind energy, beyond the outdated data (Sierra-Montoya & Madrid-López, 2025). First, it is a method that focuses on the impacts, but without contextualizing the meaning of those impacts for society and ecosystem functioning. Second, their methods provide information about the impacts on societies or on ecosystems, but not about the relationships between the two. In doing so, LCA loses part of the information about the local-global socio-ecological relations affected (positively or negatively) by wind power implementation.

The use of the word«holistic» to refer to assessments of technologies or energy transition scenarios can be challenging to define precisely. The Cambridge dictionary defines holistic as »dealing with or treating the whole of something or someone and not just a part«. However, due to the complexity involved in wind energy, it becomes challenging to evaluate all the relationships between wind power and societies and ecosystems simultaneously, combining both quantifiable (biophysical flows, monetary values) and non-quantifiable (acceptance) aspects. This has resulted in assessments classified as holistic but focusing only on one aspect of wind power, even if this relates to the ecosystem (Pezy et al., 2020) or biophysical flows (Mroue et al., 2019).

The objective of this work is to ***provide a framework for the development of metrics*** that is useful for decision-making and that can show a broader perspective on wind power development. For the definition of holistic, we will borrow the concept of socio-ecosystem (Berkes & Folke, 1998; Ostrom, 2009) in a proposal to define metrics that assess relations that matter for the maintenance of the *whole* socio-ecosystem. To define which metrics and aspects to consider within this holistic perspective, we reviewed previous works and consulted with various parties involved.

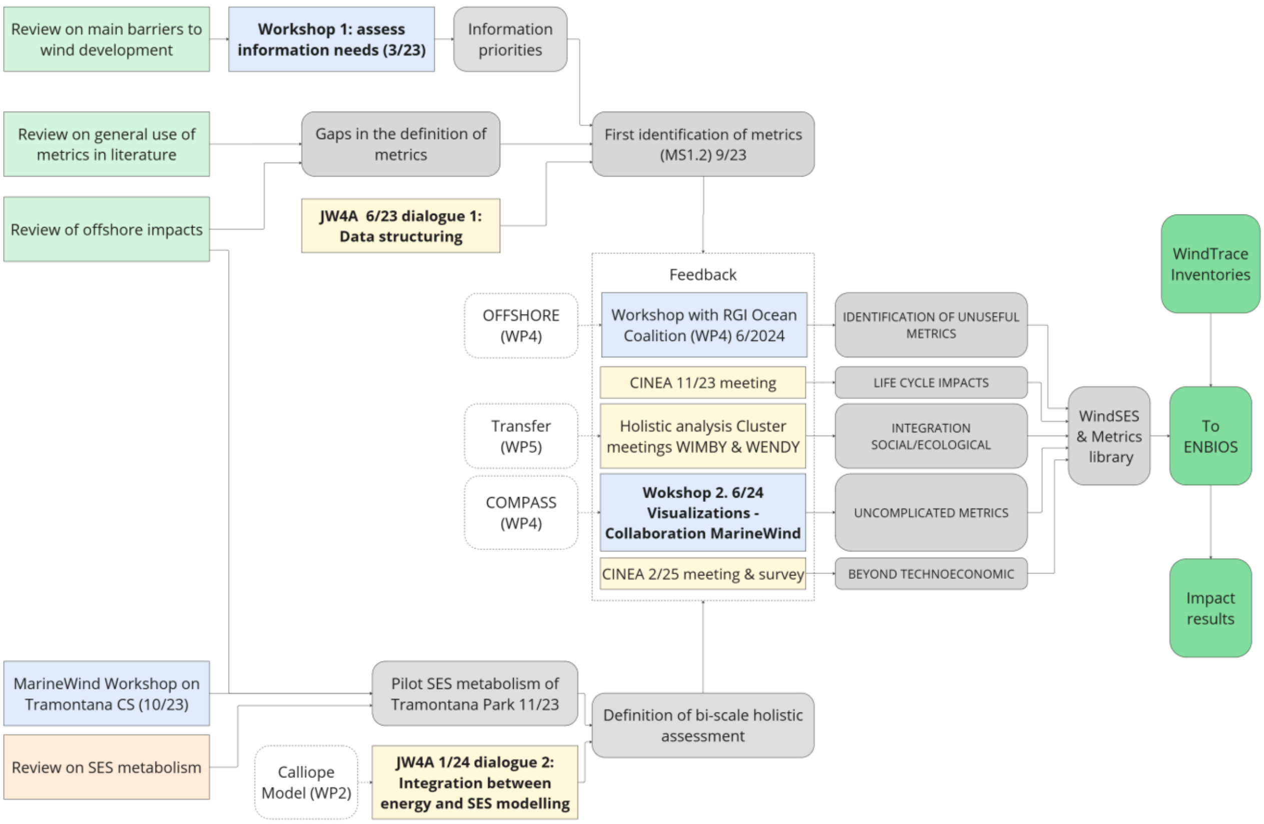
The report is structured in a first part where we identify the information gaps that have to be filled with the new metrics, followed by the description of the methodological framework, a library of potential metrics and samples on how this approach can be used in decision making.

1.1 OVERVIEW OF WORKFLOW

In this section, we introduce the workflow. For a detailed explanation of the previous steps of the methodology, please refer to section 6. This workflow considers the need to understand the reality of wind power before defining metrics. To achieve this, we used several qualitative and quantitative methods, organized under the umbrella of Quantitative Storytelling.

We combined literature reviews, participatory workshops and case studies to help define the information gaps that must be filled. Figure 1 summarizes the steps given in the methodology and their relation with interdisciplinary dialogues (Task 3.4) and dedicated stakeholder workshops (with Task 4.1), as well as with other tasks of WP1 and the modeling in WP2.

Figure 1. Steps given in the task for the definition of metrics and synergies with other work packages. Results in grey, self-organized events in bold.



We started with a literature review to identify barriers to the implementation of wind energy. This first list of barriers served as the ground for the first workshop, where we assessed the needs of information to overcome those barriers, and which resulted in a prioritization of information needs. We also run a review to identify the main gaps in the integration of metrics. We completed a more thorough review of offshore-specific metrics for wake effect as an example of impact for offshore wind power. These reviews together with the discussions during the interdisciplinary dialogue 1 helped us set together a first list of non-SES metrics.

In parallel, we reviewed the literature on the definition of sustainability metrics with a socio-ecosystem metabolism focus and produced a first categorization of impacts using as pilot the Tramontana parc project, located in the north-eastern coast of Spain. Joining this with a discussion on the integration of energy modeling and socio-ecological modeling during the interdisciplinary dialogue 2, we did a draft of a holistic framework for the definition of socio-ecological metrics.

Both intermediate outputs were reviewed in several meetings. The most significant ones would be both meetings of the wind project cluster in CINEA (in 2023 and 2025), the periodic meetings of the holistic assessment cluster for the sibling projects and presentations for Wind lab meetings, including the COMPASS (Lab 5) and the meetings of RGI's offshore coalition (Lab4). With this feedback we developed the final version of the WindSES framework and the sample metrics.

1.2 THERE IS A BROAD RANGE OF BARRIERS TO BE CONSIDERED

Our literature review (section 6.1.1) showed that:

- ***Administrative processes*** are a significant barrier to renewable energy deployment in Europe, affecting over 95% of countries (Banasiak et al., 2022). The main issues include the complexity, duration, and lack of transparency in planning and permitting procedures, which require approvals from multiple uncoordinated administrative levels (Iglesias et al., 2011). This bureaucratic red tape (Martin & Rice, 2015) leads to lengthy procedures and high transaction costs. Additionally, the absence of predefined criteria for approvals allows for personal interests to influence decisions, undermining transparency and potentially leading to legal disputes.
- ***Technical barriers*** have diminished over time as the wind industry matures (Smit et al., 2007), but challenges remain, particularly with new technologies like floating and airborne wind (Cortese, 2019; Subbulakshmi et al., 2022). Skilled personnel shortages and inadequate training programs hinder wind energy diffusion (Friebe et al., 2014). The intermittent nature of wind energy complicates grid management, requiring grid stability and supply-demand coupling (Georgilakis, 2008). Insufficient grid capacity and extension, affected by technical challenges and high costs, also poses threats to wind farm construction (Banasiak et al., 2022; Hammons, 2008).
- ***Economic and market barriers*** significantly hinder the wind industry despite declining technology costs over the past decade (Diógenes et al., 2020). Wind farm projects still require substantial initial capital and credit accessibility (Dhingra et al., 2022). Financing is further complicated by unstable support schemes, inadequate subsidies, and power pricing issues (Banasiak et al., 2022). Market-related barriers, such as the dominance of conventional retailers and energy utilities, also impede fair and independent renewable energy markets, posing greater challenges for small wind energy cooperatives.
- ***Social acceptance*** is another major barrier to wind energy diffusion, capable of slowing or halting wind farm implementation (Devine-Wright, 2005; Toke et al., 2008). Opposition often arises from the perceived unfair distribution of costs and benefits, disregard for alternative landscape valuations, and insufficient local participation in energy planning (Zografos & Martinez-Alier, 2009). Additionally, the unbalanced territorial distribution of energy infrastructure can hinder local acceptance, as the socio-economic benefits are often limited in rural areas (Duarte et al., 2022a). Ecological impacts and cumulative effects of large-scale wind deployment also fuel local opposition (Lloret et al., 2022; Maxwell et al., 2022).
- ***An unbalanced territorial distribution of benefits and impacts*** often brings to rural areas, temporary job creation and difficulties in retaining population (Duarte et al., 2022b). It also conflicts with preserving high-value agricultural lands due to an increase in farmland prices

(Haan & Simmler, 2018; Myrna et al., 2019). Local opposition also arises from ecological impacts on species and habitats, and concerns about cumulative effects of coexisting activities (Lloret et al., 2022a; Maxwell et al., 2022).

2 GAPS FOR THE HOLISTIC ASSESSMENT OF WIND POWER

2.1 LINKING BARRIERS TO METRIC NEEDS

During workshop 1 (section 6.1.2), we used the case study of Catalunya to identify potential metrics that could help alleviate the barriers mentioned above. To do so, we first identified the drivers of the barriers and then assessed their implications for the development of metrics. Table 1 and Table 2 summarize the main drivers discussed for the case of onshore and offshore wind energy respectively.

Table 1. Summary of Metric Discussion for Onshore Wind Energy in Catalonia.
»-- »for barriers that we cannot tackle from modeling.

BARRIER	DRIVERS	METRIC CONSIDERATION
Territorial Imbalance	Lack of responsibility of cities	Impacts of energy demands of cities vs generating areas (usually rural)
	Lack of energy demand management	Identification of demands with highest impacts
	Lack of compensation mechanisms	--
Lack of strategic planning	Lack of integration of key environmental parameters in energy modeling	Potential Soft link of ENBIOS and Prospective energy model in the region
		Including zoning beyond the Natura 2000 network, including bird corridors and other GIS data.
		Overlap between Spanish and Catalan priority areas
Delay in administrative process	Long processing time resulting from incomplete reports	Identification of a list of standard parameters.
	Lack of public register	--
Lack of awareness	Lack of data about the benefits of the energy transition for the general public	Environmental impacts of wind-based scenarios vs baseline scenario
Lack of participation	Lack of knowledge about actors affected	Regional environmental impacts vs energy benefits
	Lack of effective channels for participation	--
	Lack of a zoning of participation	--

Onshore, Catalunya faces a territorial imbalance between urban and rural areas, as well as coastal and interior regions. Coastal areas, heavily reliant on tourism, and urban areas, such as Barcelona, experience high population densities and energy demand. This leads to opposition to energy generation in these areas due to the impact on residents. The lack of awareness among urban populations about the benefits of reducing energy demand exacerbates this issue. **Providing information on the regionalized impacts of energy demand and the locations of energy generation, as well as the tradeoffs** between business as usual and potential scenarios could help overcome these barriers.

Table 2. Summary of Metric Discussion for Offshore Wind Energy in Catalonia.
-- for barriers that we cannot tackle from modeling.

BARRIER	DRIVERS	METRIC CONSIDERATION
Disintegration of regulation	Lack of marine models for the Catalan coast	--
	Diversity of administrations involved in permitting	Including socio-ecological parameters that are relevant for more than one administration
Difficulty in grid connection	Concentration of grid connection of offshore parks	Assessment of grid needs and related impacts
Bird/wildlife protection	Difficult to understand impacts on bird and marine wildlife	--
	Lack of monitoring methods	--
	No integration of biodiversity in energy modeling	Definition of a new method for biodiversity
Impact on tourism and fisheries	No integration of info on fisheries in environmental impacts	Connection with impacts related to Fishing and tourism activity
	Lack of knowledge about socio-ecological trade-offs	Local Social impacts vs regional energy benefits
Lack of participation	Lack of best practices in citizen participation	**As onshore

Offshore energy projects face significant regulatory disintegration, posing more difficulties than onshore projects due to the involvement of multiple regulatory bodies. A key issue is the lack of scientific knowledge about the effects of wind parks on site-specific marine dynamics. Metrics must be able to ***support the integration of indicators to facilitate administrative dialogue***. Offshore wind parks also face grid connection difficulties due to limited entry points. ***Metrics that include the impacts of different connectivity options*** on local social-ecological systems are advised.

In general, there is a lack of understanding of site-specific impacts on birds and wildlife, due to insufficient data and monitoring methods. The impact on local activities, particularly fisheries and tourism, is another significant barrier, due to the numerous socio-ecological links. ***Metrics are needed to provide initial assessments of socio-ecological impacts related to these activities,*** though further methods are needed for specific impacts. Strategic planning is also lacking, as current energy models do not include social or environmental parameters, focusing only on energy demands, costs, and emissions. There is a need **for metrics that link environmental considerations to regionalized metrics, taking into account wind park locations**. Administrative delays are another barrier, with projects evaluated by different government levels without wind-specific procedures, causing delays. **A standardized multilevel framework to speed up metric development would be helpful**. Additionally, a lack of awareness and participation are interconnected barriers, driven by insufficient knowledge about the climate crisis and the benefits of wind energy. **New metrics must be useful to raise awareness** and identify affected populations to enhance participation.

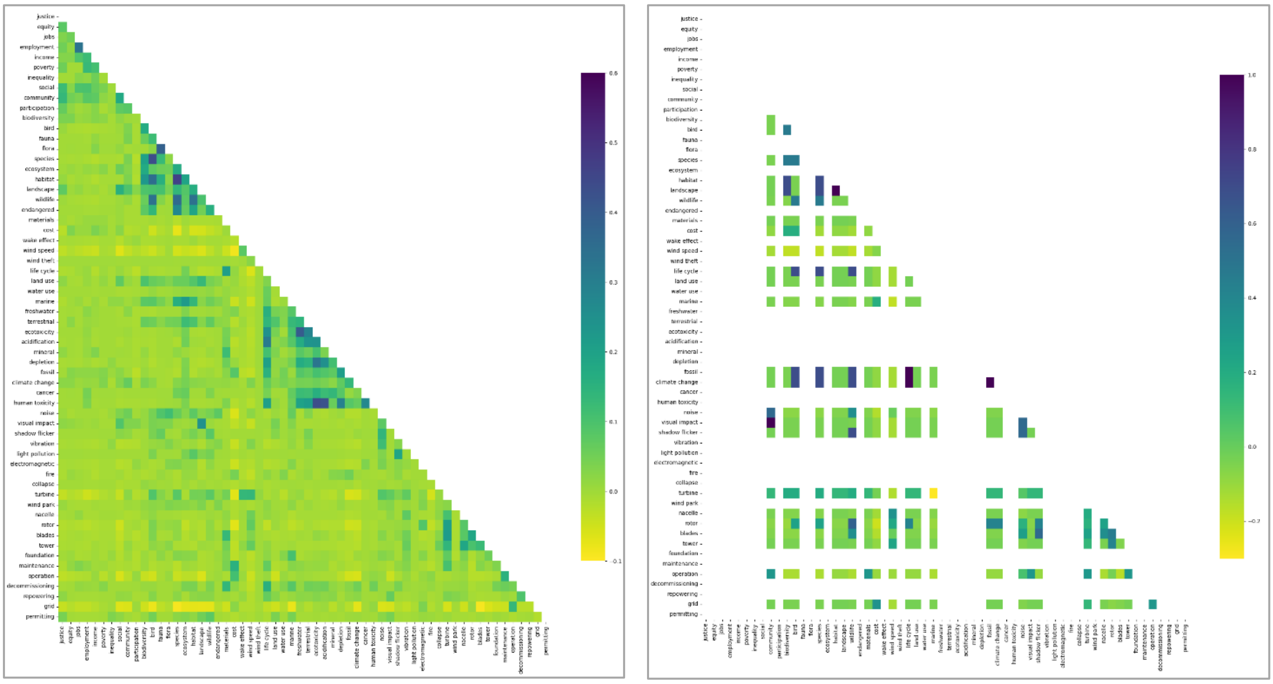
2.2 LACK OF INTEGRATION OF METRICS IN THE LITERATURE

The results of the broad literature review on scientific articles between 2010 and 2025 (Section 6.1.3) are summarized in Figure 2. The original data is publicly accessible in Zenodo (Madrid-López, 2025) and in Annex I. We analyzed the correlation of metrics in approximately 9,000 scientific articles and ***observed a lack of integration between metrics from different categories***. Works that are focused on one topic (such as justice) rarely mention impacts form other topics like water use. In the figure a slight clustering and self-feedback can be perceived. LCA, ecosystem and technical correlate higher with parameters of their same class (as shown by the triangular blue patterns around the main diagonal).

There are a few exceptions to the clustering. This is the case of “land use” that has a significantly higher correlation with parameters related to ecosystems and life cycle assessment at the same time. “Noise” is another example, illustrating connections to health issues as well as ecosystem concerns. However, in general, the strongest correlations are expected between words that form the names of LCA indicators, such as “marine ecotoxicity” or “freshwater acidification”.

Whereas a significant correlation between two parameters does not confirm their integration, a weak one **does confirm that the paired parameters are not frequently together in the literature** and thus integration cannot exist. In the case of **innovative and emerging technologies, the possibilities for this integration to happen are lower** than for conventional turbines, due to the lower number of studies. Refer to the data gaps on the right side of Figure 2, which depict airborne wind energy (AWE).

Figure 2. Correlation of impacts in literature: total wind energy (left) and airborne wind energy (right). Coverage of 9,4k articles published between 2010-2025. A bigger version can be consulted in the Annex II



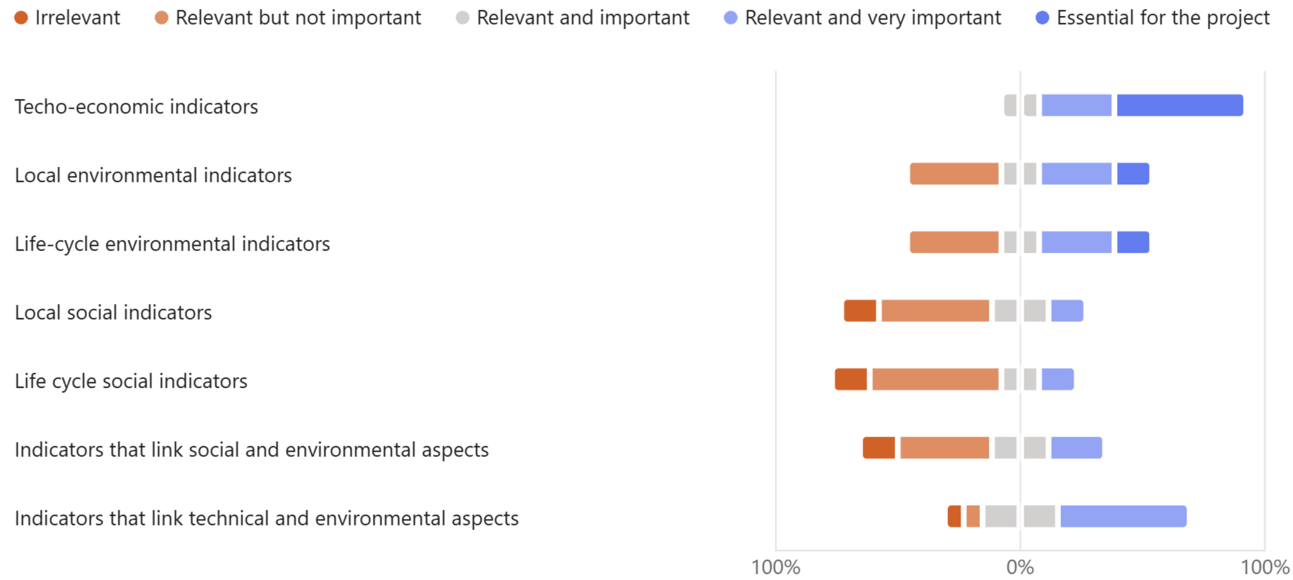
One important finding of the workshops is that participants from all sectors agreed that ***the problem is not related to the amount of data generated, but how this data was related to one another and presented.*** The literature search yielded approximately 9,000 scientific articles published over the last 15 years, supporting this affirmation.

2.3 EU-FUNDED RESEARCH IS FOCUSED ON TECHNO-ECONOMIC METRICS

We conducted a survey among participants in the wind cluster projects attending the second meeting held at CINEA in February 2025 (section 6.1.4). Colleagues with different project roles completed the questionnaire, providing data for 13 out of 27 projects. The objective of the survey was to assess the role of non-technoeconomic parameters in the development of projects. Our results show that **techno-economic parameters remain, by far, the most relevant for the projects**

that participated in the survey, with CAPEX and OPEX having significant relevance, followed closely by the link between these technical parameters and environmental ones. Local environmental impacts and life cycle impacts have an intermediate level of overall relevance, whereas those parameters related to **social indicators are reported as the least relevant**, with some projects classifying them as irrelevant. Figure 3 shows the ranking of the indicators.

Figure 3. Question 18 in the CINEA survey: " Please value from 1 (irrelevant) to 5(essential) the relevance of the groups of indicators for your work« (Work in specific projects)" 13 answers out of 27 projects



The **reason argued for excluding parameters has more to do with the design of the research** itself than with other issues, as 40% of the responses declared that they are not a priority for their projects. Other problems include a lack of data (25%) and, to a lesser extent, a lack of expertise or interest among project stakeholders (13%), which are parameters related to the project's design. Figure 4 shows the distribution of the answers. The complete survey results are available in Annex IV.

Figure 4. Question 16 in the survey: »What are the main reasons for not including indicators in your project? Please select all that apply. 13 answers out of 27 projects

2.4 THERE IS INTEREST IN LIFE CYCLE APPROACHES, BUT LCIA INDICATORS ARE NOT SUITABLE FOR SITE ASSESSMENT

In both our Workshop 1 (section 6.1.2) and the first CINEA meeting (section 6.3), the relevance of adopting a life cycle perspective that accounts for cumulative impacts was highlighted. However, the **particular setting of LCA difficulties the production of indicators that are useful for a good understanding of environmental impacts**.

Our literature review on wind-focused life cycle impact assessment (LCIA) indicators (section 6.2.1) highlights that **most of the LCA studies use generalized methods** (such as ReciPe (Huijbregts et al., 2017a) or EF v3.1 (Bassi et al., 2023)). For offshore wind farms, this is particularly problematic, as they exert multiple pressures on the marine environment, including noise, vibrations, light pollution, chemical discharges, electromagnetic fields, and habitat disturbances that are not covered in those methods.

These pressures can lead to ecological effects such as species displacement, altered behaviors, collision risks, and hydrodynamic changes (OCEaN Offshore Coalition for Energy and Nature, 2024). There have been some advances in creating specific Life Cycle Impact Assessment (LCIA) methods for concrete wind power and offshore-related impacts; however, **these are still a minority and are not yet site-specific**. For instance, a study assesses monopile installation generated underwater noise that disrupts cetaceans' echolocation (Middel & Verones, 2017). Another study covers how offshore wind farms also influence population dynamics by altering local fishing activities and contributing to artificial reef formation due to the increased surface area available for colonization (Ouro et al., 2024).

During the Oceans Coalition meeting (section 6.2.2), participants **strongly advised against using LCA indicators for site assessment,** highlighting their tendency to **generalize environmental impacts** without accounting for the geographic, temporal, or causal specificity that characterizes such effects. Attendees emphasized that **the impact of local biodiversity on each case should be assessed on a site-specific basis, as it is highly dependent on the ecosystem characteristics** and technical design of each offshore wind farm.

Still, while they were deemed unreliable for site-specific environmental assessments, LCA indicators offer a **broad screening on cumulative impacts when a lower resolution is sufficient** and an **opportunity to understand impacts beyond the site of operation**. They simply do not offer the complete picture of holistic wind impacts. Therefore, we retained conventional LCIA indicators for both onshore and offshore activities and complemented them with a socio-ecosystem analysis.

Another handicap in the inclusion of life-cycle impacts is the lack of understanding of the perspective itself. Participants of our second workshop (described in section 6.3.1) **found the life-cycle perspective challenging to grasp**. This highlights the need for thorough communication efforts.

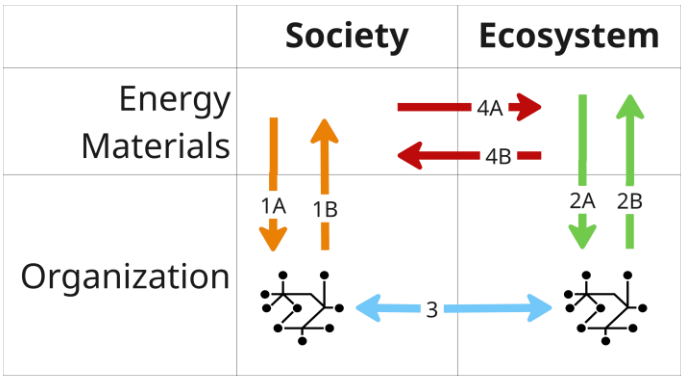
3 WINDSES: A FRAMEWORK FOR THE DEFINITION OF HOLISTIC ASSESSMENT METRICS

In this section, we propose a framework for the holistic assessment of wind power. We will begin by introducing the concept of socio-ecosystems as »holarchic« systems. We will then define a protocol to structure the metrics based on ENBIOS, which combines LCA and the Multi-Scale Integrated Assessment of Socio-Ecosystem Metabolism. LCA has been discussed in Section 2, and the workings of MuSIASEM as a method for analyzing the sustainability of energy systems are covered in Section 3.2.

3.1 HOLISTIC ASSESSMENT: A PROPOSAL FROM SOCIO-ECOSYSTEM METABOLISM

The term *socio-ecosystem* is used broadly to highlight the interdependencies between societies and ecosystems. A certain socio-ecosystem representation and the parameters used for analyzing it are typically used with a particular purpose in mind (Giampietro & Mayumi, 2003). Very often, socio-ecosystems are defined as *holarchies* (Koestler, 1969), that is, as a set of nodes (or subsystems) that are simultaneously part of a larger entity or entities in themselves. This means, for example, that the society can be represented as a full system or as a part of the socio-ecosystem, depending on the purpose of the analysis. The same applies to the wind sector.

Figure 5. Representation of the four types of relations involved in the metabolism of socio-ecosystems



Social systems exchange materials and energy with their surrounding ecosystems. In doing so, they behave like living systems, and as such, they also have a *metabolism*. In order to survive, societies need a permanent inflow of materials and energy (Giampietro et al., 2013) which they dissipate into a permanent outflow of residuals and emissions. Following the laws of thermodynamics, this is what keeps societies far from the equilibrium (which would mean death). There are societal structures that maintain those in and outflows.

In metabolism studies, the socio-ecosystem is represented as a nested network, which can be analyzed at various levels. Madrid-López & Giampietro (2015) proposed a framework for the representation of the metabolism of socio-ecosystems based on two variables: how societies *interact* with the ecosystem (exchanging materials and energy) and how they *organize* internally. We built on this framework for our holistic assessment.

Figure 5 summarizes the four main relations that are assessed in the metabolism of socio-ecosystems:

- 1A and 1B refer to the use (or emissions) of materials and energy by the society. They are measured as intensive variables in terms of energy flow, using a unit of social service, such as euros or jobs. These flows offer insight into their role in maintaining society and the potential damage that can result from alterations.
- 4A and 4B are the total energy and material demands and wastes of the society. They are measured in absolute terms (total kg of materials, total Ha of land use). These flows provide an indication of the scale of a society's activity (its footprint).
- 2A and 2B represent the energy and material flows or sink capacities provided by ecosystems (or the Earth) and are measured in both relative and absolute terms. They are the constraints imposed by ecosystems (or the Earth) on resource-demanding social activities.
- 3 represents the nested character of the socio-ecosystem. It is usually studied qualitatively, using, for example, the geographical distribution of social activities.

These four relations can be used to characterize the metabolism of any socio-ecological system. A ***transition*** then supposes a change in the regular pattern of the represented relations. In the case of the energy transition, this can be the way society uses energy (2) the total amount of energy it uses (4), the capacity of the ecosystem/earth to provide it (3) and/or the relation with the ecosystem (3, regional changes due to urbanization, for example).

In this framework, **wind power** is one of the nodes within the social system, part of the higher node that is the energy sector and that is responsible for collecting energy (4B) from wind resources (2B), but which also uses energy and other resources (1A) and which has a certain regional distribution (3). In doing so, it requires inputs from different parts of society, such as financial contributions or labor. Whereas life cycle assessment focuses on calculating total material and energy flows (4A and 4B, which involve inventories), the framework of SES metabolism offers the possibility of contextualizing those in terms of, for example, the societal nodes maintained by those flows. Even if LCA produces results per unit of output (for instance, per kWh or MW), the ultimate purpose is still the calculation of those total flows (4), which are later on used as the foundation for life cycle impact assessment (LCIA).

Figure 6. SES representation of the energy sector within the society, depicting its relevance for the maintenance of other social nodes and the relation with the ecosystem.

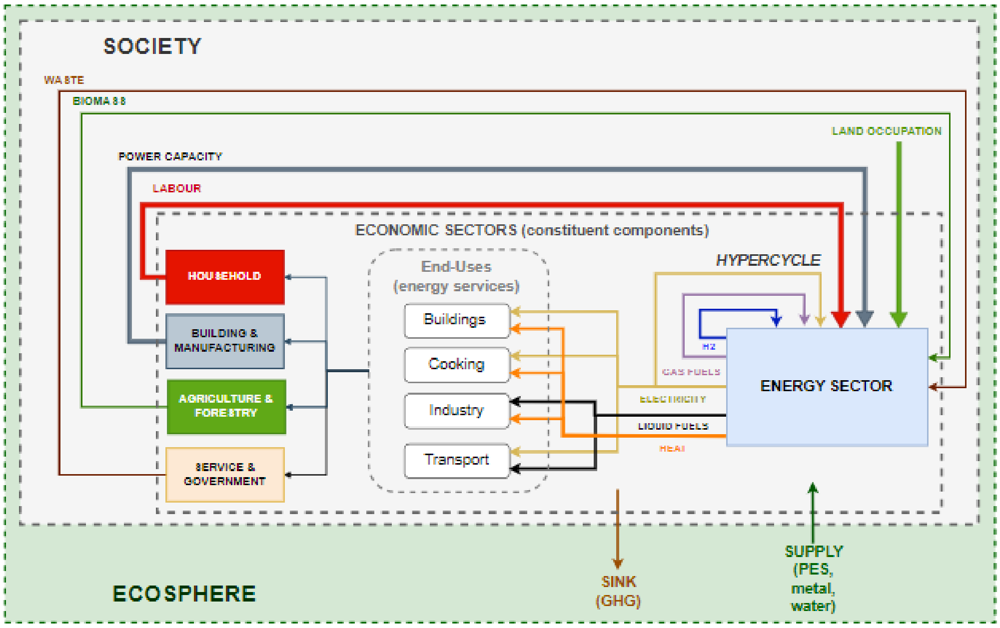


Figure 6 provides a more detailed representation of this social network and its relationship with the energy sector. If we aim for scenarios of the energy sector that alter the type and amount of energy provided to society, the relationships that utilize this energy will also need to change, as will the relationships with the ecosystem.

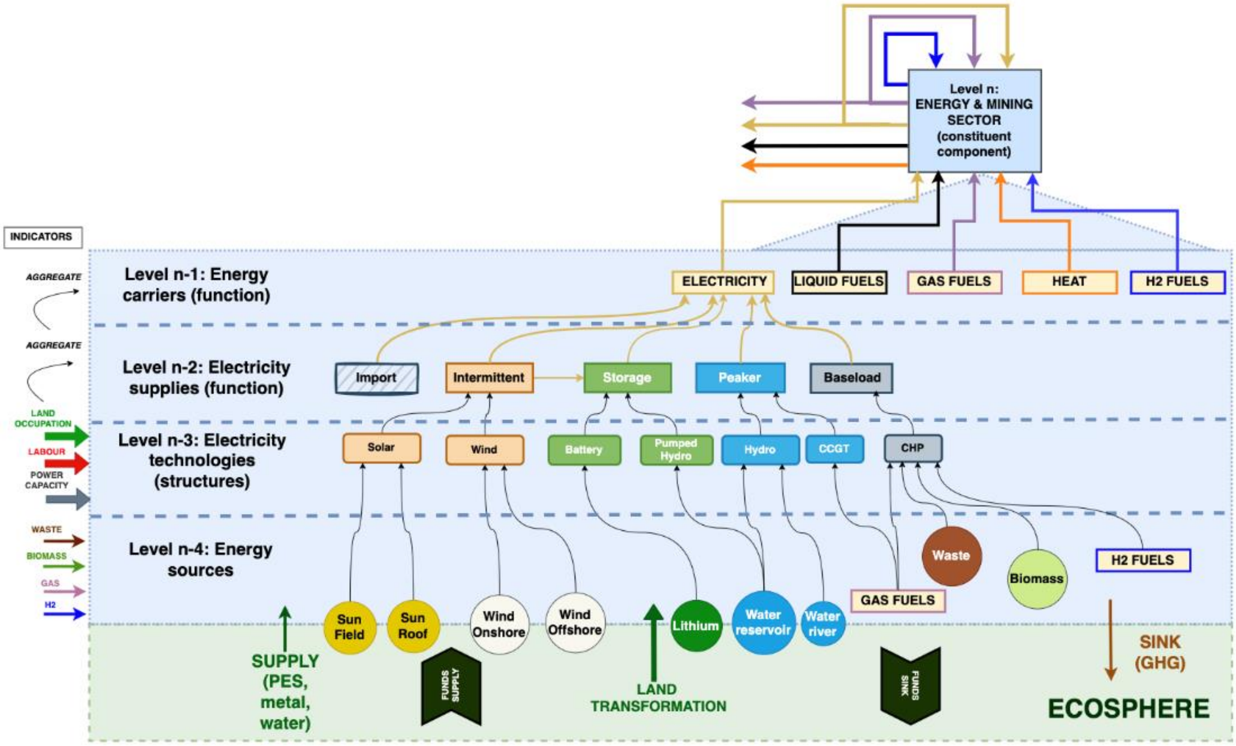
3.2 ASSESSING SOCIO-ECOSYSTEMS WITH MUSIASEM

The Multi-Scale Integrated Assessment of Socio-Ecosystem Metabolism (MuSIASEM) (Giampietro et al., 2009) is an accounting framework used to perform sustainability assessment of socio-ecosystems transition scenarios. It does so by analyzing changes in each of the four relations shown above. These relations are represented with the following tools, also exemplified in Figure 10:

- A qualitative ***dendrogram*** illustrating the nested relationships between social nodes. It can be disaggregated as needed, and the levels and nodes represented are flexible and adaptable to the case study, allowing for site-specific analysis if necessary, while also facilitating connections to higher levels (e.g., energy system).
- A representation of flows 1, 2 and 4 (A and B) called a ***grammar***, that serves for the identification of the levels of analysis that are relevant for the study and that will guide the design of specific metrics.
- A multi-level matrix that **displays these socio-ecological metrics** and their relationships.

Figure 7 illustrates an example of the energy system structure in MuSIASEM for assessing the electricity system, which can be used to examine the trade-offs between different technological shares considered in transition scenarios.

Figure 7. Example of a MuSIASEM dendrogram for assessing the electricity sector.



The analytical structuring of the energy system in the dendrogram allows the link between local analysis and global ones. At the lower levels, the resolution of data and metrics needs to be higher than at the upper levels. Additionally, at the lower levels, it is more challenging to establish standardized metrics, and we would rather discuss metric types that can be tailored for each case study. Indeed, most of the methodological development of LCIA for the adaptation to site-specific metrics (section 2.4) are based on the combination of other methodologies like Ecosystem Services (Woods et al., 2018).

In MuSIASEM, four checks can be performed to assess the compatibility of an energy system scenario within its socio-ecological context: (i) viability, (ii) feasibility, (iii) desirability, and (iv) openness. Once we have defined the type and size of flows 4A and 4B (i.e., total energy use by type), we assess how this influences the entire socio-ecosystem (and whether the change is sustainable).

i. During the **viability** check, we assess whether the changes in the energy system can still support societies (or what changes society must undergo). We use metrics related to flows 1A and 1B to assess this. In MuSIASEM, this refers to the widely used techno-economic approach to evaluate wind power.

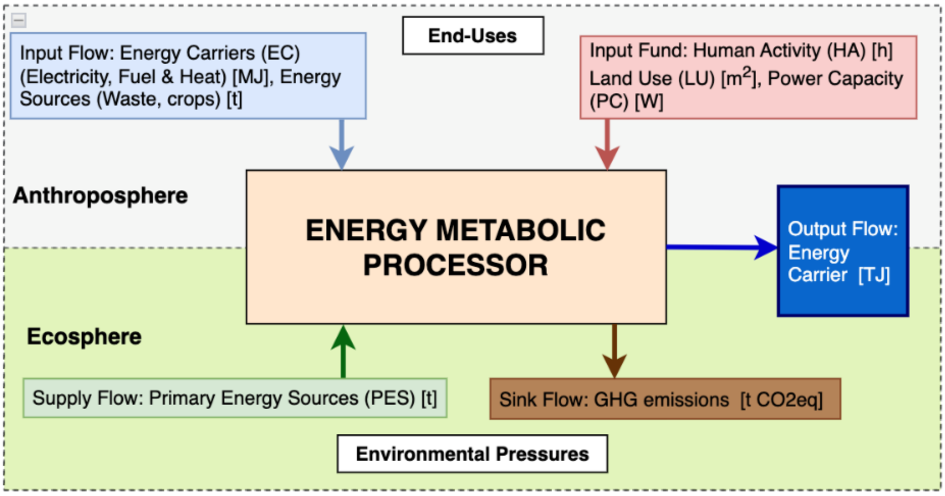
    a. The **openness** check is part of the viability assessment and evaluates the level of external dependence of a particular socio-ecosystem, for example, regarding energy technology imports.

ii. The **feasibility** check assesses if those changes are compatible with the ecosystem, or what changes the ecosystem will experience to accommodate them. The metrics to assess this are related to flows 2A and 2B. This is typically done borrowing concepts and methods from natural sciences.

iii. The **desirability** check is related to the acceptance of the changes in those flows 1,2 and 3 and the cascaded changes in social organization and the ecosystems. This is a collaborative exercise and requires methods from the social sciences to be completed.

These four checks are based on the definition of all social and ecological nodes as processors (Di Felice et al., 2019). These can be either structural (wind turbine) or functional (wind sector), depending on whether they have a physical support or not. For either option a processor is always characterized by the relation between input and output (Figure 8) in a very similar way to how LCA processes are characterized with technical coefficients.

Figure 8. Conceptual definition of a processor in MuSIASEM



LCA processes (or activities) and MuSIASEM processors are different in that the MuSIASEM processor includes a differentiation of the inputs in flow and fund variables. *Flows* in MuSIASEM are defined as in LCA: the inputs or outputs that are consumed or produced by the processor. Examples of flows are electricity input, electricity production, water use, material use. *Funds* represent elements that are not consumed when they are used, such as labor or a wind turbine, but that have to be maintained, usually by consuming flows. Funds are the ones responsible for the consumption or the production of the flows and processors in MuSIASEM are also considered funds on their own. In Figure 5, flows are represented by relations 1,2 and 4, whereas the funds would be each node in the network. Table 3 shows the flow and fund variables most widely used in the description of a processor in MuSIASEM.

Also, MuSIASEM processors may not have a physical sustain (if they are functional), whereas LCA processes are always based on a physical structure. However, they both differentiate between social and natural flows; both have inputs and outputs to the environment; and both include conceptually the value chain. In practical terms we can argue that an LCA activity is one type of MuSIASEM structural processors that do not include social or natural fund variables.

Table 3. Standard processor variables used in MuSIASEM to create metrics

Variable	Input/Output of processors	Acronym and Units
Fund	**Power capacity**. Installed capacity of energy technologies.	PC (W)
Fund	**Human activity**. The total amount of hours dedicated to activities in society, including paid work but also self-maintenance activities such as sleeping.	HA (hours)
Fund	**Land use.** The total surface of land occupied by a certain activity. It can be appropriated by occupation or by absorbing the capacities of the ecosystem that maintains it. Includes water resources appropriation.	LA (Ha)
Flow	**Material inputs.** Total material required for the processor to function or to be produced. It is equivalent to material inputs in LCA.	MI (tones, m^3)
	Water use. Total water consumption for the processor's operation or manufacturing. It is equivalent to water use in LCA	WU (m^3)
Flow	**Energy inputs.** The total energy required for the processor to function. It is equivalent to energy inputs in LCA. They can be measured as:	
	Primary energy sources. Amount of resources available for energy extraction. (Natural gas, oil, Solar Radiation, Wind Speed)	PES (tones, m^3, W/m^2, m/s…)
	Gross energy availability. Amount of energy that can be extracted from PES.	GEA (thermal, J, or electricity (Kwh))
	Net energy availability. Amount of energy carriers produced by the energy system, taking into account losses during the transformations.	NEA (thermal, J, or electricity (Kwh))
	Energy end-use. The energy that has been effectively used by consumers. It can consider the losses in distribution as well as those related to misuse.	EU (thermal, J, or electricity (Kwh))

3.2.1 METRICS FOR SUSTAINABILITY CHECKS IN MUSIASEM

A MuSIASEM protocol does not have a fixed set of metrics. Instead, it has a fixed set of flow and fund variables presented above, which can be used to develop metrics tailored to a specific case. There are, however, two types of metrics: intensive and extensive. *Intensive metrics* are calculated as the ratio between flow and fund variables and determine how societies and ecosystems use or produce a flow. *Extensive metrics* can be calculated either with flow or fund variables and provide information about the size of the interaction. Table 4 presents a summary of the most widely used metrics for assessing the feasibility and viability of energy systems in MuSIASEM.

Table 4. Commonly used metrics in a MuSIASEM assessment

Check	Metric Type	Description	Acronym and units	LCA?
Viability	Ext (Flow)	**Total Energy Throughput**. The total amount of energy demanded by a social activity, or at a specific analytical level. It can be any of the energy flow variables described above.	TET (J, kWh)	Yes
	Int (flow/fund)	**Energy Metabolic Rate**. Amount of energy required per hour of human activity, per social activity, or at an analytical level.	EMR (J,kWh/hour)	No
	Int (flow/flow)	**Economic Energy Intensity**. Amount of energy used per unit of value-added, per social activity, or analytical level.	EEI (J,kWh/Euro)	No
	Int (flow/flow)	**Economic Labor Productivity**. Amount of value added per hour of human activity, per social activity, or analytical level.	ELP (Euro/h)	No
	Int (flow/fund)	**Intensity of power capacity.** The ratio between energy input and the power capacity of a specific part of the energy system.	IPC (kWh, J/ MW)	Yes
Feasibility	Ext (Flow)	**Land Appropriation.** Quantitative and qualitative damage created to land.	LA (ton, m^3)	No
	Ext (Flow)	**Water Appropriation.** Quantitative and qualitative damage created to water.	WA Various	No
	Int (Flow/Fund)	**Environmental Intensity of power capacity.** The ratio between an input flow or fund (water, material, land) and the power capacity of a certain part of the energy system.	EPC (ton, m^3, kWh, J/ MW)	Yes

Despite an established conceptual definition of the four checks in MuSIASEM, the development of metrics has been more fruitful for the viability of energy systems (Di Felice et al., 2024; Giampietro et al., 2013; González-López & Giampietro, 2018; Parra et al., 2018; Ripa et al., 2021). The feasibility assessment has mostly been developed in the analysis of water systems (Cabello Villarejo & Madrid López, 2014; Madrid-López et al., 2014) and in considering the dynamics of the ecosystem (Lomas & Giampietro, 2017). It requires the integration of other concepts and frameworks that are better suited for analyzing environmental impacts.

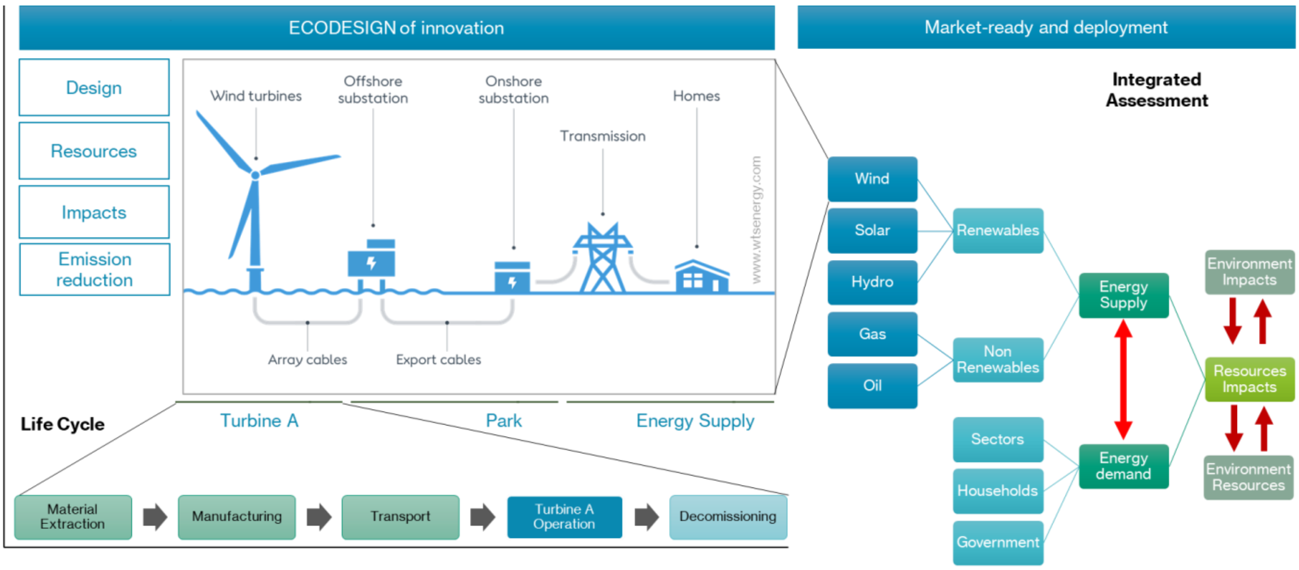
3.3 WINDSES: THE FRAMEWORK

WindSES is an application of the ENBIOS (Madrid-López et al., 2021) framework created specifically for tailoring metrics relevant to decision-making about the energy transition in Europe. The framework is based on the “closing” of a MuSIASEM dendrogram for wind analysis in Europe, which connects from the site-specific park level to the global energy system perspective. In this way, both the cumulative aspects of LCA plus the holistic aspects of SES are covered. Figure 9 illustrates the methodological implementation between the two frameworks.

3.3.1 INTEGRATION OF LCA AND MUSIASEM

We begin by analyzing the life cycle impacts using an LCIA method that is relevant to the assessment. The inventories for this assessment can be extracted from databases such as Ecoinvent or GaBi. However, for thorough, high-resolution wind power data, we recommend using WindTrace (Sierra-Montoya, 2024) and the technical database of deliverable 1.1 (Sierra Montoya & Madrid López, 2025). This part is more closely related to the technical aspects of the park or the turbine itself and could be considered part of a decision-making process that optimizes the park's design.

Figure 9. Schematic representation of the ENBIOS adaptation for wind power.



We then insert this assessment in the MuSIASEM framework, where the holistic metrics are defined and help contextualize the LCA. In doing so, we move towards the deployment of wind energy as a sector, where decisions related to zone prioritization, energy security, and global impacts are relevant. Here, we can relate the analysis to issues of distributive justice (who bears the burden and benefits) as well as procedural justice (how decisions about these topics are made).

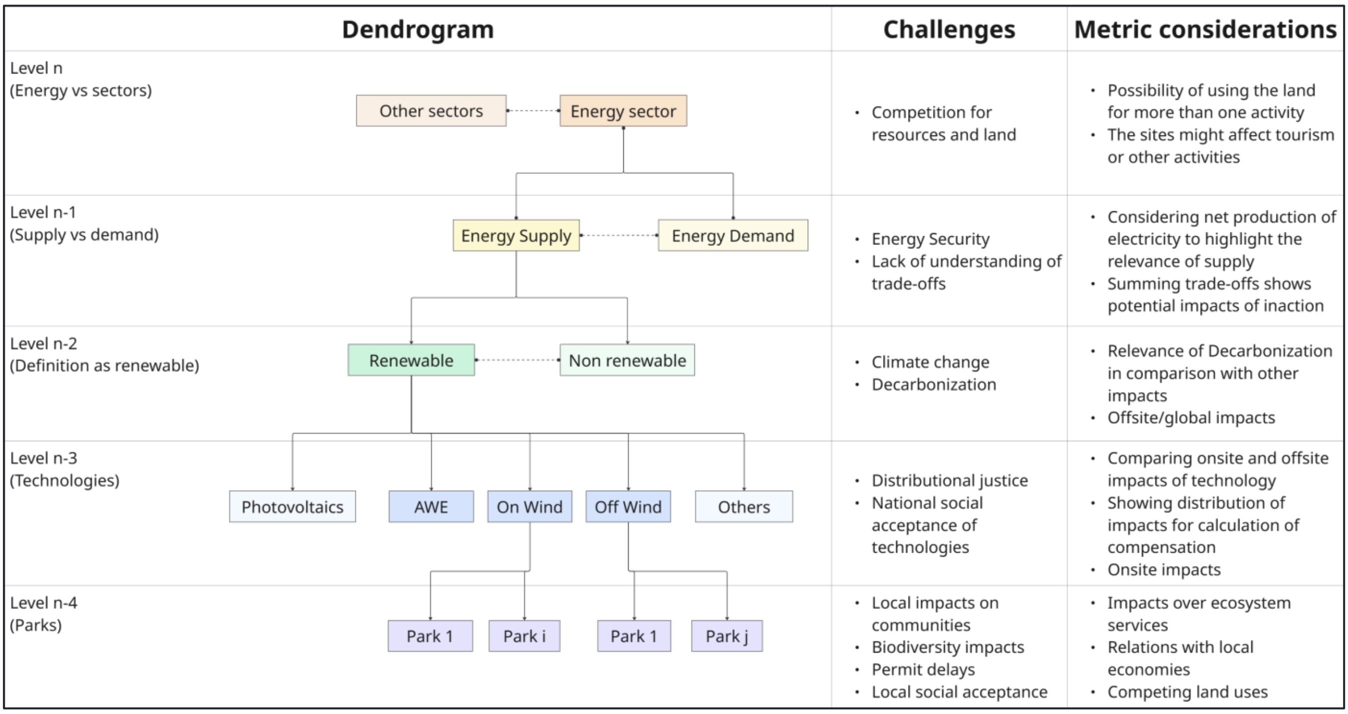
3.3.2 DEFINITION OF THE ANALYTICAL LEVELS

Figure 10 shows the detail of the adaptation of the MuSIASEM part of ENBIOS for its use within JUSTWIND4ALL. It relates the challenges in implementing wind power to the considerations for metric development highlighted during discussions in various forums.

- The **level n** represents the societal level and illustrates the relationship between the energy sector and other sectors, including other economic sectors such as agriculture or tourism, as well as local communities in their capacity as households.
- **Level n-1** includes the energy supply sector, defined in WindSES as a functional node (and therefore without a structure). The relevant metrics at this level examine the ability of the new wind-led configuration of the energy system to meet demand. This is included for illustration purposes only. In JUSTWIND4ALL, the configuration of the energy supply sector is optimized considering a given demand projection for the year 2050. Relevant metrics here relate global impacts or material use (such as the total amount of minerals) to the net energy production of the sector.

- **Level n-2** illustrates the distinction between renewable and non-renewable technologies. At this level, the conceptualization of technologies as renewable or non-renewable is based on comparing the demand for a resource with the Earth's ability to replenish it. Therefore, we will examine metrics that relate real emissions to targeted emissions or the use of resources with known reserves. It will also relate to offsite impacts, that is, those that occur elsewhere and are not directly on the site of installation.
- **Level n-3** showcases the diversity of technological options, maintaining a functional approach. This level is relevant for decision-making about what technology should be prioritized in policy-making or what technology would be better to choose by an energy community, broadly speaking (e.g. wind vs photovoltaics). The relevant metrics here relate to comparing the performance of the technologies from different perspectives. At this level, it is crucial to understand the aggregated impacts that this technology will have on the municipality or region where it is installed.
- **Level n-4** is structural and represents the actual parks and the sites that host them. At this level, the particularities of the ecosystem and the social system need to be understood and connected. This is the level that *sees* the tangible structures and, therefore, the one that connects with ecosystem issues. Issues such as noise level, wake effect, or flickering effect are relevant at this level only, as they would not have any meaning when aggregated to the upper levels. It is at this structural level that the information about the park's design is relevant, and LCA impacts are calculated using this level as the starting point, even though they are only aggregated to a level where they are relevant.

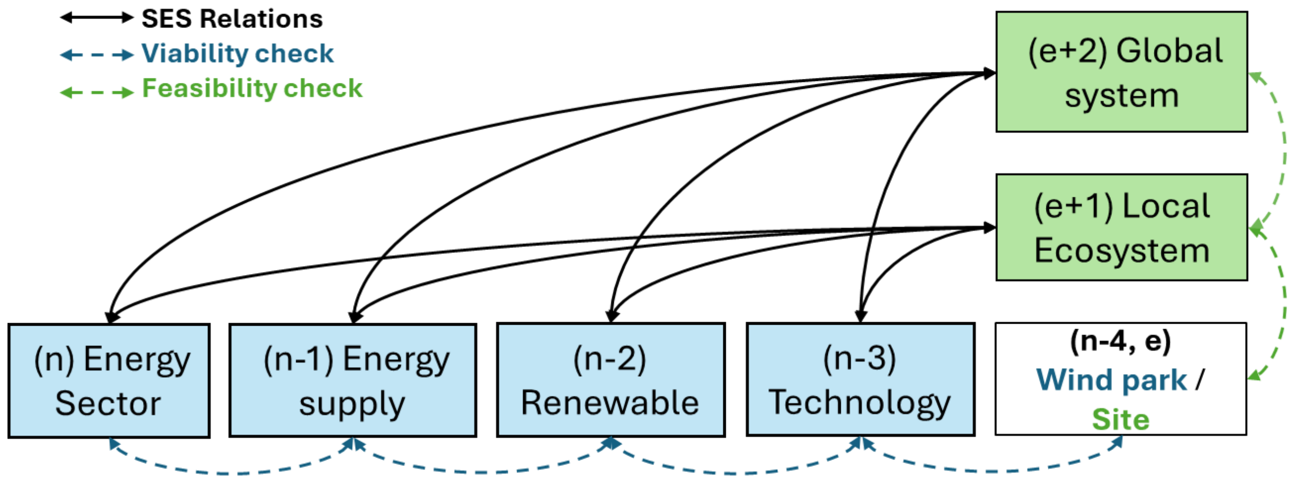
Figure 10. Dendrogram used in the metric definition for JUSTWIND4ALL, in relation to challenges in implementing wind power and key considerations for the metrics.



3.3.3 A GRAMMAR TO CONNECT WIND AND SOCIO-ECOSYSTEMS

The grammar **represents the relevant levels** of the energy system in relation to the levels of the ecosystem. For simplicity, Figure 11 illustrates only the analytical levels defined in Figure 10. The relationship between the levels of the energy system is shown in blue, and the levels relevant to analysing the feasibility of the proposed energy system are in green.

Figure 11. Grammar for defining wind energy metrics. Social aspects are covered in the n levels. Environmental aspects are covered in the E levels.



- **Level E represents the site where** the wind parks are located and which will be transformed during installation. This is the level connected to the environmental impact assessment of permits, for example, and the tender calls.
- **Level e+1** encompasses the local ecosystem surrounding the site and the ecosystem services associated with it, including provisioning, regulation, and cultural services. The local ecosystem also connects with other economic and non-economic social activities, such as fishing in the case of offshore wind or agriculture in the case of onshore wind.
- **Level e+2** displays the global system and the ecosystem services associated with the Earth, typically related to regulation (atmosphere). This level is relevant as it considers the cumulative impacts that occur beyond the ecosystem where the site is located and are related to the life cycle of the technology.

3.3.4 INTEGRATION WITH ECOSYSTEM SERVICES

Ecosystem services (ES) are ecological functions that support human well-being and needs through provisioning, regulating cultural, and supporting services (Millennium Ecosystem Assessment, 2003). In WindSES, the ES framework is used to highlight ecological functions that are often overlooked by market or LCA indicators and can be used to track the disturbance of ecosystems. It is relevant at the park/site level (n-4/E) and its relationship with the surrounding ecosystem and local community. We adopt here the Common International Classification of Ecosystem Services (CICES v5.1) Feu clic o toqueu aquí per escriure text.,., summarized in Table 5. The case study in Section 5 provides an example of implementing the ecosystem service framework for the prospective evaluation of parks.

Table 5. Common International Classification of Ecosystem Services (CICES), main categories.

CICES Theme	CICES Class	TEEB Categories
Provisioning	Nutrition	Food, Water
	Materials	Raw Materials, Genetic resources, Medicinal resources, Ornamental resources
	Energy	
Regulating and Maintenance	Regulation of wastes	Air purification, Waste treatment (esp. water purification)
	Flow regulation	Disturbance prevention or moderation, Regulation of water flows, Erosion prevention
	Regulation of physical environment	Climate regulation (incl. C sequestration), Maintaining soil fertility
	Regulation of biotic environment	Gene pool protection, Lifecycle maintenance, Pollination, Biological control
Cultural	Symbolic	Information for cognitive development
	Intellectual and Experiential	Aesthetic information, Inspiration for culture, art and design, Spiritual experience, Recreation & tourism

CICES has a total of 67 high-definition classes of ecosystem services. For each of them, we have identified the relevant indicators related to wind energy and defined proxies that can serve as indicators. The tables of proxy indicators for provisioning, regulation and cultural services used for the development of metrics for wind energy, can be consulted in Annex III.

4 METRICS FOR HOLISTIC WIND ASSESSMENTS

4.1 THE PURPOSE OF THE METRICS

Using the framework presented in section 3, this section introduces a set of metrics defined for the holistic assessment of wind energy. The purpose of this library is to serve as a deposit of metrics from which decision-makers and analysts can borrow and build, depending on the purpose of the assessment. One very important consideration in selecting metrics from this library is that **each metric is valid at its own level but may be irrelevant at other levels**. For example, the information about the aggregated wake effect of the whole wind power sector at level n-1 (energy supply) lacks meaning. It is, therefore, essential to make a conscious metric choice.

The metrics are structured to evaluate the sustainability of wind power implementation scenarios at the five levels represented in Figure 10. The library distinguishes between the analysis at the wind park level (structural and site-specific) and diverse views of wind energy as a sector of society (functional). The structural perspective is addressed at level n-4/E in Figure 11, which illustrates the park and the site where it is installed. The functional perspective can be examined at levels n to n-3, as explained above.

We organize the library based on the three checks presented in section 3.2: feasibility, viability, and desirability. We differentiate between structural and functional levels, identifying opportunities where a life cycle perspective could be beneficial. These metrics have been defined to help overcome barriers to implementing wind energy, incorporating insights from workshops and interactions with wind labs. This approach complements the existing techno-economic metrics used to assess wind implementation; therefore, those techno-economic metrics are not included in the library. We provide a companion to the library that includes a compilation of the intermediate work we have done, which may be useful for the development of the metrics. In the SI information, the reader can find an Excel file with variables published in previous studies that are available and can be used for calculating metrics,

The metrics have been tested in a pilot study for Catalunya (functional levels) and a specific site, which has not yet been developed, namely the Tramontana Park in northern Catalunya. We will continue testing the metrics in the case studies of the JUSTWIND4ALL project. We will also create a protocol to help us integrate some of them into the ENBIOS tool, producing a Python workflow that incorporates them as parameters.

4.2 A NOTE ON ENERGY SYSTEM SCENARIOS

In JUSTWIND4ALL, we assess four types of wind-related energy configurations:

- Scenarios generated through participatory processes or by policies, most notably the Member States' National Energy and Climate Plans (NECPs). We refer to these configurations as scenarios, as they are low-resolution sets of indications for either a future energy mix (level n-3) or decarbonization objectives (n-2).
- High-resolution energy system configurations calculated using an energy system optimization model (ESOM), which typically provides more geographical granularity comparable to that of n-3 technologies.
- A database of actual installations with a regional component (same as above, level n-3)
- A Wind Park project (n-4)

ESOMs are a specific type of energy model used to calculate optimal energy configurations, typically based on techno-economic parameters. Their main inputs include spatial-temporal data that describes energy demand, renewable area potentials, capacity factors, and techno-economic assumptions about technologies. Internally, ESOMs define a linear cost-minimization problem under constraints. The outputs consist of cost-minimal energy system configurations (installed capacity) and operations (energy conversion, transmission, and storage over time) based on these assumptions or, alternatively, near-cost-minimal designs. Thus, the modeled energy system is always viable, as supply must meet demand in both space and time.

In JUSTWIND4ALL, we utilized the Calliope framework (Launer, 2024), which incorporates assumptions about the production processes of crucial materials, such as steel, cement, and plastic, alongside the technologies represented in the future energy system, among others. However, every ESOM has its own assumptions, and it is recommended that before developing the metrics presented here, the life cycle inventories are aligned with them. In the case of Calliope, the background inventories must be adjusted to reflect Calliope's demand assumptions. Additionally, the foreground inventories are adjusted to match the supply technologies.

4.3 METRICS FOR VIABILITY

In WindSES, the viability check assesses to what point the wind-related energy configurations under assessment meet two constraints:

i) Achievable, given their demand for technology and manufactured products (such as steel) compared to the economy's capacity to produce them.

ii) Able to provide energy in the type and amount needed to meet the demand.

When the analysis focuses on the results of ESOMs, as mentioned above, condition ii) is met, as this is precisely a condition for optimization. Consequently, the viability check would focus on the second condition. Table 6 summarizes the viability metrics by level.

One strategy to achieve a system’s viability is to import those technologies and materials from abroad. This corresponds to the “openness” check described in Section 3.2 above. Assessing openness requires the introduction of parameters related to international trade that are beyond the scope of the project. Therefore, we will not propose metrics specific to openness in this work.

Table 6. Summary of viability metrics

Type of level	Constraint	Level	Metric & Unit	Description
Structural	Material	n-4 link to n	Land Use Compatibility (LUC) (%)	Share of land used by the park that can be used for other activities
			Water Use Compatibility (WUC) (%)	Share of water used by the park that can be reused for other activities/reused after other activities
	Socio-economic	n-4 link to n-1	Park-to-Region Contribution (P2RC) (%)	Contribution of the park to regional electricity production, as a percentage of community electricity demand to regional demand.
			Electricity community surplus (ECS) (%)	Net contribution of the community to regional electricity production per kWh demanded by the community hosting the park.
Functional	Material	n-3	Material Performance (MP_{n-3}) (kg/kWh)	The total amount of man-made materials used in the life cycle of a *wind technology* per net kWh of electricity produced.
		n-2	Material Performance (MP_{n-2}) (kg/kWh)	Total amount of man-made materials used in the life cycle of a scenario of *mixed renewable* technologies per net kWh of electricity produced.
		n-1	Total Material Demand (TMD) (Ton)	Total amount of man-made materials used in the life cycle of a scenario of mixed renewable technologies
		n-1	Unmet Material Demand (UMD) (%)	Fraction of the total material demand that cannot be met through the region's internal economic production.
	Socio-economic	n-3 link to n-1	Net Technological relevance (NTR) (%)	Net production of electricity from a wind technology per unit of net energy supply.

4.3.1 STRUCTURAL (PARK) LEVEL (N-4)

At the park level, viability metrics provide information about the park's competition with other activities for local resources within the community, as well as the park's contribution to the regional energy system. These metrics are useful for decision-making in conversations about the distribution of benefits and the potential impacts of the park on the local community’s energy consumption.

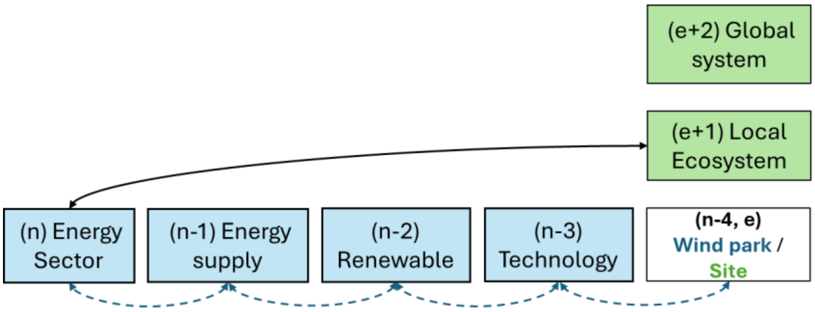
4.3.1.1 Land Use Compatibility (LUC) (%)

The Land Use Compatibility (LUC) represents the proportion of the park's land that can be utilized for activities other than those designated for the park. This metric provides information about the likelihood of the park being integrated with other activities, connecting the park (n-4) and its surrounding ecosystem (E+1) with the competition between the energy sector and other sectors (level n). For the same park, compatibility can be calculated with various activities, including agriculture and tourism.

For a set of i activities, it can be calculated with the expression:

Eq. 1 $$LUC_{(1,i)} = \frac{Area\ compatible\ for\ the\ activity}{Total\ area\ of\ influence\ of\ the\ park} * 100$$

Figure 12. LUC and WUC route in grammar



4.3.1.2 Water Use Compatibility (WUC) (%)

The Water Use Compatibility (WUC) indicates the proportion of water used by the park that can be reused for other purposes or after different activities. This metric is similar to LUC but considers volumes of water instead. It reaches more meaning for offshore wind. In this case, it refers to the volumes of sea appropriated by the wind park that are compatible with other uses, such as fishing or tourism. It follows the equation:

Eq. 2 $$WUC_{(1,i)} = \frac{Volume\ of\ water\ for\ compatible\ uses}{Total\ volume\ used\ by\ the\ park} * 100$$

4.3.1.3 Park-to-Region Contribution (P2RC) (%)

The Park-to-Region Contribution (P2RC) measures the park's contribution to regional electricity production in relation to its share of the community's electricity demand in the region. This metric addresses the need to quantify the relevance of the community hosting a site (n-4) in supporting electricity production (n-1) within a specific scenario. Its calculation follows:

Eq. 3 $$P2RC = \frac{\frac{Electricity\ production\ of\ the\ park}{Electricity\ production\ of\ the\ region}}{\frac{Electricity\ demand\ of\ the\ hosting\ community}{Electricity\ demand\ of\ the\ region}} * 100$$

Noting that if the result is less than 100%, the park production does not meet the community's share of electricity demand but rather compensates for part of the community's electricity use. In turn, if it is higher than 100%, it indicates how much more the community is contributing to the supply than to the demand, demonstrating the legitimacy the community would have in requesting benefits from the park. A result near 100 means that its contributions are similar.

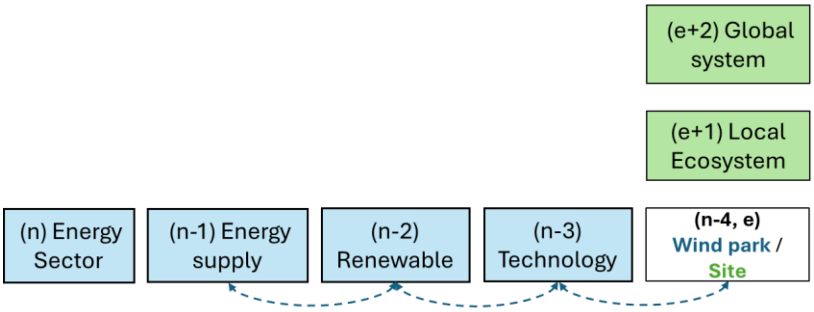
4.3.1.4 Electricity Community Surplus (ECS) (%)

The Electricity Community Surplus (ECS) represents the net electricity supply of the park (n-4) per kilowatt-hour (kWh) demanded (n-1) by the community hosting the park. It shows, for each kWh consumed by the community, how much electricity is provided to the energy system, considering the cumulative energy demand throughout its life cycle. It is calculated as:

Eq. 4 $$ECS = \frac{Park\ elec.\ production - Park\ equivalent\ elec.\ demand - Community\ elec.\ demand}{Community\ electricity\ demand} * 100$$

Where the park's equivalent electricity demand is the energy demand of the park's life cycle, as accounted for in the MuSIASEM variable *Net energy requirement (Mechanical)*.

Figure 13. P2RC and ECS route in grammar



4.3.2 FUNCTIONAL LEVELS (N TO N-3)

At the levels from technologies (n-3) to the energy sector (n), the metrics focus on assessing the performance of different technologies and their contribution to achieving the energy scenario, as well as on how these technologies will be produced. This set of metrics is more relevant to decision-making at the regional level, such as for defining a prioritization of technologies or industrial targets in energy plans and describing tenders.

4.3.2.1 Material Performances (MPn-3) (MPn-2) (kg/kWh)

The Material Performance (MP) represents the total amount of man-made materials used in the life cycle of a wind technology (n-3) or a scenario of mixed energy technologies (n-2) per net kilowatt-hour (kWh) of electricity produced. It is calculated for each relevant material with the following expressions:

Eq. 5 $$MP_{n-3} = \frac{Life\ cycle\ material\ i\ in\ technology\ j}{Life\ production\ technology\ j}$$

Eq. 6 $$MP_{n-2} = \frac{Life\ cycle\ material\ i\ in\ configuration\ x}{Life\ production\ technologies\ in\ configuration\ x}$$

4.3.2.2 Material Relevance (MR) (%)

The Material Relevance (MR) indicates the contribution of a specific man-made material (just as glass fibre or steel) to the total materials used throughout the life cycle of a technology (n-3), encompassing the period from design to installation. It provides insight into the wind sector's dependence on other sectors (n). This metric can facilitate discussions about prioritizing technologies to achieve a domestic production target of 40% for the technology outlined in the Net Zero Industry Act, for example. It is calculated as:

Eq. 7 $$MR_{n-3} = \frac{Life\ cycle\ demand\ material\ i\ in\ technology\ j}{Total\ material\ demand\ technology\ j} * 100$$

Eq. 8 $$MR_{n-2} = \frac{Life\ cycle\ demand\ material\ i\ scenario\ s}{Total\ material\ demand\ scenario\ s} * 100$$

4.3.2.3 Technological Material Demand (TMD) (Ton)

The Technological Material Demands (TMD) represents the total amount of technosphere materials used in the life cycle of a scenario involving mixed renewable technologies. It provides insight into the overall material requirements (E) linked to a region's energy supply sector (n-1). Its calculation follows:

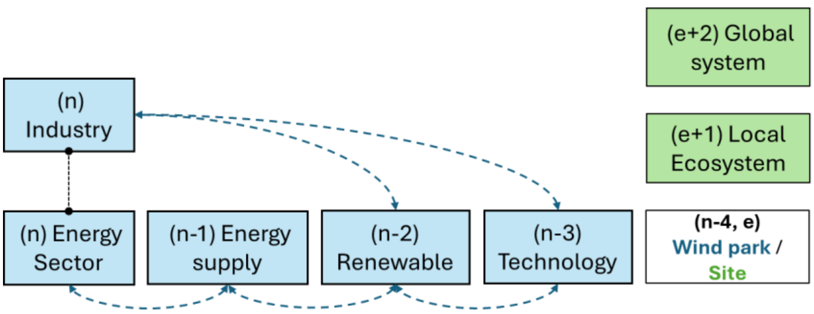
Eq. 9 $$TMD = Total\ material\ i\ used\ in\ life\ cycle\ of\ technologies\ in\ scenario\ s.$$

4.3.2.4 Unmet Material Demand (UMD) (%)

The Unmet Material Demand (UMD) represents the fraction of the Total Material Demand (TMD) (n-1) that cannot be met through the region's internal economic production (n). It assists in identifying bottlenecks of the domestic economic system to the implementation of the technology. It is calculated as:

Eq. 10 $$UMD = \frac{TMD - Domestic\ production\ of\ material\ i}{TMD} * 100$$

Figure 14. Grammar routes for MP, MR, TMD and UMD

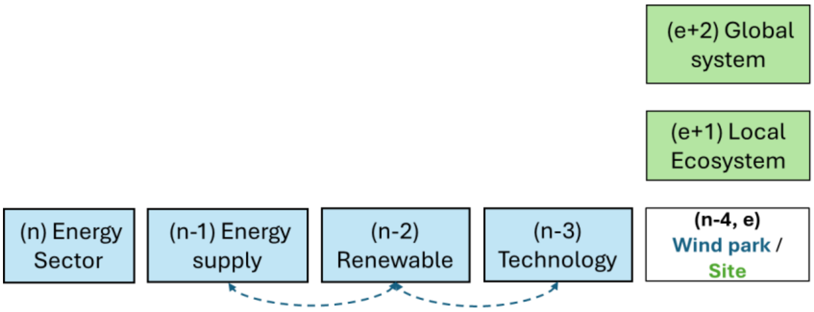


4.3.2.5 Net Technological Relevance (NTR) (%)

The Net Technological Relevance (TR) metric measures the net production of electricity from a wind technology per unit of net energy supply. It provides information about the actual contribution of each technology (n-3) to the actual electricity production (n-1), considering the demands of the life cycle of the technology. It is calculated as:

Eq. 11 $$NTR = \frac{Electricity\ production\ of\ technology\ j - Electricity\ equivalent\ demand\ of\ technology\ j}{Electricity\ production\ of\ energy\ supply - Electricity\ equivalent\ demand\ of\ energy\ supply} * 100$$

Figure 15. Grammar route for NTR



4.4 METRICS FOR FEASIBILITY

In WindSES, the feasibility check assesses to what point the wind-related energy configurations under the assessment meet these constraints:

i) The accumulated demand for resources through the life cycle can be met with Earth's reserves.
ii) The disturbance to ecosystems is within set limits
iii) The contribution to global change is within set limits

The scenarios defined by ESOMs typically address the need to design an energy system configuration that supports a specific climatic scenario. The most widely used scenario sets that human activities should not result in a global average temperature increase of more than 2ºC (Intergovernmental Panel on Climate Change, 2022). To achieve this, ESOMs typically consider and cap emissions as part of the optimization process. Consequently, the third condition is generally met in configurations calculated by ESOMs.

Table 7. Summary of feasibility metrics

Type of level	Constraint	Level	Metric & Unit	Description
Structural	Resources	n-4, E	Onsite Land use (OnLU)(%)	Share of the onsite land transformed by the park in the total land of the CORINE category of the community
			Onsite Water appropriation (OnWAPP, Hm3)	Onsite use of water from basins considered with a bad or poor ecological status as established by the WFD
		n-4, E+1	Ecological disruption (ED_x) as a change of: **General:** • Wind Speed Change (WSC) (%) • Collision with Aerial Fauna (COL) (no) **Onshore:** • Terrestrial Habitat Loss (OnHL) (km^2) **Offshore:** • Sea Stratification Period (OR) (days) • Nutrient Regulation (NR) (Nitrates) • Carbon Sequestration Capacity (CSC) (%) • Offshore Biodiversity Density (OfBD) (kg/km^2)	
	Global Change	n-4, E+2	Avoided Local emissions (ALE) (Ton)	Emissions avoided in the community due to the presence of the park.
Functional	Resources	n-3, E+2	Raw Material Demand (RMD_{n-3}) (Ton)	Total amount of raw materials used in the life cycle of a *wind technology.*
		n-2, E+2	Raw Material Demand (RMD_{n-2}) (Ton)	Total amount of raw materials used in the life cycle of all technologies in a *scenario*.
	Ecosystem	n-3, E+1 (onsite and offsite)	Offsite screenings (Of_X)	A battery of indicators from ReciPe and EF LCIA methods calculated for offsite activities related to different wind power technologies.
	Global changes	n-2, E+2	Avoided Global emissions (AGE) (Ton)	Net emissions avoided globally due to the technology mix of the supply

As commented above in section 3.3.4, the assessment of ecosystems affected by a park at level n-4 cannot be based on life cycle assessment, given the generalist of its impact assessment methods. We propose to use the ecosystem service framework instead. So, the metrics presented at the structural level for the feasibility check relate these to potential metrics for their assessment. Table 7 summarizes the feasibility metrics. While a separation between onshore and offshore was not necessary for defining viability metrics, it is essential for feasibility metrics. Additionally, it is noted that many metrics based on ecosystem services and local environmental changes require experimental data, which may not always be feasible. Still, enough studies exist that can be used to assess the trend of metrics. The library's supplementary material includes recommendations for sources from previous studies.

4.4.1 STRUCTURAL (PARK) LEVEL (N-4)

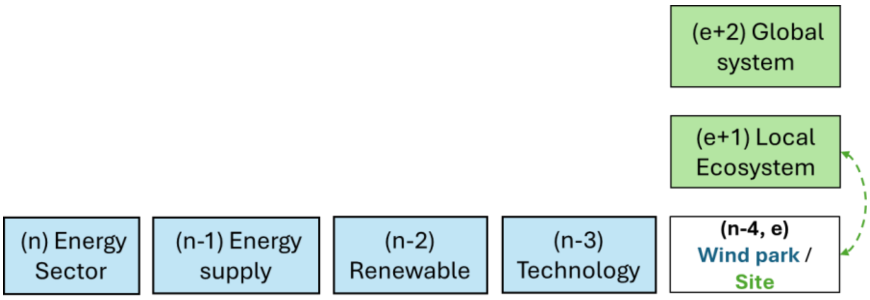
Similarly to the viability metrics for the structural level, the feasibility metrics can also be used for developing a more holistic evaluation in tenders. The challenge with feasibility metrics is that to better understand the local ecosystem, and due to their specificity, there may not be data available for all metrics in every location.

4.4.1.1 Onsite Land Use (OnLUS) (%)

The Onsite Land Use (OnLU) represents the proportion of land transformed by the park (n-4) compared to the total land in that CORINE category within the ecosystem of the community hosting the site (E+1). It compares the total availability of a specific type of land in a community with the changes that occur to that land. It requires GIS to assess specific land and adds a qualitative dimension to the discussions about land occupation. The logical route in the grammar is shown in Figure 16 and the metric is calculated as:

Eq. 12 $$OnLU = \frac{Land\ occupied\ by\ the\ site\ of\ the\ park\ in\ each\ CORINE\ category}{Total\ land\ in\ CORINE\ catgory\ in\ municipality} * 100$$

Figure 16. Route on the grammar for OnLU



4.4.1.2 Onsite Water Appropriation (OnWAPP, Hm³)

The Onsite Water Appropriation (OnWAPP) refers to the onsite use of water by the site (n-4) from basins in the local environment (E+1) with a poor or bad ecological status, as defined by the Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy (WFD). In the WFD, water bodies are classified according to their ecological status, which ranges from High, indicating no or very minor deviation from natural conditions, to Bad, reflecting severe deviation. The intermediate categories are Good (slight deviation), Moderate (moderate deviation), and Poor (major deviation). It also follows the route in Figure 16 and it is calculated as:

Eq. 13 $$OnWAPP = \frac{Land\ of\ site\ on\ each\ WFD\ class}{Total\ land\ of\ WFD\ classes\ in\ municipality} * 100$$

4.4.1.3 Ecological disruptions (EcDis_x) (%)

The Ecological Disruptions (EcDis_x) assesses the changes in important ecological (E+1) parameters that are typically affected by wind parks (n-4). The logic in the grammar is also covered by Figure 16. The list of the parameters included in WindSES are:

- General:
    - **Wind Speed Change (WSC) (%):** it measures changes in the strength or the orientation of the wind.
    - **Collision with Aerial Fauna (COL) (no):** counts the number of collisions in the park.

- Onshore:
  - **Terrestrial Habitat Loss (OnHL) (km^2):** represents the land transformed due to the installation.
- Offshore
  - **Sea Stratification Period (OR) (days):** indicates the period during which the stratification of the sea occurs.
  - **Nutrient Regulation (NR) (Nitrates):** measures the ability to mix the upper layers of the sea, using nitrates concentration as a proxy.
  - **Carbon Sequestration Capacity (CSC) (%):** reflects changes in the phytoplankton population.
  - **Offshore Biodiversity Density (OfBD) (kg/km^2):** represents the variety of biodiversity, indicated by the presence and frequency of hake fish.

Sources for the calculation of these disruptions can be found in the excel file of the supplementary information. The metric is calculated as:

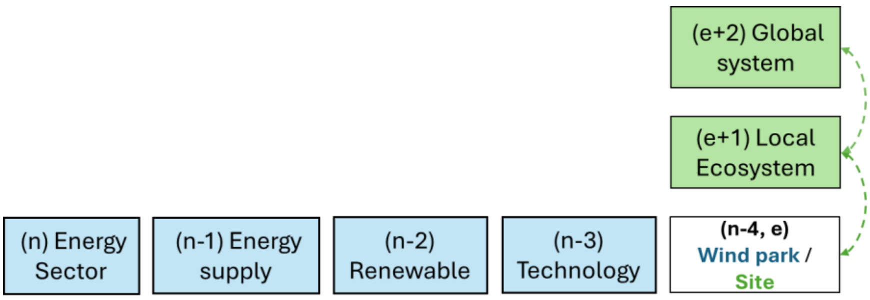
Eq. 14 $$EcDis = \frac{Scenario\ Value - Baseline\ Value}{Baseline\ Value} * 100$$

4.4.1.4 Avoided Local Emissions (ALE) (Ton)

The Avoided Local Emissions (ALE) provides an indication of the emission reduction (E+2) of the community hosting the site due to the electricity production of the park (n-4). It gives an idea of the benefits of the new installation to contribute to the debate about its trade-offs. As emissions are not localized in an ecosystem, they form part of the level E+2, the global system, following the grammar route in Figure 17. They are calculated as:

Eq. 15, $$ALE = Scenario\ emission\ by\ substance - baseline\ emissions\ by\ substance$$

Figure 17. Route on the grammar for ALE



4.4.2 FUNCTIONAL LEVELS (N TO N-3)

Calculating the feasibility metrics for the functional levels, like the viability metrics, need the precalculation of all metrics at the highest resolution level, which is the site or park. This step is only applicable for constructing the upper level. However, the metrics obtained are not relevant at the structural level, which requires more specific methods, such as the one outlined in section 4.4.1.3.

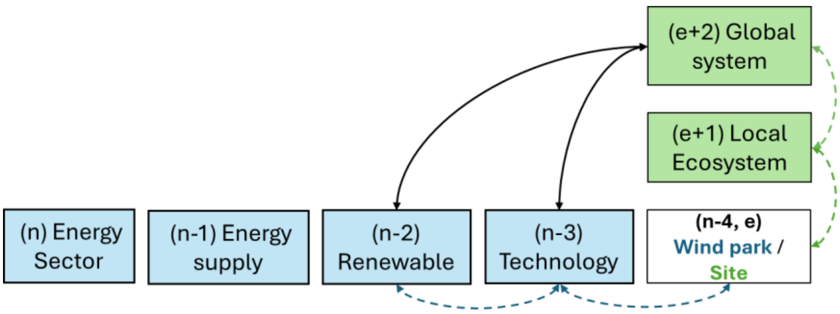
4.4.2.1 Raw Material Demand (RMDn-3) (RMDn-2) (Tom)

The Raw Material Demand (RMD) refers to the total amount of each raw material extracted from the Earth (E+2) that is used in the life cycle of wind technology (n-3) or other technologies within a decarbonization scenario (n-2). This metric focuses on the total material to facilitate later comparisons with known material reserves, unlike the viability metric of Material Performance, which refers to natural materials (such as raw materials like iron) rather than manufactured materials (such as steel). It follows the route in Figure 18 and follows the expression:

Eq. 16, $RMD_{n-3} = Sum\ of\ inventory\ flows\ for\ raw\ material\ i\ in\ technology\ j$

Eq. 17, $RMD_{n-2} = Sum\ of\ inventory\ flows\ for\ raw\ material\ i\ in\ Scenario\ s$

Figure 18. Route on the grammar for RMD, Of_X, GAE, NSEP



4.4.2.2 Offsite LCA Screenings (Of_X)

The Offsite screening (Of_X) adapts metrics already established in LCA to address a wide range of non-site-specific impacts that can be utilized for an initial assessment of levels where this specificity is unnecessary (n-3 to n). Two methods have been used for the analysis, listed in Table 8**Error! No s'ha trobat l'origen de la referència.**: ReciPe (Huijbregts et al., 2017a) and EF (Bassi et al., 2023) Also, the route is shown in Figure 18. LCIA metrics are calculated for offsite activities related to various wind power technologies (n-3), and from there, they can be developed for different scenarios (n-2). In any case, the total is always assessed at the functional levels, following the expressions:

Eq. 18, $Of\_X_{n-3} = Sum\ of\ offsite\ impact\ i\ in\ technology\ j$

Eq. 19, $Of\_X_{n-2} = Sum\ of\ offsite\ impact\ i\ in\ scenario\ s$

Table 8. LCA categories integrated in WinSES from the two methods widely used.

ReCiPe 2016 Midpoint Indicators	**Units**	**Environmental Footprint Indicators**	**Units**
Climate Change	kg CO_2 eq	Climate Change	kg CO_2 eq
Ozone Depletion	kg CFC-11 eq	Ozone Depletion	kg CFC-11 eq
Terrestrial Acidification	kg SO_2 eq	Acidification	mol H^+ eq
Freshwater Eutrophication	kg P eq	Eutrophication (freshwater)	kg P eq
Marine Eutrophication	kg N eq	Eutrophication (marine)	kg N eq
Human Toxicity	kg 1,4-DCB eq	Human Toxicity (cancer effects)	CTUh
Human Toxicity	kg 1,4-DCB eq	Human Toxicity (non-cancer effects)	CTUh
Photochemical Oxidant Formation	kg NMVOC	Photochemical Ozone Formation	kg NMVOC
Particulate Matter Formation	kg PM_{10} eq	Particulate Matter	kg $PM_{2.5}$ eq
Terrestrial Ecotoxicity	kg 1,4-DCB eq	--	
Freshwater Ecotoxicity	kg 1,4-DCB eq	Ecotoxicity (freshwater)	CTUe
Marine Ecotoxicity	kg 1,4-DCB eq	--	
Ionising Radiation	kBq U235 eq	Ionising Radiation (human health)	kBq U235 eq
Agricultural Land Occupation	m^2a crop eq	Agricultural Land Use	^{2}a crop eq
Urban Land Occupation	m^2a crop eq		
Natural Land Transformation	m^2	Land Use	m^2
Water Depletion	m^3	Water Use	m^3
Mineral Resource Scarcity	kg Cu eq	Resource Use (minerals and metals)	kg Sb eq
Fossil Resource Scarcity	kg oil eq	Resource Use (fossils)	kg oil eq

4.4.2.3 Global Avoided Emissions (GAE) (Ton)

The Global Avoided Emissions (GAE) quantify the emissions of various substances that will be avoided globally (E+2) due to the new technological mix within the energy supply sector (n-2) in the updated configurations of the energy system. Although CO2 is frequently included in energy system optimization models (ESOMs) as a constraint, other emissions that are harmful to ecosystems and human health are often excluded. If the primary argument for changing the energy system is to avoid climate change, then it is worth understanding how emissions are distributed. The GAE follows Figure 18 and is calculated as:

Eq. 20, $GAE = Emissions\ of\ the\ BAU - Emissions\ of\ Scenarios$

4.4.2.4 Net socio-ecological performance (NSEP) (x/kWh)

The Net Socioecological Performance (NSEP) reflects the global cumulative impacts (E+2) generated by wind technology (n-3) or a specific scenario (n-2) in relation to its net energy production. This metric incorporates life cycle assessments within the categories presented in Table 8 (in this case, total) and considers only the net energy production after deducting the life cycle costs with the expression:

Eq. 21 $$NEP_{(n-3)} = \frac{Total\ life\ cycle\ impact\ of\ technology\ j}{Net\ energy\ production}$$

Eq. 22 $$NEP_{(n-2)} = \frac{Total\ life\ cycle\ impact\ of\ scenario\ s}{Net\ energy\ production}$$

5 ASSESSING A NEW PARK IN THE CATALAN REGION

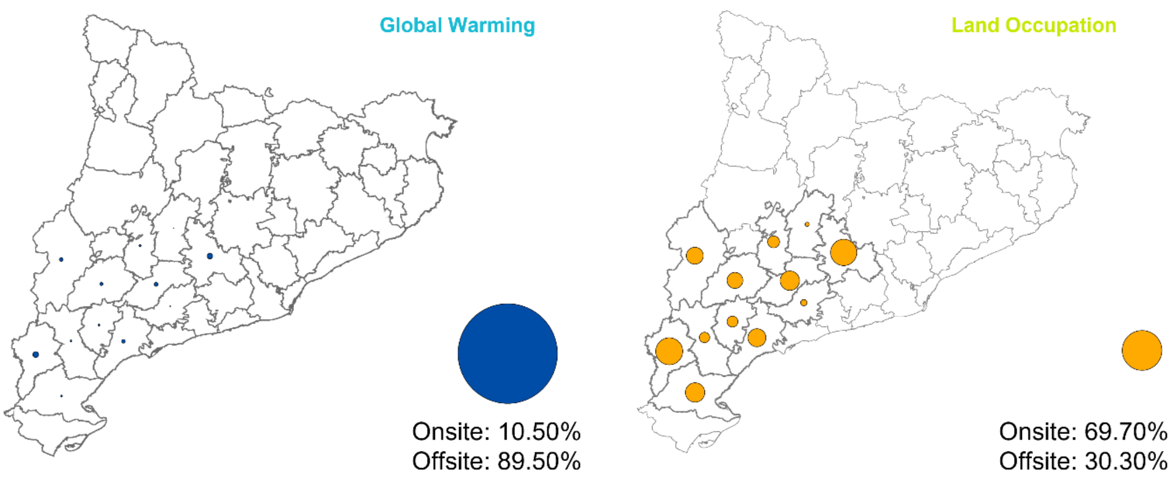
The region of Catalunya in Northeastern Spain served as a pilot location for developing the metrics library. It was utilized for testing the functional levels. Catalonia was a pioneer in wind energy development in Spain, with the first modern wind turbine installed in Vilopriu (Baix Empordà) in 1984 and the country's first wind farm commissioned shortly after in Garriguella. However, this deployment progress was interrupted after 2009 due to a lack of political will and regulations, which halted new projects for over a decade. As a result, Catalonia now lags behind in wind energy implementation, with only 5.8% of gross electricity production coming from wind in 2022 (2,587.8 GWh of 44,535.8 GWh) (ICAEN, 2022). In recent years, there have been efforts to reverse this trend and in 2024, 72 new renewable energy projects totaling over 1,190 MW were approved, including offshore and offshore wind, as well as photovoltaics (RedElectrica, 2025).

5.1 THE CONTEXT OF THE CATALAN WIND POWER SYSTEM

During the workshops, it was highlighted that the general public has a perception of regional misalignment in the distribution of impacts, with urban areas, such as Barcelona, demanding resources and rural areas bearing the impacts of producing those resources. To understand this, we conducted an analysis to assess the distribution of burdens in the current wind sector in Catalonia. We asked ourselves about the distribution of those impacts and their comparison with the current demands. To do so, we mapped the onsite and offsite environmental impacts by region.

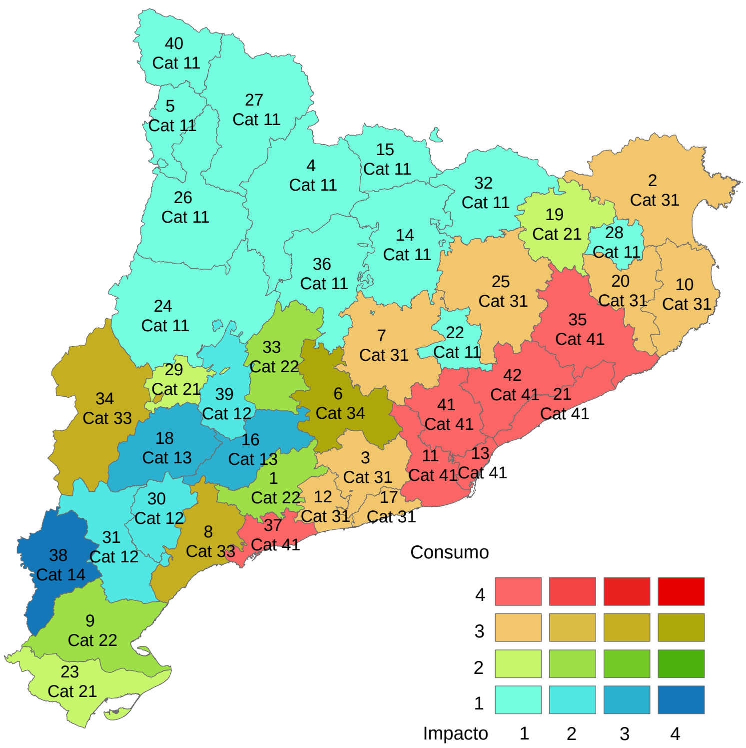
Figure 19 illustrates the differences in the distribution of two impacts with varying perceptions among the general public. In terms of global warming potential, Catalunya has a distinct external character, with nearly 90% of the impact occurring far from the wind parks. This is the result of manufacturing processes and raw material extraction happening in regions with energy systems that are still heavily dependent on fossil fuels. Conversely, the land occupation- an impact that is highly noticeable to inhabitants and the general public- has a greater onsite component, thereby creating a stronger perception of the impact burden in the regions surrounding the wind turbines.

Figure 19. Onsite and offsite impacts of wind turbines in Catalunya for (a) Global Warming, and (b) Land Occupation.



When comparing demand and supply, it is observed that each is concentrated in different areas, thus creating an unequal distribution of the burden of impacts and demands for electricity. In Figure 20, the bright red areas indicate the highest local electricity demand and lower-impact areas. As can be seen, the Barcelona Metropolitan Region and Maresme (Cat 41), which are highly populated areas, concentrate the highest demand, whereas the Garrigues and Conca de Barberà regions (18, 16, and 38) in the windy southwest carry a larger share of the electricity demand burden.

Figure 20. Distribution of bivariate metrics electricity demand and material demands.



5.1.1 METHODS

We borrowed the method developed in the LIVEN project (Sierra-Montoya et al., 2023) to separate onsite and offsite impacts. This approach systematically disaggregates wind turbine inventories by identifying and isolating onsite activities, involving a tier-by-tier exploration of the supply chain using Brightway 2.5 (Mutel, 2017). These processes include excavation and land preparation, fuel consumption by construction and maintenance machinery, the development of auxiliary roads, operational emissions, and the dismantling and disposal of infrastructure at end-of-life. This methodology builds on the separation of structural and functional components in ENBIOS (and WIndSES), as the precise location of power infrastructure (n-4) is crucial for accurately assessing the spatial distribution of environmental impacts at level n-3 and up.

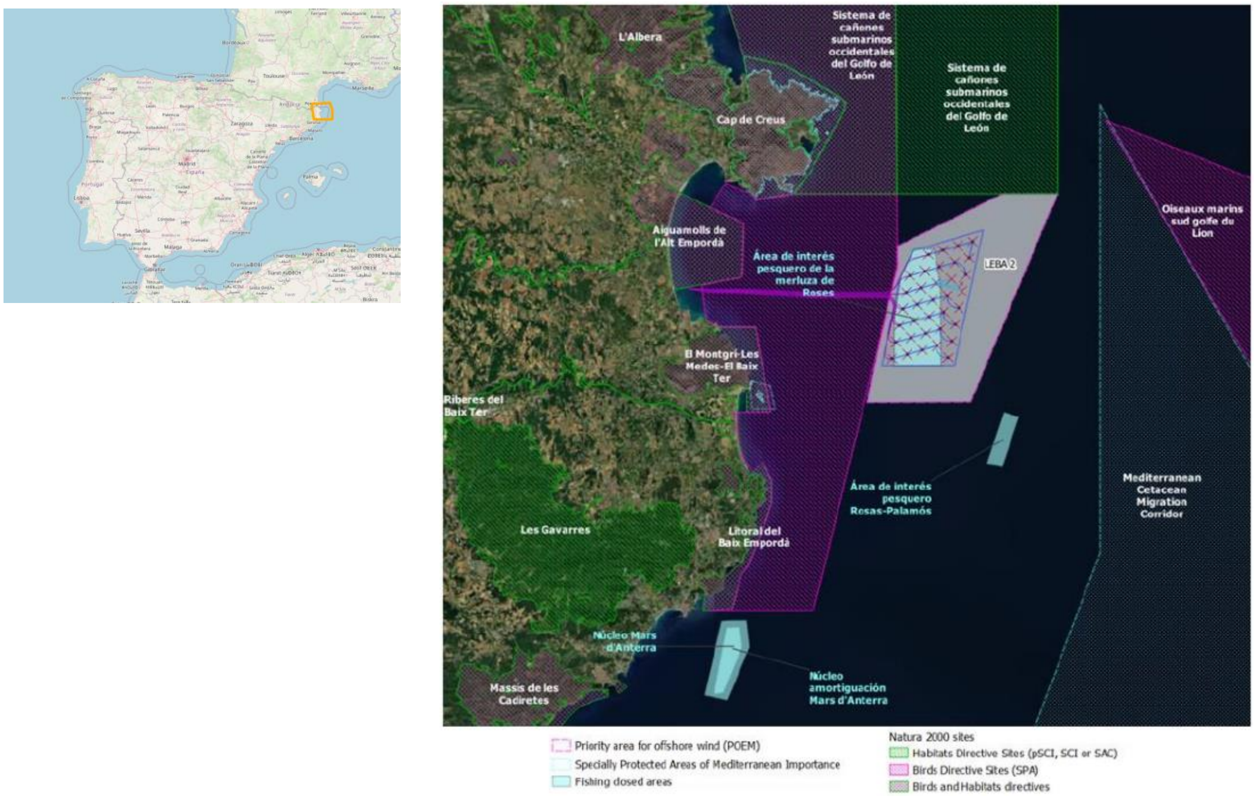
Hre we used wind turbine and electricity production inventories from Ecoinvent 3.9.1 (Wernet et al., 2016). To ensure comparability, we selected inventories with consistent geographic attributions, specifically *Rest of the World* for wind turbine infrastructure and *Spain* for electricity production. Life-cycle impact assessment (LCIA) was performed to quantify onsite impacts, utilizing the spatially disaggregated inventories. In contrast, total impacts (i.e., onsite + offsite) were derived from unmodified Ecoinvent inventories. We selected two impact indicators from the ReCiPe 2016 v1.1

midpoint (H) method (Huijbregts et al., 2017): Global Warming (GW) and Land Occupation (LO). Wind power plant locations across Catalunya were compiled (ICAEN, n.d.), and installed capacity was aggregated at the county level.

5.2 CASCADE SES EFFECTS OF POTENTIAL WAKE IN TRAMUNTANA PARK

With this reality in mind, we conducted a small assessment of the impacts of the wake effect of Tramuntana, an initiative to construct an offshore park that has faced significant local opposition. We collaborated with the MarineWind project to organize workshops related to this case study (Section 7.3.1) and tested the metrics developed, involving key stakeholders in decision-making about the park. Additionally, we invited modelers from the Catalan Energy Institute (ICAEN) to comment on our work at the regional level, following several iterations in the development of the metrics.

Figure 21. Priority area for offshore wind (LEBA-2) and surrounding MPAs in the North Catalan Sea .



The area of the future Park Tramuntana is located in the northern Catalan Sea, 24 km from the coast, within a polygon designated as a high-priority site for wind development (LEBA-2) by the Spanish Maritime Spatial Planning Ordinance (POEM) (Figure 21). LEBA-2 is located on the continental shelf on muddy substrate and characterized by a seasonally stratified water column with depths ranging from 120 to 180 m (Diez-Caballero et al., 2022). The hydrodynamic regime is determined by the Western Mediterranean Oscillation (WeMO), the regional climate index that, when in a positive phase, entails low sea surface temperature, increased rainfall, and strong wind mixing, which are favorable conditions for planktonic productivity (Martín et al., 2012).

Primary productivity in the Catalan Sea is controlled by nutrient inputs from rain-induced river runoff and a strong, persistent northeasterly wind that marine biologists have identified as an important fertilization agent, known by locals as *la tramuntana* (Estrada et al., 2022). Annual wind speed averages 8-9 m s^{-1} (Dirección General de la Costa y el Mar, 2023) and in colder autumn months, mixes stratified layers of the water column differentiated by temperature, resulting in an upwelling of nutrient-rich water to the surface that creates viable conditions for a photosynthetic bloom in the winter (Van Berkel et al., 2020). These underlying mechanisms are expected to account for 1/3 of annual primary productivity in the Catalan Sea which averages an estimated 158 g C m^{-2} yr^{-1} (Bosc et al., 2004; Estrada, 1996). After winter mixing, dissolved inorganic nitrogen (NO_3^- + NO_2^-, DIN) concentrations in the sea surface spike with averages up to 4.47±1.18 mmol m^{-3} and primary productivity reaches an average of 1024±523 mg C m^{-2} d^{-1} with considerable interannual variability (Estrada et al., 2014).

In this pilot, we aim to address the question: Will the wake effect impact other activities in the SES region of Park Tramuntana?

5.2.1 RESULTS

5.2.1.1 Interactions

The persistent directionality of *la tramuntana* and its dominant role in fertilization dynamics in the Catalan Sea indicate that the wake effect's impact on primary productivity could be considerable in Parc Tramuntana. Furthermore, the 15 MW capacity of Parc Tramuntana turbines compared to the 2-3 MW turbines used in most currently installed OWFs test sites may result in larger wind wake disparities with a greater potential to alter fertilization dynamics.

Apart from wind energy, this region is appropriated by commercial, recreational, and traditional actors. The aforementioned fertilization dynamics give rise to the exceptionally rich biodiversity observed in this region with regard to secondary production and fisheries compared to the rest of the oligotrophic Mediterranean Sea (Alcaraz et al., 2007). As such, LEBA-2 is situated in an area of high market and cultural value, both in terms of fishing and aesthetic importance.

Notably, Parc Tramuntana would overlap with a community-managed no-take zone that local fishers agreed to protect for its importance as a breeding ground for the hake (*Merluccius merluccius*), an abundant key economic species for the Catalan Sea with a biomass index of 956 kg km^{-2} (Figure 22) (Sion et al., 2019). In Catalonia, 873.24 t of hake was captured and sold for €6,287,000 in 2022 (Institut Català de Recerca per la Governança del Mar, 2023). This population has been experiencing steady population decline over the past two decades, with landings in the Roses Port decreasing by ~75% since 1991 (Sala-Coromina et al., 2021). From an ecological perspective, the degree of fishing over the last decades in addition to shipping, pollution, and tourism is placing mounting pressure on sensitive species and important habitats. From a social perspective, this area presents a dilemma of marine spatial use conflict among different stakeholders, stemming from economic, cultural, and ecological value perspectives.

Fishing alone provides a complex dilemma of marine spatial use as industrial, recreational, and artisanal fishers contend for the same resources with different motivations. Economically speaking, the Gulf of Roses port alone generated €7.5 million of income in the year 2022 (IDESCAT, 2023). For artisanal fishers, this represents not only their livelihood (average salary about €15,000 yr^{-1}), but also a cultural practice enabled by intergenerational knowledge and collaboration that links them to an ancestral heritage (Gómez, 2022). Artisanal fishing is the second most prominent modality for catch and income of the hake, making up about 6% of total annual catch while industrial trawling makes up about 90% (Institut Català de Recerca per la Governança del Mar, 2023). Artisanal fishers in Catalonia spend an average of 257 d yr^{-1} fishing for about 11.5 hr d^{-1} (Dedeu et al., 2020).

Recreational fishing, on the other hand, is primarily motivated by the value of social interactions, generating €90 million per year in income for governmental agencies and the tourism industry in Catalonia (Gómez, 2022). In Catalonia, most recreational fishers report making about 35 trips per year, with an average of 2,700 annual trips occurring in the Gulf of Roses (Pujol Baucells et al., 2023). Bottom trawls cause the greatest impact on the shelf area[1].

In addition to the community-managed fishing closed areas, the region's notable biodiversity has led to the establishment of eight marine protected areas (MPA), aimed at restoring the health of the ecosystem (Lloret et al., 2022b). These MPAs support low-impact recreational activities such as snorkeling, swimming, and kayaking, which are recognized for providing physical and mental health benefits to local actors (Lloret et al., 2023).

In addition to supporting the trophic web, phytoplankton serve as the biological carbon pump of the sea, assimilating atmospheric carbon dioxide into usable forms for the entire ecosystem. Primary productivity in the Spanish Mediterranean Sea is estimated to possess a carbon sink capacity of 6.23 million tons CO_2 per year (Melaku Canu et al., 2015). Alongside renewable energy development, protecting this vital ecosystem function is crucial for decarbonization, particularly when considering the effects of the overarching feedback loop created by climate change pressures on these sensitive species.

Historic trends show intense sea surface warming (2.8±0.4 °C 100 yrs^{-1}) from 1981 to 2021, which reinforces vertical stratification, and thus, reduces the efficiency of wind-induced mixing of the water column (Vargas-Yáñez et al., 2023). This aligns with previous studies on climate change effects on the Catalan Sea, which suggest a likely scenario of reduced rainfall and wind, warmer sea surface temperatures, and a prolonged stratification period (Calvo et al., 2011). This is noteworthy because further reducing wind speed via OWFs may exacerbate the period of nutrient-depleted conditions and alter planktonic metabolism, which is already threatened by climate change. Additionally, sea surface warming and the strengthening of stratification are thought to be contributing factors to the observed decline in hake biomass (Sala-Coromina et al., 2021). Furthermore, stratified shelf habitats such as found in the Catalan Sea between 70 and 150 m deep are known to play an important role in climate change resilience as thermocline buffers greater depths from warming (Lloret et al., 2023).

The Parc Tramuntana wind farm itself is expected to generate 1800 GWh yr^{-1} of renewable electricity, preventing an estimated 16 million tons of CO_2 emissions over its expected operation lifetime (Diez-Caballero et al., 2022).

5.2.1.2 Representation

Figure 22 illustrates the ecosystem services affected by the local impacts generated by Parc Tramuntana. We identified risks of habitat and hydrodynamic disruptions due to the Wake effect, which occurs when wind speeds decrease downstream of offshore wind farms and can impact ecosystems, although this is often overlooked. Research indicates that downstream wind speed reductions can range from 5% to 90%, over distances of 5 to hundreds of kilometers.

[1] https://natura2000.eea.europa.eu/Natura2000/SDF.aspx?site=ESZZ16001

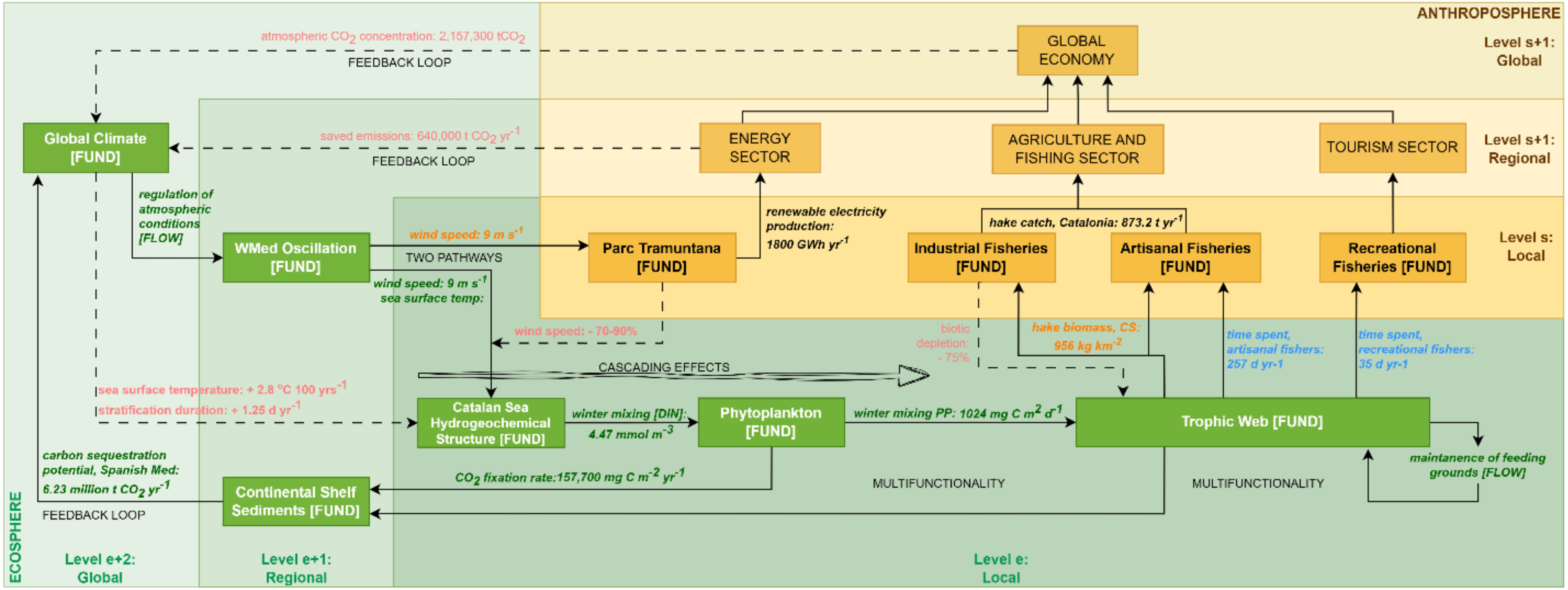
The extent of the effect varies based on environmental conditions and wind farm design, including turbine height, capacity, and layout. These changes can alter water column mixing, which affects nutrient distribution, plankton productivity, and the habitats of fish and other marine species. Over time, this can disrupt local food webs and biodiversity. This can lead to socio-economic impacts on sectors like fishing, which rely on stable species population dynamics. Higher-scale impacts, such as climate change and overfishing, can amplify or reduce ecological processes through positive ("+") or negative ("-") feedback loops, thereby influencing environmental outcomes. Table 9 presents the changes in the selected indicators; however, not all could be calculated due to the need to link them with other modeling activities.

Table 9. Calculation of indicators for the ecological disruption metric

Ecosystem Level/ Component	Ecosystem Service	Indicator	Value	Disruption
Global Climate (E+2)	Bioclimatic regulation	Temperature	14 °C	+1,5 °C
Local Climate (E+2)	Kinetic energy provision	Wind speed	11 m/s	-32%
Marine Ecosystem (E+1)	Oceanic regulation	Stratification period	27 days	- 9%
Hydrochemical cycle (E+1)	Nutrient regulation	Nitrate surface concentration	3,21 $mmol/m^3$	NA
Biodiversity (E+1)	Species regulation	Hake density (Proxy)	956 kg/km^2	-17%
Phytoplankton population (E+1)	Carbon regulation	CO_2 sequestration	0,36 mg/m^3	NA
Fish Population (E+1)	Fish Provision	Hake catch	23146 kg/year	

We estimate **that the wake effect would result in a potential 32% reduction in wind speed, which would decrease nitrate concentration at the surface by approximately 9%**. This would induce a decline in the plankton population, resulting in a decrease in the carbon regulation ES, which would reduce the marine ecosystem's CO2 sequestration potential by 17%. This is considering that, as this is a pilot case study, some values were not calculated because the links between the variables were too weak to establish strong correlations and predict changes in functions and patterns. This was notably the case for the impact on the hake population, which belongs to a high trophic level in the food web and depends on a multitude of other variables that go beyond the scope of the analysis.

Figure 22. Quantitative representation of the Tramuntana Project in the socio-ecological system of Roses and Catalunya.



5.2.2 METHODOLOGY

To build the diagram of the SES metabolism of Tramuntana, we first identified the relevant ES in the socio-ecological system studied through literature review. The relevant indicators associated with each ecosystem service were mapped. Ecosystem functions impacted directly or downstream of the wake effect were linked to ES based on the tables covered in Annex III. Table 9 shows the mapping of ecosystem services and relevant indicators to complete the diagram.

In the second phase, we assessed the current state of the socio-ecological system where the offshore wind (OFW) park will be established. This involved collecting biophysical data to fill in parameters for each **run of the Ecological Disruption metric**, including ecosystem service, such as wind velocity, nitrate levels, fish biomass, and chlorophyll-a concentration, over a defined spatial and temporal scope. We calculated averages over extended periods and determined correlation coefficients between various ecological variables (e.g., wind velocity and nitrate concentration) to understand the interconnections among ecosystem components.

For heterogeneous categories like fish populations, we used proxy data to capture overall trends. In our case study, we selected hake as a proxy for fish stocks because it is the second most economically significant species, accounting for 13.11% of fishing revenue, and is currently declining due to industrial fishing practices like trawling. Hake serves as a valuable indicator for linking ecological, social, and economic variables, helping us evaluate synergistic impacts.

Next, we utilized technical data from the offshore wind farm (OWF) to assess the impacts of the wake effect on various ecological components and quantify the cascading disruptions to ecosystem services (ES), enabling us to provide a comprehensive evaluation of the socio-ecological impacts for the implementation scenario. To measure these impacts, we compared the Baseline values (representing the current state of the ecosystem) with the Scenario values (representing the state of the ecosystem after the OWF implementation).

5.3 TAKEHOME MESSAGES

We have two final considerations that we have learned from these exercises. First, at the site level, it is more complicated to conduct all modeling using the same holistic framework. Given the level of resolution required, other detailed methods for understanding food web dynamics or the local economy may be necessary. Still, the method can identify the cascade effects for preliminary screening, which can help speed up the tendering process. A second important consideration is that this type of analysis can help identify loops that would otherwise go unappreciated in an energy modeling workflow, such as the reduction in CO_2 sequestration resulting from the decline of primary producers due to the wake effect. Third, a consideration of the assessment levels and how environmental levels (E: E+2) do not necessarily align with the levels of the energy system (n-4:n).

Still, it is interesting to know the regional distribution of impacts before assessing specific parks. On-site contributions to some impacts are minimal, whereas for other impacts, they are substantial and the regional distribution of burdens and demands is important too.

6 METHODOLOGICAL DETAILS OF WORKFLOW

In this section we cover the methodological details of the workflow for the definition of WindSES.

6.1 IDENTIFICATION OF PRIORITIES

6.1.1 IDENTIFICATION OF BARRIERS FROM LITERATURE

In preparation for workshop 1, we carried out a review of the literature on barriers to wind energy deployment. For this, we identified scientific articles that related to this topic employing Google Scholar as a search engine using the following keywords: “barriers”, “obstacles”, “conflict”, “opposition”, “wind energy”, “wind power”, “wind farms”, “wind development”. The main sources reviewed were scientific articles that documented barriers across the World and a report of a project on renewable energy barriers and best practices in Europe (Banasiak et al., 2022).

6.1.2 WORKSHOP ON IDENTIFICATION OF METRICS TO SOLVE BARRIERS FOR THE IMPLEMENTATION OF WIND POWER (MARCH 2023).

We organized a workshop entitled "Barriers of Wind Energy in Catalunya and the ENBIOS Socio-Environmental Impact Assessment", held at the Institute for Environmental Science and Technology, in Barcelona in March 2023. The workshop aimed to identify the parameters that must be included in a holistic assessment of wind power, and that were related to the main barriers for its implementation. The attendees of the workshop were policymakers, industry representatives, NGOs, and civil society operating in Catalunya, a case study. The public report covers with more detail the agenda, methods and participants (Pérez-Sánchez et al., 2023).

The workshop activities departed from the abovementioned identification of the general barriers to the implementation of wind energy from the literature (STEP1) and was implemented in the following steps:

- **STEP 2: ASSESSING BARRIERS TO THE IMPLEMENTATION: WORLD CAFÉ.** An open discussion using the World Cafe methodology was organized to identify barriers to onshore and offshore wind energy projects in Catalunya. Participants were divided into two groups, each focusing on either onshore or offshore barriers. Each group discussed the question, "What are the barriers to the implementation of (off/onshore) wind energy deployment in Catalunya?" for 60 minutes, facilitated by a moderator and note-taker. Discussions were primarily in Catalan, with some translation for non-Catalan speakers.
- **STEP 3: PRIORITISATION OF BARRIERS.** The World Cafe discussions resulted in a broad network of barriers, which were then prioritized using an adaptation of the Eisenhower matrix. Barriers were assessed based on their impact on wind power implementation and the urgency of addressing them. The goal was to identify which barriers should be prioritized by the JW4A team for the next steps of the project. Stakeholders discussed and adjusted the placement of each barrier within the matrix, fostering a collective reflection on different perspectives.
- **STEP 4: IDENTIFICATION OF INFORMATION NEEDS.** The next step involved identifying information needs to incorporate the barriers into the modeling process. Using an adaptation of methods from Süsser et al. (2021), the QTDIAN toolbox was developed to include parameters for energy modeling. The process involved two rounds of group-level assessment for the five prioritized barriers. In the first round, participants identified barrier drivers and related metrics. In the second round, these proposals were discussed to reach a consensus on

metric definitions and relevant data sources. The resulting metrics and data were included in ENBIOS, leading to the development of new methods when necessary.

Figure 23. Discussion session (left) and panel (right) during the workshop

6.1.3 UNDERSTANDING PATTERNS OF IMPACT ASSESSMENT IN THE LITERATURE

In order to understand the main gaps in the literature, we completed a review of scientific articles searched in Scopus. The search returned 9.461 journal articles published between 2010 and 2025 (covering 90% of the articles published) in the areas energy, environmental science, engineering, earth sciences and social sciences. The search was completed with the following parameters:

(TITLE-ABS-KEY ("wind energy" OR "wind power") AND TITLE-ABS-KEY ("impacts")) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "SOCI")) AND (LIMIT-TO (DOCTYPE , "ar"))

We then assessed the correlation between the following corpus of words, that was selected considering barriers identified in the first workshop (section 6.1.1). The set of words analysed is covered in Table 10. The resulting database with the references analyzed and the identification of relations between them can be found as.csv file in Zenodo.

Table 10. Impact-related words included in the correlation analysis.

Social	Environmental	LCA	Parameters	Technical
justice	biodiversity	life cycle	materials	nacelle
equity	bird	land use	cost	rotor
jobs	fauna	water use	wake effect	blades
employment	flora	marine	wind speed	tower
income	species	freshwater	wind theft	foundation
poverty	ecosystem	terrestrial	turbine	maintenance
inequality	habitat	ecotoxicity	wind park	operation

social	landscape	acidification		decommissioning
community	wildlife	mineral		repowering
participation	endangered	depletion		grid
		fossil		permitting
		climate change		

6.1.4 UNDERSTANDING THE USE OF METRICS IN EU FUNDED PROJECTS

Using the opportunity for networking provided by the second meeting at CINEA, we run a survey with the objective of understanding the relevance given to holistic indicators in different projects, and also to explore the interest of other projects in our approach. The survey was run online after an internal piloting at UAB. Annex III show

6.2 UNDERSTANDING THE SPECIFICS OF OFFSHORE

One of the conclusions of workshop 1 that was also reinformed at the first CINEA meeting was the need to consider not only the direct impacts at the site of installation, but also the accumulated impacts through the life cycle of a product. During the discussions in the interdisciplinary dialogue 1, it was highlighted that most of the LCA impact assessment methods are very general and mostly valid for onshore wind assessments but failed short for offshore wind deployment.

6.2.1 LITERATURE REVIEW ABOUT WIND OFFSHORE IMPACTS

We conducted a literature review to identify offshore-specific LCA methods (Table 11). These indicators encompass noise pollution effects on cetaceans, benthic species impact, collision risk, and seabed disturbance. While the first three indicators are unique to offshore wind energy, the seabed disturbance indicator applies more broadly to various anthropogenic activities affecting the marine environment, including but not limited to offshore wind turbine installations. Additionally, we compiled Life Cycle Impact Assessment (LCIA) indicators from established LCIA methods that address marine-related impacts (Table 12). These existing indicators provide a foundation for assessing offshore wind farms within the broader context of life-cycle-based environmental evaluation.

Table 11. Offshore wind LCIA indicators.

Reference	Indicator	Units	Summary
Middel & Verones, 2017	Noise pollution effect on cetaceans	Affected animals*year	• Avoidance behaviour of cetaceans due to pile-driving operations (installation) • Considers data on five cetacean species of low-, mid- and high-frequency • Data taken from a wind farm in the North Sea • Potential application: system level (not local) – North Sea
Li et al., 2023	Benthic species	Potentially Disappeared Fraction of species (PDF)	• Considers impacts of bottom-fixed turbines during the use phase: (1) Artificial reef (2) Seabed Occupation (3) Trawling avoidance • Distinguishes impacts according to distance to pile and type of soil • Potential application: system level – North Sea
Baulaz et al., 2024	Collision impact indicator	PDF/GWh	• Considers data on 1344 species: (1) Birds' vulnerability to collisions (2) Species Richness (3) Exposure to collisions • Potential application: system level (not local) - World

Woods & Verones, 2019	Seabed damage	Sabed Occupation (PDF·m^{-2}) and Transformation (PDF·yr·m^{-2})	• Impacts on benthic species from seabed disturbance via abrasion and extraction. • Potential application: system level (not local) – World

Table 12. LCIA indicators in marine environments already included in LCIA methods.

Reference	Indicator	Units	Summary
Bassi et al., 2023	Marine Eutrophication (EF v3.1)	kg N-Eq	• Fraction of nutrients reaching marine end compartment (N). These includes ammonia, NOx and NO2 emissions to air • Potential application: system OR local - World
Huijbregts et al., 2017	Marine Ecotoxicity (ReCiPe 2016)	kg 1,4-DCB-eq to marine water	• Change in PDF of marine species due to a change in the environmental concentration of a chemical (bromomethane, dichloromethane, monochloromethane, and tetrachloromethane) • Potential application: system OR local - World

6.2.2 PRESENTING AT RGI'S OCEAN COALITION WORKSHOP (WP4)

As we observed that LCA has evolved to to address some of the specificities of wind turbines in general and offshore in particular, we tested the validity of these for decision making. We participated in one of the OCEaN mitigation task meetings in June 2024, facilitated by the Renewables Grid Initiative (RGI). At the meeting, we presented these indicators, and engaged in discussions with coalition members regarding their potential application in our analysis within JustWind4All.

6.3 INTERDISCIPLINARY DIALOGUES

We used the project meetings to run sessions within the interdisciplinary dialogues task (1.3). WE run three workshops JW4A 6/23 dialogue 1: Discussion about data
JW4A 1/24 dialogue 2: Integration between energy and SES modelling
CINEA 2/25 projects survey
JW4A 3/25 workshop 3: Interdisciplinarity and fit for purpose

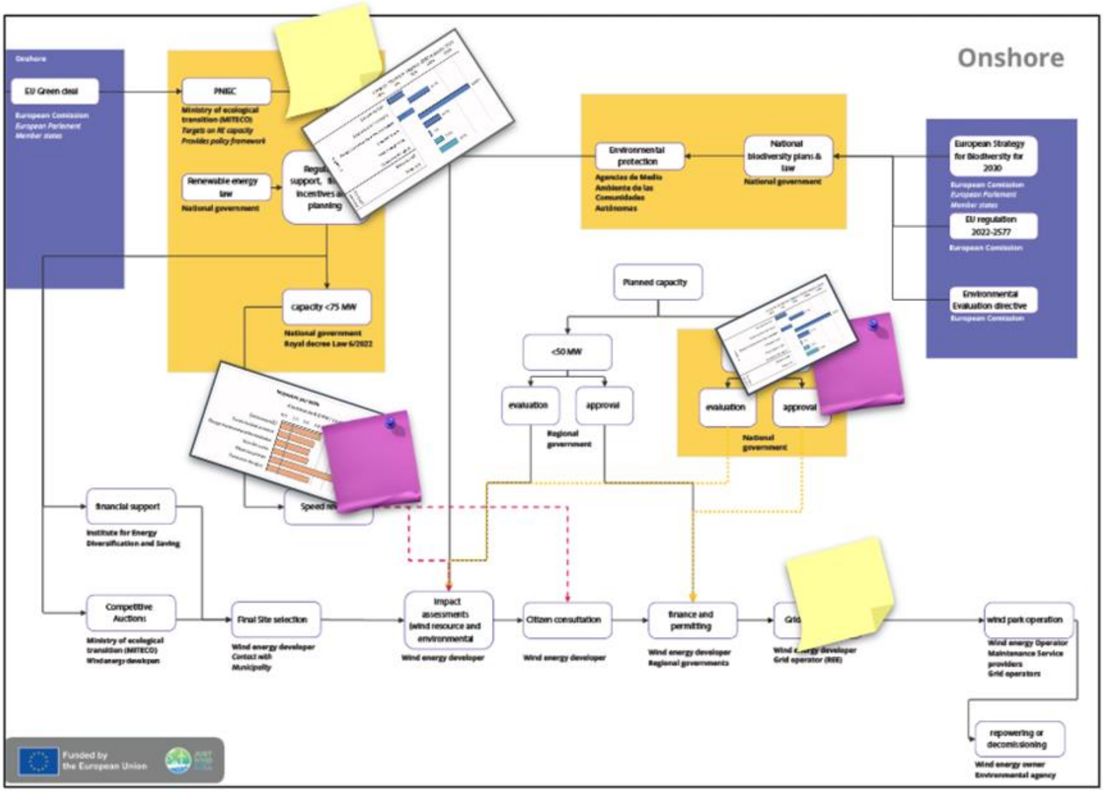
We attended two meetings of the Wind project Cluster in CINEA. The first one, held in November 2023, focused on XX. The second meeting. Held in February 2025 dealt with XXX. During the first cluster meetings we learnt that the project Marine Wind had the same case study as JUSTWIND4ALL.

Around the second CINEA meeting, we run a survey to gather information about the type of indicators other projects were developing or using. The transcript of the survey can be consulted in the Annex.

6.3.1 WORKSHOP ON ASSESSING THE USEFULNESS OF VISUALIZATIONS IN THE DECISION MAKING PROCESS

In collaboration with the marine Wind project, the LIVENlab and DRIFT research teams led a session on June 12, 2024, at the Cofradia de Pescadors Sant Telm in Arenys de Mar, Barcelona. The workshop entitled "Impacting wind energy: using Holistic impact mapping as a strategy for more effective and just wind energy development" aimed to identify opportunities for improving the fitness of the WIndSES framework and metrics by sharing and exploring the results of the holistic assessment. In attendance were more than 20 stakeholders from industry and institutions in the context of governance for wind energy planning and installation. This helped determine how the breadth of information from WP1 can be effectively visualized and selected in such a way that is most effective for the invited stakeholders and how they can be used in the different stages in the wind energy development cycle.

Figure 24. Example of functioning of the workshop: poster with the governance policymaking process for energy transition and the technical and regulatory process for specific wind park permitting and construction. Over this poster, participants located the figures and post-its of colour according to the current use of the information and added comments grounding their choices.



The workshop had a short introduction of life cycle perspective and the holistic assessment, which included presentation of the results of JustWind4All. Then, participants were distributed in 3 groups according to the regional scope of their work: country, region and local. The activity involved the explanation of 4 different figures with main results of the project, the localization of those figures in the process of wind park permitting and construction where the information was considered useful, and determining whether that information was already in use or not according to the color of the post-it. We also left some time for debate among the participants.

Through this workshop, JustWind4All was able to determine how participating actors from industry and administration understand the life cycle perspective of wind energy impacts. The analyzed results of the project will address different technological aspects (turbines, technologies and the entire electrical system) and regional areas of the electrical system (technologies, regional distribution and national level). This perspective goes far beyond carbon emissions. Holistic impact assessment is based on life cycle assessment and the socio-ecological metabolism perspective. By doing so, the potential value of holistic assessment as a source of information for decision-making processes was explored. The workshop also helped to learn how these methods can be used in the development of wind energy in Spain to improve decision-making.

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Deliverable 1.2 Annexes

ANNEX I. PARAMETER CORRELATION MATRIX

	justice	equity	jobs	employmer	income	poverty	inequality	social	community	participatio	biodiversity	bird	fauna	flora	species	ecosystem	habitat	landscape	wildlife	endangere	materials	cost	wake effect	wind speed	wind theft	life cycle	land use	water use	marine
justice	1	0.079719	0.033147	0.051995	0.029144	0.055774	-0.00342	0.124107	0.132653	0.066641	0.036899	0.008353	-0.00375	-0.00202	-0.00439	-6.03E-05	0.009985	0.07366	0.002804	-0.00398	-0.00119	-0.02419	-0.00853	-0.0312	-0.00076	-0.01485	0.017699	-0.00306	-0.01459
equity	0.079719	1	0.05187	0.016313	0.030275	-0.00248	-0.00237	0.027083	0.05275	0.02028	0.037377	-0.00772	-0.0026	-0.0014	-0.00892	0.00772	-0.00731	0.003661	-0.00629	-0.00275	-0.00764	0.035579	-0.00591	-0.01583	-0.00053	-0.01028	-0.00573	-0.00212	0.00079
jobs	0.033147	0.05187	1	0.333383	0.091996	-0.00359	0.027706	0.097296	0.038543	-0.00145	0.007443	-0.01115	-0.00375	-0.00202	-0.00439	-6.03E-05	-0.00029	0.01323	-0.00908	-0.00398	-0.00119	0.008499	-0.00853	-0.0272	-0.00076	3.62E-05	-0.00828	-0.00306	0.0081
employmer	0.051995	0.016313	0.333383	1	0.123554	0.131692	0.019355	0.101378	0.081522	0.007702	0.01301	-0.01461	-0.00491	-0.00265	-0.01039	0.010164	-0.00597	-0.00338	-0.0119	-0.00521	0.008149	0.007675	-0.01118	-0.03476	-0.001	0.009036	0.009042	-0.00401	-0.00754
income	0.029144	0.030275	0.091996	0.123554	1	0.110207	0.0554	0.061333	0.074721	0.026941	0.027004	-0.01094	0.012664	0.031044	-0.01998	0.004059	-0.01636	0.002809	-0.01407	-0.00617	0.008486	0.038348	-0.01323	-0.04055	-0.00118	-0.01818	-0.00439	-0.00474	0.006882
poverty	0.055774	-0.00248	-0.00359	0.131692	0.110207	1	-0.00222	0.040629	0.017959	-0.00726	0.017876	-0.00724	-0.00243	-0.00131	-0.00837	0.025087	-0.00686	-0.00823	-0.0059	-0.00258	0.007941	0.016712	-0.00554	-0.00796	-0.0005	0.001781	0.014562	-0.00199	-0.00948
inequality	-0.00342	-0.00237	0.027706	0.019355	0.0554	-0.00222	1	0.00048	0.005853	0.00874	-0.00451	-0.0069	-0.00232	-0.00125	-0.00798	-0.00646	-0.00654	0.006053	-0.00562	-0.00246	-0.00683	-0.00607	-0.00528	-0.01287	-0.00047	-0.00919	-0.00513	-0.00189	0.015317
social	0.124107	0.027083	0.097296	0.101378	0.061333	0.040629	0.00048	1	0.177951	0.074226	0.018891	0.003592	-0.00144	0.01213	-0.01233	0.058495	-0.00689	0.159328	0.00148	0.006596	0.004278	0.023255	-0.02133	-0.06485	-0.0023	0.006856	0.074112	-0.00922	0.016337
community	0.132653	0.05275	0.038543	0.081522	0.074721	0.017959	0.005853	0.177951	1	0.08173	0.002688	0.034596	0.041622	-0.00468	0.041589	0.030949	0.039189	0.096725	0.015792	-0.0092	-0.00812	-0.02038	-0.00299	-0.03676	-0.00177	-0.00802	0.00957	-0.00708	-0.0003
participatio	0.066641	0.02028	-0.00145	0.007702	0.026941	-0.00726	0.00874	0.074226	0.08173	1	8.77E-05	-0.00782	-0.00758	-0.00409	-0.02178	-0.01067	-0.01618	0.026497	-0.01238	-0.00804	-0.00746	-0.01456	0.008144	-0.01875	-0.00155	-0.02628	-0.00368	-0.00619	0.012351
biodiversity	0.036899	0.037377	0.007443	0.01301	0.027004	0.017876	-0.00451	0.018891	0.002688	8.77E-05	1	0.170955	0.059999	-0.00267	0.203004	0.175986	0.228594	0.095079	0.060435	0.076407	-0.00705	-0.00546	-0.01125	-0.02893	-0.00101	0.0031	0.097923	-0.00403	0.078703
bird	0.008353	-0.00772	-0.01115	-0.01461	-0.01094	-0.00724	-0.0069	0.003592	0.034596	-0.00782	0.170955	1	0.121408	0.02243	0.436597	0.073151	0.351567	0.100677	0.341154	0.140616	-0.00241	-0.04549	-0.01084	-0.04475	-0.00154	-0.00743	0.061896	0.011372	0.081169
fauna	-0.00375	-0.0026	-0.00375	-0.00491	0.012664	-0.00243	-0.00232	-0.00144	0.041622	-0.00758	0.059999	0.121408	1	0.385019	0.128603	0.053944	0.158894	0.105602	0.028771	-0.0027	-0.00749	-0.0201	-0.00579	-0.02117	-0.00052	-0.01007	0.051663	-0.00208	0.045688
flora	-0.00202	-0.0014	-0.00202	-0.00265	0.031044	-0.00131	-0.00125	0.01213	-0.00468	-0.00409	-0.00267	0.02243	0.385019	1	0.018382	0.052628	0.024063	0.042309	-0.00332	-0.00146	-0.00404	-0.00714	-0.00312	-0.00053	-0.00028	-0.00544	0.032292	-0.00112	0.015226
species	-0.00439	-0.00892	-0.00439	-0.01039	-0.01998	-0.00837	-0.00798	-0.01233	0.041589	-0.02178	0.203004	0.436597	0.128603	0.018382	1	0.171746	0.462703	0.137333	0.359902	0.273295	-0.02141	-0.07485	-0.00881	-0.05163	-0.00178	-0.0052	0.060588	0.008151	0.162031
ecosystem	-6.03E-05	0.00772	-6.03E-05	0.010164	0.004059	0.025087	-0.00646	0.058495	0.030949	-0.01067	0.175986	0.073151	0.053944	0.052628	0.171746	1	0.195085	0.087288	0.078529	0.064419	0.000286	-0.01431	-0.00934	-0.03959	-0.00144	0.047859	0.061064	0.012897	0.220119
habitat	0.009985	-0.00731	-0.00029	-0.00597	-0.01636	-0.00686	-0.00654	-0.00689	0.039189	-0.01618	0.228594	0.351567	0.158894	0.024063	0.462703	0.195085	1	0.163802	0.342406	0.191691	-0.01062	-0.05415	0.003813	-0.04683	-0.00146	-0.00464	0.087683	0.012636	0.13685
landscape	0.07366	0.003661	0.01323	-0.00338	0.002809	-0.00823	0.006053	0.159328	0.096725	0.026497	0.095079	0.100677	0.105602	0.042309	0.137333	0.087288	0.163802	1	0.101201	0.050706	-0.01212	-0.05079	-0.01392	-0.059	-0.00175	-0.02075	0.131808	0.00852	0.023957
wildlife	0.002804	-0.00629	-0.00908	-0.0119	-0.01407	-0.0059	-0.00562	0.00148	0.015792	-0.01238	0.060435	0.341154	0.028771	-0.00332	0.359902	0.078529	0.342406	0.101201	1	0.158149	-0.01208	-0.03579	-0.00626	-0.03156	-0.00126	-0.01982	0.042275	0.016354	0.055046
endangere	-0.00398	-0.00275	-0.00398	-0.00521	-0.00617	-0.00258	-0.00246	0.006596	-0.0092	-0.00804	0.076407	0.140616	-0.0027	-0.00146	0.273295	0.064419	0.191691	0.050706	0.158149	1	-0.00794	-0.02246	-0.00614	-0.01135	-0.00055	-0.01069	0.030049	-0.0022	0.031432
materials	-0.00119	-0.00764	-0.00119	0.008149	0.008486	0.007941	-0.00683	0.004278	-0.00812	-0.00746	-0.00705	-0.00241	-0.00749	-0.00404	-0.02141	0.000286	-0.01062	-0.01212	-0.01208	-0.00794	1	0.002382	-0.01061	-0.04395	-0.00153	0.209019	-0.00331	0.0116	0.013212
cost	-0.02419	0.035579	0.008499	0.007675	0.038348	0.016712	-0.00607	0.023255	-0.02038	-0.01456	-0.00546	-0.04549	-0.0201	-0.00714	-0.07485	-0.01431	-0.05415	-0.05079	-0.03579	-0.02246	0.002382	1	-0.02282	-0.08475	-0.00606	0.014417	0.006825	-0.00072	-0.04021
wake effect	-0.00853	-0.00591	-0.00853	-0.01118	-0.01323	-0.00554	-0.00528	-0.02133	-0.00299	0.008144	-0.01125	-0.01084	-0.00579	-0.00312	-0.00881	-0.00934	0.003813	-0.01392	-0.00626	-0.00614	-0.01061	-0.02282	1	0.079955	-0.00118	-0.01807	-0.01279	-0.00472	-0.00772
wind speed	-0.0312	-0.01583	-0.0272	-0.03476	-0.04055	-0.00796	-0.01287	-0.06485	-0.03676	-0.01875	-0.02893	-0.04475	-0.02117	-0.00053	-0.05163	-0.03959	-0.04683	-0.059	-0.03156	-0.01135	-0.04395	-0.08475	0.079955	1	0.024497	-0.05916	-0.02792	-0.01727	-0.04634
wind theft	-0.00076	-0.00053	-0.00076	-0.001	-0.00118	-0.0005	-0.00047	-0.0023	-0.00177	-0.00155	-0.00101	-0.00154	-0.00052	-0.00028	-0.00178	-0.00144	-0.00146	-0.00175	-0.00126	-0.00055	-0.00153	-0.00606	-0.00118	0.024497	1	-0.00205	-0.00115	-0.00042	-0.00202
life cycle	-0.01485	-0.01028	3.62E-05	0.009036	-0.01818	0.001781	-0.00919	0.006856	-0.00802	-0.02628	0.0031	-0.00743	-0.01007	-0.00544	-0.0052	0.047859	-0.00464	-0.02075	-0.01982	-0.01069	0.209019	0.014417	-0.01807	-0.05916	-0.00205	1	0.032748	0.058739	0.06269
land use	0.017699	-0.00573	-0.00828	0.009042	-0.00439	0.014562	-0.00513	0.074112	0.00957	-0.00368	0.097923	0.061896	0.051663	0.032292	0.060588	0.061064	0.087683	0.131808	0.042275	0.030049	-0.00331	0.006825	-0.01279	-0.02792	-0.00115	0.032748	1	-0.00459	-0.01171
water use	-0.00306	-0.00212	-0.00306	-0.00401	-0.00474	-0.00199	-0.00189	-0.00922	-0.00708	-0.00619	-0.00403	0.011372	-0.00208	-0.00112	0.008151	0.012897	0.012636	0.00852	0.016354	-0.0022	0.0116	-0.00072	-0.00472	-0.01727	-0.00042	0.058739	-0.00459	1	0.005531
marine	-0.01459	0.00079	0.0081	-0.00754	0.006882	-0.00948	0.015317	0.016337	-0.0003	0.012351	0.078703	0.081169	0.045688	0.015226	0.162031	0.220119	0.13685	0.023957	0.055046	0.031432	0.013212	-0.04021	-0.00772	-0.04634	-0.00202	0.06269	-0.01171	0.005531	1
freshwater	-0.00547	-0.00379	-0.00547	0.022733	0.004208	-0.00355	-0.00339	-0.00972	0.021888	-0.01106	-0.00721	-0.01104	-0.00371	-0.002	-0.00418	0.031585	-8.33E-05	-0.00383	0.003008	-0.00394	0.018886	0.032536	-0.00845	-0.01472	-0.00076	0.158141	0.044266	0.032101	0.084835
terrestrial	-0.00574	0.022869	-0.00574	0.006755	0.003223	-0.00373	-0.00355	-0.00436	-0.00503	-0.0116	0.063415	0.05421	0.023502	0.048577	0.052127	0.119226	0.097936	0.028453	0.070745	0.021702	0.017005	-0.02341	0.003308	-0.01694	-0.00079	0.142406	0.091572	0.030359	0.130661
ecotoxicity	-0.00426	-0.00295	-0.00426	0.013572	-0.00661	-0.00277	-0.00264	-0.00417	0.001204	-0.00862	-0.00562	-0.0086	-0.00289	-0.00156	0.012041	0.045664	-0.00814	-0.00977	-0.007	-0.00307	0.042423	4.92E-05	-0.00658	-0.02406	-0.00059	0.248526	0.044032	-0.00236	0.106173
acidificatio	-0.00553	-0.00383	-0.00553	0.007565	-0.00857	-0.00359	-0.00342	-0.00995	-0.00423	-0.01117	-0.00729	-0.01115	-0.00375	-0.00202	-0.01289	0.051841	-0.00029	-0.00404	-0.00908	-0.00398	0.04802	-0.02419	-0.00853	-0.02319	-0.00076	0.312635	0.017699	0.031734	0.08374
mineral	0.016231	-0.00348	-0.00502	0.009694	0.033664	-0.00326	-0.00311	-0.0004	-0.00222	-0.01016	0.009567	-0.01013	-0.00341	-0.00184	0.016299	0.00192	-0.00959	-0.01151	0.00481	-0.00361	0.119793	-0.01466	-0.00775	-0.01955	-0.00069	0.109215	0.035309	-0.00278	0.019993
depletion	-0.00791	-0.00548	-0.00791	2.97E-05	-0.01227	-0.00514	0.016965	-0.00501	-0.00629	-0.00917	-8.64E-05	-0.01596	-0.00537	-0.0029	-0.01248	0.03609	-0.01512	-0.01814	-0.013	-0.00569	0.053335	0.008461	-0.01222	-0.01654	-0.00109	0.203542	0.015516	0.020059	0.048176
fossil	-0.00386	0.025844	0.018403	0.019942	0.018786	0.029365	0.005191	0.022948	-0.00079	-0.02756	0.006814	-0.00498	-0.00576	-0.00752	-0.01615	0.038845	-0.01562	-0.0024	0.003854	-0.00708	0.024109	0.084516	-0.02447	-0.03419	-0.00284	0.152559	0.014062	0.048705	0.004504
climate cha	0.021915	0.020551	0.004262	0.010786	0.008372	0.032644	-0.01193	0.029629	0.064736	-0.00937	0.037336	0.020462	-0.00443	-0.00706	0.027437	0.042555	0.025691	0.018863	0.011729	0.010595	0.012427	0.006383	-0.00672	0.036252	-0.00267	0.065982	0.026457	0.042268	0.027365
cancer	-0.00171	-0.00118	-0.00171	0.045401	-0.00265	-0.00111	-0.00106	-0.00515	-0.00396	-0.00346	-0.00225	-0.00345	-0.00116	-0.00063	0.050669	0.063555	-0.00327	-0.00392	0.035416	-0.00123	-0.00341	-0.00303	-0.00264	-0.00965	-0.00024	0.043292	-0.00256	-0.00095	0.068484
human toxi	-0.00375	-0.0026	-0.00375	0.03862	-0.00581	-0.00243	-0.00232	-0.0113	-0.00868	-0.00758	-0.00494	-0.00756	-0.00254	-0.00137	0.003744	0.038688	-0.00716	-0.00859	-0.00616	-0.0027	0.035913	-0.0201	-0.00579	-0.02117	-0.00052	0.208712	0.013475	-0.00208	0.056805
noise	0.004822	-0.0087	-0.00387	-0.00316	-0.00253	-0.00816	0.006216	0.03447	0.055555	-0.00354	0.009923	0.044803	0.093726	0.113628	0.06238	0.027603	0.077609	0.029421	0.043477	0.075322	-0.01182	-0.05994	-0.00806	0.020918	-0.00174	-0.01369	0.00453	-0.00696	0.065459
visual impa	0.0201	0.014687	0.006189	0.000532	0.006115	-0.00502	-0.00478	0.092461	0.031367	0.03337	0.011011	0.040537	0.035654	0.034999	0.006439	0.000347	0.007416	0.249352	0.004412	-0.00556	-0.00834	-0.03063	-0.01192	-0.03783	-0.00107	0.000668	0.044502	-0.00428	0.028584
shadow flic	-0.00229	-0.00159	-0.00229	-0.00301	-0.00356	-0.00149	-0.00142	0.025238	0.015209	-0.00464	-0.00302	0.042137	0.066604	-0.00084	-0.00535	0.020561	0.044882	0.015445	0.081722	-0.00165	-0.00458	-0.0025	-0.00354	-0.00334	-0.00032	-0.00616	0.027718	-0.00127	0.012083
vibration	-0.0085	-0.00588	-0.0085	-0.01114	-0.01317	-0.00552	0.015137	-0.02121	-0.01966	-0.01718	-0.00155	0.00842	0.012861	0.031345	0.008022	-0.00245	0.003962	-0.01382	0.017189	0.02901	-0.00407	-0.0395	-0.00485	0.033415	-0.00118	-0.02283	-0.01273	-0.0047	0.012262
light polluti	-0.00132	-0.00092	-0.00132	-0.00174	-0.00205	-0.00086	-0.00082	-0.00399	-0.00306	-0.00268	-0.00175	0.037816	-0.0009	-0.00048	-0.00309	0.040603	0.082772	0.032813	0.047167	-0.00095	-0.00264	-0.01049	-0.00204	-0.00747	-0.00018	-0.00356	-0.00198	-0.00073	-0.0035
electromag	-0.00891	-0.00617	-0.00891	-0.01168	-0.01381	-0.00579	-0.00552	-0.02265	-0.01527	0.012414	-0.00253	-0.01187	-0.00604	0.029636	0.032374	0.01564	0.015111	-0.02043	0.015102	-0.00641	-0.00548	-0.04403	-0.01376	-0.02023	-0.00123	-0.01929	-0.01335	-0.00493	0.028531
fire	-0.01012	0.008407	0.000585	-0.00506	-0.01568	-0.00657	-0.00626	-0.00081	-0.01394	-0.0043	-0.01334	-0.00961	0.008865	-0.0037	-0.01419	0.009611	0.009096	-0.01363	-0.00347	-0.00728	0.007033	0.04283	-0.01562	-0.03273	-0.0014	0.018125	-0.00078	0.032908	-0.01415
collapse	-0.00419	-0.0029	-0.00419	-0.0055	-0.0065	-0.00272	-0.0026	-0.01263	-0.0097	-0.00848	0.013841	0.004365	-0.00284	-0.00153	-0.00978	0.005729	-0.00801	0.001741	-0.00689	-0.00302	-0.00837	-0.01604	-0.00647	-0.01314	-0.00058	-0.01127	-0.00628	-0.00232	-0.00112
turbine	-0.03477	-0.01921	-0.02871	-0.0462	-0.03286	-0.01579	-0.00841	-0.03778	0.022116	-0.02023	-0.00754	0.091609	0.030813	0.005313	0.082652	-0.01064	0.049997	0.047553	0.078562	0.016436	0.049887	-0.06955	0.133571	0.135683	0.014443	-0.01058	-2.86E-05	-0.02385	0.002307
wind park	0.006967	-0.00516	-0.00745	-0.00976	-0.00217	-0.00484	-0.00461	-0.00745	0.001898	-0.00055	0.01214	0.021319	0.016134	0.036468	0.026963	0.02462	0.0164	0.034411	-0.00338	0.034596	-0.0002	-0.01516	-0.00209	-0.01218	-0.00103	0.018827	-0.00148	-0.00412	0.019806
nacelle	-0.00589	-0.00408	0.012271	-0.00772	-0.00913	-0.00382	-0.00365	-0.00515	-0.01363	-0.01191	0.006069	0.015592	-0.00399	-0.00216	-0.00575	-0.01113	-0.00515	-0.00539	0.001486	-0.00424	0.015972	-0.0129	0.002761	0.05329	-0.00081	0.012137	0.003375	-0.00326	-0.01555
rotor	-0.01816	-0.01258	-0.01816	-0.02381	-0.01607	-0.0118	-0.01125	-0.04613	-0.00912	-0.00242	-0.0145	0.038397	0.005905	0.010211	0.017573	-0.03432	-0.01164	-0.01672	0.015885	-0.01307	0.007913	-0.06849	-0.00376	0.070874	-0.00251	-0.0321	0.001937	-0.01006	-0.03098
blades	-0.01284	-0.00889	-0.00431	-0.0103	-0.01436	-0.00834	-0.00795	-0.03277	-0.00708	-0.02167	-0.01043	0.034284	-0.00871	-0.0047	0.015006	-0.01968	-0.00188	-0.01801	0.015582	0.002576	0.13058	-0.01961	-0.00313	0.031726	-0.00178	-0.00825	-0.01351	-0.00711	-0.01056
tower	-0.01087	-0.00753	-0.01087	-0.01425	-0.00386	-0.00706	-0.00673	-0.02582	0.010197	-0.01193	-0.01433	0.018365	0.007306	0.023178	-0.01218	-0.01517	-0.01546	0.001838	0.000559	-0.00782	0.049468	-0.03043	0.015813	0.068998	-0.0015	0.013082	-0.00958	-0.00602	-0.00135
foundation	-0.00217	0.005526	-0.01158	-0.00797	0.000392	-0.00752	0.007969	-0.01858	0.00233	-0.01868	0.006225	-0.00912	0.019788	-0.00424	0.030839	0.023559	0.022838	-0.01394	-0.00746	0.004701	0.034318	-0.02658	-0.0056	-0.02834	-0.0016	0.019564	-0.00472	0.02743	0.105526
maintenanc	-0.01407	0.012803	0.032892	0.017526	-0.00145	0.002879	-0.00871	-0.01254	-0.00831	-0.01663	0.005301	-0.01653	-0.00954	-0.00515	-0.02592	0.002836	-0.00193	-0.01477	-0.00868	0.000725	0.039634	0.153116	-0.00639	-0.01942	-0.00195	0.067638	-0.01582	-0.00779	0.02715
operation	-0.03051	-0.02297	-0.01778	-0.01454	0.006652	-0.02526	-0.00313	-0.05713	-0.02436	0.010199	-0.03938	-0.0503	-0.0081	0.008967	-0.04113	-0.0279	-0.02782	-0.06095	-0.00585	0.001879	-0.01008	0.110326	0.005184	-0.04384	-0.00642	0.008784	-0.04605	0.008656	-0.0068
decommiss	-0.00547	-0.00379	0.014052	0.007779	0.004208	0.026416	-0.00339	-0.00295	-0.00403	-0.00124	0.007656	0.008651	-0.00371	-0.002	0.004393	0.042066	0.041399	-0.00383	0.039001	-0.00394	0.138144	0.022634	-0.00845	-0.0309	-0.00076	0.158141	0.004915	0.032101	0.084835
repowering	0.020293	-0.003	-0.00433	-0.00568	-0.00671	-0.00281	-0.00268	0.012557	0.011766	-0.00876	-0.00571	0.028511	-0.00294	-0.00159	0.022355	-0.00818	0.017886	0.023052	0.023148	-0.00312	0.003886	-0.00519	0.009385	-0.01935	-0.0006	0.064185	0.026595	-0.0024	0.007829
grid	-0.03746	-0.02106	-0.0342	-0.03267	-0.02153	-0.00853	-0.00097	-0.06693	-0.06138	0.006255	-0.04804	-0.08048	-0.02984	-0.0161	-0.09109	-0.07433	-0.07015	-0.07461	-0.07224	-0.02261	-0.04632	0.021445	-0.0168	-0.01649	-0.00608	-0.02903	-0.04619	-0.01848	-0.07785
permitting	0.042567	-0.00314	-0.00453	-0.00594	-0.00702	-0.00294	0.035102	0.019002	-6.50E-05	-0.00916	0.011964	0.05023	-0.00307	-0.00166	0.020473	0.029366	0.016363	0.052694	0.079381	-0.00326	-0.00905	-0.016	-0.00699	-0.01094	-0.00063	-0.01217	0.040672	-0.00251	0.043308

marine	freshwater	terrestrial	ecotoxicity	acidificatio	mineral	depletion	fossil	climate cha	cancer	human toxi	noise	visual impa	shadow flic	vibration	light polluti	electromag	fire	collapse	turbine	wind park	nacelle	rotor	blades	tower	foundation	maintenan	operation	decommis	repowering	grid	permitting
-0.01459	-0.00547	-0.00574	-0.00426	-0.00553	0.016231	-0.00791	-0.00386	0.021915	-0.00171	-0.00375	0.004822	0.0201	-0.00229	-0.0085	-0.00132	-0.00891	-0.01012	-0.00419	-0.03477	0.006967	-0.00589	-0.01816	-0.01284	-0.01087	-0.00217	-0.01407	-0.03051	-0.00547	0.020293	-0.03746	0.042567
0.00079	-0.00379	0.022869	-0.00295	-0.00383	-0.00348	-0.00548	0.025844	0.020551	-0.00118	-0.0026	-0.0087	0.014687	-0.00159	-0.00588	-0.00092	-0.00617	0.008407	-0.0029	-0.01921	-0.00516	-0.00408	-0.01258	-0.00889	-0.00753	0.005526	0.012803	-0.02297	-0.00379	-0.003	-0.02106	-0.00314
0.0081	-0.00547	-0.00574	-0.00426	-0.00553	-0.00502	-0.00791	0.018403	0.004262	-0.00171	-0.00375	-0.00387	0.006189	-0.00229	-0.0085	-0.00132	-0.00891	0.000585	-0.00419	-0.02871	-0.00745	0.012271	-0.01816	-0.00431	-0.01087	-0.01158	0.032892	-0.01778	0.014052	-0.00433	-0.0342	-0.00453
-0.00754	0.022733	0.006755	0.013572	0.007565	0.009694	2.97E-05	0.019942	0.010786	0.045401	0.03862	-0.00316	0.000532	-0.00301	-0.01114	-0.00174	-0.01168	-0.00506	-0.0055	-0.0462	-0.00976	-0.00772	-0.02381	-0.0103	-0.01425	-0.00797	0.017526	-0.01454	0.007779	-0.00568	-0.03267	-0.00594
0.006882	0.004208	0.003223	-0.00661	-0.00857	0.033664	-0.01227	0.018786	0.008372	-0.00265	-0.00581	-0.00253	0.006115	-0.00356	-0.01317	-0.00205	-0.01381	-0.01568	-0.0065	-0.03286	-0.00217	-0.00913	-0.01607	-0.01436	-0.00386	0.000392	-0.00145	0.006652	0.004208	-0.00671	-0.02153	-0.00702
-0.00948	-0.00355	-0.00373	-0.00277	-0.00359	-0.00326	-0.00514	0.029365	0.032644	-0.00111	-0.00243	-0.00816	-0.00502	-0.00149	-0.00552	-0.00086	-0.00579	-0.00657	-0.00272	-0.01579	-0.00484	-0.00382	-0.0118	-0.00834	-0.00706	-0.00752	0.002879	-0.02526	0.026416	-0.00281	-0.00853	-0.00294
0.015317	-0.00339	-0.00355	-0.00264	-0.00342	-0.00311	0.016965	0.005191	-0.01193	-0.00106	-0.00232	0.006216	-0.00478	-0.00142	0.015137	-0.00082	-0.00552	-0.00626	-0.0026	-0.00841	-0.00461	-0.00365	-0.01125	-0.00795	-0.00673	0.007969	-0.00871	-0.00313	-0.00339	-0.00268	-0.00097	0.035102
0.016337	-0.00972	-0.00436	-0.00417	-0.00995	-0.0004	-0.00501	0.022948	0.029629	-0.00515	-0.0113	0.03447	0.092461	0.025238	-0.02121	-0.00399	-0.02265	-0.00081	-0.01263	-0.03778	-0.00745	-0.00515	-0.04613	-0.03277	-0.02582	-0.01858	-0.01254	-0.05713	-0.00295	0.012557	-0.06693	0.019002
-0.0003	0.021888	-0.00503	0.001204	-0.00423	-0.00222	-0.00629	-0.00079	0.064736	-0.00396	-0.00868	0.055555	0.031367	0.015209	-0.01966	-0.00306	-0.01527	-0.01394	-0.0097	0.022116	0.001898	-0.01363	-0.00912	-0.00708	0.010197	0.00233	-0.00831	-0.02436	-0.00403	0.011766	-0.06138	-6.50E-05
0.012351	-0.01106	-0.0116	-0.00862	-0.01117	-0.01016	-0.00917	-0.02756	-0.00937	-0.00346	-0.00758	-0.00354	0.03337	-0.00464	-0.01718	-0.00268	0.012414	-0.0043	-0.00848	-0.02023	-0.00055	-0.01191	-0.00242	-0.02167	-0.01193	-0.01868	-0.01663	0.010199	-0.00124	-0.00876	0.006255	-0.00916
0.078703	-0.00721	0.063415	-0.00562	-0.00729	0.009567	-8.64E-05	0.006814	0.037336	-0.00225	-0.00494	0.009923	0.011011	-0.00302	-0.00155	-0.00175	-0.00253	-0.01334	0.013841	-0.00754	0.01214	0.006069	-0.0145	-0.01043	-0.01433	0.006225	0.005301	-0.03938	0.007656	-0.00571	-0.04804	0.011964
0.081169	-0.01104	0.05421	-0.0086	-0.01115	-0.01013	-0.01596	-0.00498	0.020462	-0.00345	-0.00756	0.044803	0.040537	0.042137	0.00842	0.037816	-0.01187	-0.00961	0.004365	0.091609	0.021319	0.015592	0.038397	0.034284	0.018365	-0.00912	-0.01653	-0.0503	0.008651	0.028511	-0.08048	0.05023
0.045688	-0.00371	0.023502	-0.00289	-0.00375	-0.00341	-0.00537	-0.00576	-0.00443	-0.00116	-0.00254	0.093726	0.035654	0.066604	0.012861	-0.0009	-0.00604	0.008865	-0.00284	0.030813	0.016134	-0.00399	0.005905	-0.00871	0.007306	0.019788	-0.00954	-0.0081	-0.00371	-0.00294	-0.02984	-0.00307
0.015226	-0.002	0.048577	-0.00156	-0.00202	-0.00184	-0.0029	-0.00752	-0.00706	-0.00063	-0.00137	0.113628	0.034999	-0.00084	0.031345	-0.00048	0.029636	-0.0037	-0.00153	0.005313	0.036468	-0.00216	0.010211	-0.0047	0.023178	-0.00424	-0.00515	0.008967	-0.002	-0.00159	-0.0161	-0.00166
0.162031	-0.00418	0.052127	0.012041	-0.01289	0.016299	-0.01248	-0.01615	0.027437	0.050669	0.003744	0.06238	0.006439	-0.00535	0.008022	-0.00309	0.032374	-0.01419	-0.00978	0.082652	0.026963	-0.00575	0.017573	0.015006	-0.01218	0.030839	-0.02592	-0.04113	0.004393	0.022355	-0.09109	0.020473
0.220119	0.031585	0.119226	0.045664	0.051841	0.00192	0.03609	0.038845	0.042555	0.063555	0.038688	0.027603	0.000347	0.020561	-0.00245	0.040603	0.01564	0.009611	0.005729	-0.01064	0.02462	-0.01113	-0.03432	-0.01968	-0.01517	0.023559	0.002836	-0.0279	0.042066	-0.00818	-0.07433	0.029366
0.13685	-8.33E-05	0.097936	-0.00814	-0.00029	-0.00959	-0.01512	-0.01562	0.025691	-0.00327	-0.00716	0.077609	0.007416	0.044882	0.003962	0.082772	0.015111	0.009096	-0.00801	0.049997	0.0164	-0.01125	-0.01164	-0.00188	-0.01546	0.022838	-0.00193	-0.02782	0.041399	0.017886	-0.07015	0.016363
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0.055046	0.003008	0.070745	-0.007	-0.00908	0.00481	-0.013	0.003854	0.011729	0.035416	-0.00616	0.043477	0.004412	0.081722	0.017189	0.047167	0.015102	-0.00347	-0.00689	0.078562	-0.00338	0.001486	0.015885	0.015582	0.000559	-0.00746	-0.00868	-0.00585	0.039001	0.023148	-0.07224	0.079381
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0.013212	0.018886	0.017005	0.042423	0.04802	0.119793	0.053335	0.024109	0.012427	-0.00341	0.035913	-0.01182	-0.00834	-0.00458	-0.00407	-0.00264	-0.00548	0.007033	-0.00837	0.049887	-0.0002	0.015972	0.007913	0.13058	0.049468	0.034318	0.039634	-0.01008	0.138144	0.003886	-0.04632	-0.00905
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0.06269	0.158141	0.142406	0.248526	0.312635	0.109215	0.203542	0.152559	0.065982	0.043292	0.208712	-0.01369	0.000668	-0.00616	-0.02283	-0.00356	-0.01929	0.018125	-0.01127	-0.01058	0.018827	0.012137	-0.0321	-0.00825	0.013082	0.019564	0.067638	0.008784	0.158141	0.064185	-0.02903	-0.01217
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0.005531	0.032101	0.030359	-0.00236	0.031734	-0.00278	0.020059	0.048705	0.042268	-0.00095	-0.00208	-0.00696	-0.00428	-0.00127	-0.0047	-0.00073	-0.00493	0.032908	-0.00232	-0.02385	-0.00412	-0.00326	-0.01006	-0.00711	-0.00602	0.02743	-0.00779	0.008656	0.032101	-0.0024	-0.01848	-0.00251
1	0.084835	0.130661	0.106173	0.08374	0.019993	0.048176	0.004504	0.027365	0.068484	0.056805	0.065459	0.028584	0.012083	0.012262	-0.0035	0.028531	-0.01415	-0.00112	0.002307	0.019806	-0.01555	-0.03098	-0.01056	-0.00135	0.105526	0.02715	-0.0068	0.084835	0.007829	-0.07785	0.043308
0.084835	1	0.144867	0.399927	0.170249	0.080868	0.170453	0.086415	0.046268	0.123924	0.197165	-0.01245	-0.00765	-0.00227	-0.00841	-0.00131	-0.00882	0.000787	-0.00415	0.011755	-0.00737	-0.00583	-0.01799	-0.00411	-0.01076	-0.01146	0.01768	0.005441	0.014294	0.020574	-0.00073	-0.00449
0.130661	0.144867	1	0.284916	0.236552	0.056243	0.148884	0.069855	0.042379	0.118135	0.215253	0.028861	-0.00802	0.042316	0.02782	-0.00137	0.002412	0.010127	-0.00435	-0.0141	0.006163	-0.00611	-0.0069	-0.00511	-0.01128	-0.00295	0.00803	0.000892	0.050775	0.019238	-0.0205	-0.0047
0.106173	0.399927	0.284916	1	0.245903	0.106114	0.327768	0.10655	0.053648	0.159632	0.438332	-0.0097	-0.00596	-0.00177	-0.00655	-0.00102	-0.00687	-0.0078	-0.00323	-0.00558	-0.00574	-0.00454	-0.01401	0.012156	-0.00838	0.003236	0.009402	-0.00698	0.046298	0.028516	-0.00016	-0.00349
0.08374	0.170249	0.236552	0.245903	1	0.037486	0.25016	0.090755	0.039568	0.1227	0.422568	-0.01257	-0.00772	-0.00229	-0.0085	-0.00132	-0.00891	0.000585	-0.00419	-0.01661	-0.00745	-0.00589	-0.01816	0.004212	-0.01087	0.00723	0.009413	-0.00823	0.053101	0.020293	0.004951	-0.00453
0.019993	0.080868	0.056243	0.106114	0.037486	1	0.112244	0.073077	0.021287	0.135192	0.059071	-0.00187	-0.00702	-0.00209	-0.00772	-0.0012	-0.0081	0.026091	-0.00381	-0.02149	-0.00677	-0.00535	-0.01651	-0.01167	-0.00988	-0.00019	-0.01278	-0.00721	0.016486	0.023129	-0.02563	-0.00412
0.048176	0.170453	0.148884	0.327768	0.25016	0.112244	1	0.209038	0.071599	0.084941	0.294086	0.006435	-0.01106	-0.00328	-0.01217	-0.0019	-0.01276	0.030614	-0.006	0.000742	0.009587	-0.00843	-0.0173	-0.00042	-0.01556	-0.00997	-0.00365	-0.02623	0.005878	-0.0062	-0.00111	-0.00649
0.004504	0.086415	0.069855	0.10655	0.090755	0.073077	0.209038	1	0.133233	0.011545	0.084217	-0.01922	-0.0047	-0.00853	-0.01702	-0.00492	-0.0227	0.05169	-0.00096	-0.05749	-0.00696	-0.01668	-0.04615	-0.01586	-0.01743	-0.0187	-0.01403	-0.05084	0.0246	0.01224	-0.02088	0.003484
0.027365	0.046268	0.042379	0.053648	0.039568	0.021287	0.071599	0.133233	1	0.031896	0.064763	-0.02003	-0.01	0.006111	-0.02192	-0.00462	-0.02003	0.003793	-0.01462	-0.0529	-0.00843	-0.01501	-0.0426	-0.02662	-0.02271	0.002544	-0.0181	-0.05829	0.052209	0.022361	-0.07101	0.005698
0.068484	0.123924	0.118135	0.159632	0.1227	0.135192	0.084941	0.011545	0.031896	1	0.273122	-0.00389	-0.00239	-0.00071	-0.00263	-0.00041	0.036164	-0.00313	-0.0013	-0.01637	-0.0023	-0.00182	-0.00562	-0.00397	-0.00336	-0.00358	-0.00435	0.006116	-0.00169	-0.00134	-0.00311	-0.0014
0.056805	0.197165	0.215253	0.438332	0.422568	0.059071	0.294086	0.084217	0.064763	0.273122	1	-0.00853	-0.00524	-0.00156	-0.00576	-0.0009	-0.00604	-0.00686	-0.00284	-0.00477	-0.00505	-0.00399	-0.01232	-0.00871	-0.00737	0.005967	0.001961	0.015283	0.053681	-0.00294	0.013317	-0.00307
0.065459	-0.01245	0.028861	-0.0097	-0.01257	-0.00187	0.006435	-0.01922	-0.02003	-0.00389	-0.00853	1	0.076278	0.140774	0.117444	0.0331	0.039584	-0.00857	0.001899	0.09056	0.021956	-0.00523	0.0033	0.028307	0.002228	0.028643	-0.00384	0.007475	0.005113	0.001223	-0.06043	0.021467
0.028584	-0.00765	-0.00802	-0.00596	-0.00772	-0.00702	-0.01106	-0.0047	-0.01	-0.00239	-0.00524	0.076278	1	-0.00321	-0.00276	-0.00185	0.004957	0.001261	-0.00586	0.069729	0.031074	0.017901	0.001383	0.00046	0.006368	0.017647	-0.01402	-0.04426	0.006399	0.064807	-0.05442	0.044493
0.012083	-0.00227	0.042316	-0.00177	-0.00229	-0.00209	-0.00328	-0.00853	0.006111	-0.00071	-0.00156	0.140774	-0.00321	1	0.026863	0.192023	0.025317	0.021464	-0.00174	0.03609	-0.00309	-0.00244	0.007331	0.015116	-0.00451	-0.00481	0.012931	-0.01164	0.044553	-0.0018	-0.01826	-0.00188
0.012262	-0.00841	0.02782	-0.00655	-0.0085	-0.00772	-0.01217	-0.01702	-0.02192	-0.00263	-0.00576	0.117444	-0.00276	0.026863	1	-0.00204	0.010085	-0.00854	0.010217	0.071323	0.007442	0.07425	0.016769	0.052887	0.061828	0.037659	0.029661	0.012046	0.00438	-0.00666	-0.02914	-0.00696
-0.0035	-0.00131	-0.00137	-0.00102	-0.00132	-0.0012	-0.0019	-0.00492	-0.00462	-0.00041	-0.0009	0.0331	-0.00185	0.192023	-0.00204	1	-0.00213	-0.00242	-0.001	-0.00011	-0.00178	-0.00141	-0.00435	-0.00308	-0.0026	-0.00277	-0.00337	-0.01112	-0.00131	-0.00104	-0.01054	-0.00109
0.028531	-0.00882	0.002412	-0.00687	-0.00891	-0.0081	-0.01276	-0.0227	-0.02003	0.036164	-0.00604	0.039584	0.004957	0.025317	0.010085	-0.00213	1	-0.00292	-0.00676	0.024484	0.033087	-0.0095	0.090977	-0.0207	-0.00503	0.028401	-0.00799	0.008781	0.003392	0.008424	0.039306	0.00743
-0.01415	0.000787	0.010127	-0.0078	0.000585	0.026091	0.030614	0.05169	0.003793	-0.00313	-0.00686	-0.00857	0.001261	0.021464	-0.00854	-0.00242	-0.00292	1	-0.00767	-0.05333	-0.01363	-0.01078	-0.03325	-0.01406	-0.01437	-0.01078	-0.02142	0.022454	0.011591	-0.00793	-0.01552	0.00474
-0.00112	-0.00415	-0.00435	-0.00323	-0.00419	-0.00381	-0.006	-0.00096	-0.01462	-0.0013	-0.00284	0.001899	-0.00586	-0.00174	0.010217	-0.001	-0.00676	-0.00767	1	0.007601	0.013305	0.019414	-0.00563	0.023892	0.057423	0.003582	-0.00038	-0.01011	-0.00415	-0.00329	0.000951	-0.00344
0.002307	0.011755	-0.0141	-0.00558	-0.01661	-0.02149	0.000742	-0.05749	-0.0529	-0.01637	-0.00477	0.09056	0.069729	0.03609	0.071323	-0.00011	0.024484	-0.05333	0.007601	1	0.025681	0.105595	0.206416	0.218583	0.141298	0.071606	0.106576	-0.00827	0.008699	0.039448	-0.05412	0.004527
0.019806	-0.00737	0.006163	-0.00574	-0.00745	-0.00677	0.009587	-0.00696	-0.00843	-0.0023	-0.00505	0.021956	0.031074	-0.00309	0.007442	-0.00178	0.033087	-0.01363	0.013305	0.025681	1	-0.00794	-0.01523	-0.01095	-0.0072	-0.0156	0.004382	-0.00088	0.007179	0.030875	-0.00334	-0.0061
-0.01555	-0.00583	-0.00611	-0.00454	-0.00589	-0.00535	-0.00843	-0.01668	-0.01501	-0.00182	-0.00399	-0.00523	0.017901	-0.00244	0.07425	-0.00141	-0.0095	-0.01078	0.019414	0.105595	-0.00794	1	0.085462	0.082397	0.185394	0.04065	0.021762	0.004331	0.012505	0.018511	-0.04687	-0.00483
-0.03098	-0.01799	-0.0069	-0.01401	-0.01816	-0.01651	-0.0173	-0.04615	-0.0426	-0.00562	-0.01232	0.0033	0.001383	0.007331	0.016769	-0.00435	0.090977	-0.03325	-0.00563	0.206416	-0.01523	0.085462	1	0.184692	0.101984	-0.01393	-0.02364	-0.02298	-0.01173	-0.00634	0.00712	-0.00734
-0.01056	-0.00411	-0.00511	0.012156	0.004212	-0.01167	-0.00042	-0.01586	-0.02662	-0.00397	-0.00871	0.028307	0.00046	0.015116	0.052887	-0.00308	-0.0207	-0.01406	0.023892	0.218583	-0.01095	0.082397	0.184692	1	0.124459	0.014562	0.025981	-0.02085	-0.00411	-0.01006	-0.08923	-0.00014
-0.00135	-0.01076	-0.01128	-0.00838	-0.01087	-0.00988	-0.01556	-0.01743	-0.02271	-0.00336	-0.00737	0.002228	0.006368	-0.00451	0.061828	-0.0026	-0.00503	-0.01437	0.057423	0.141298	-0.0072	0.185394	0.101984	0.124459	1	0.054939	0.008717	-0.01733	-0.00068	-0.00852	-0.06122	-0.00891
0.105526	-0.01146	-0.00295	0.003236	0.00723	-0.00019	-0.00997	-0.0187	0.002544	-0.00358	0.005967	0.028643	0.017647	-0.00481	0.037659	-0.00277	0.028401	-0.01078	0.003582	0.071606	-0.0156	0.04065	-0.01393	0.014562	0.054939	1	0.031428	-0.00748	0.045502	-0.00907	-0.04771	0.001962
0.02715	0.01768	0.00803	0.009402	0.009413	-0.01278	-0.00365	-0.01403	-0.0181	-0.00435	0.001961	-0.00384	-0.01402	0.012931	0.029661	-0.00337	-0.00799	-0.02142	-0.00038	0.106576	0.004382	0.021762	-0.02364	0.025981	0.008717	0.031428	1	0.152328	0.057191	0.00891	-0.04328	-0.002
-0.0068	0.005441	0.000892	-0.00698	-0.00823	-0.00721	-0.02623	-0.05084	-0.05829	0.006116	0.015283	0.007475	-0.04426	-0.01164	0.012046	-0.01112	0.008781	0.022454	-0.01011	-0.00827	-0.00088	0.004331	-0.02298	-0.02085	-0.01733	-0.00748	0.152328	1	0.047212	9.47E-05	0.13469	-0.0148
0.084835	0.014294	0.050775	0.046298	0.053101	0.016486	0.005878	0.0246	0.052209	-0.00169	0.053681	0.005113	0.006399	0.044553	0.00438	-0.00131	0.003392	0.011591	-0.00415	0.008699	0.007179	0.012505	-0.01173	-0.00411	-0.00068	0.045502	0.057191	0.047212	1	0.095162	-0.02379	-0.00449
0.007829	0.020574	0.019238	0.028516	0.020293	0.023129	-0.0062	0.01224	0.022361	-0.00134	-0.00294	0.001223	0.064807	-0.0018	-0.00666	-0.00104	0.008424	-0.00793	-0.00329	0.039448	0.030875	0.018511	-0.00634	-0.01006	-0.00852	-0.00907	0.00891	9.47E-05	0.095162	1	-0.02616	-0.00355
-0.07785	-0.00073	-0.0205	-0.00016	0.004951	-0.02563	-0.00111	-0.02088	-0.07101	-0.00311	0.013317	-0.06043	-0.05442	-0.01826	-0.02914	-0.01054	0.039306	-0.01552	0.000951	-0.05412	-0.00334	-0.04687	0.00712	-0.08923	-0.06122	-0.04771	-0.04328	0.13469	-0.02379	-0.02616	1	-0.02016
0.043308	-0.00449	-0.0047	-0.00349	-0.00453	-0.00412	-0.00649	0.003484	0.005698	-0.0014	-0.00307	0.021467	0.044493	-0.00188	-0.00696	-0.00109	0.00743	0.00474	-0.00344	0.004527	-0.0061	-0.00483	-0.00734	-0.00014	-0.00891	0.001962	-0.002	-0.0148	-0.00449	-0.00355	-0.02016	1

ANNEX II. HIGH RESOLUTION CORRELATION CHARTS

Figure S. 1. High resolution metric correlation matrix for all technologies

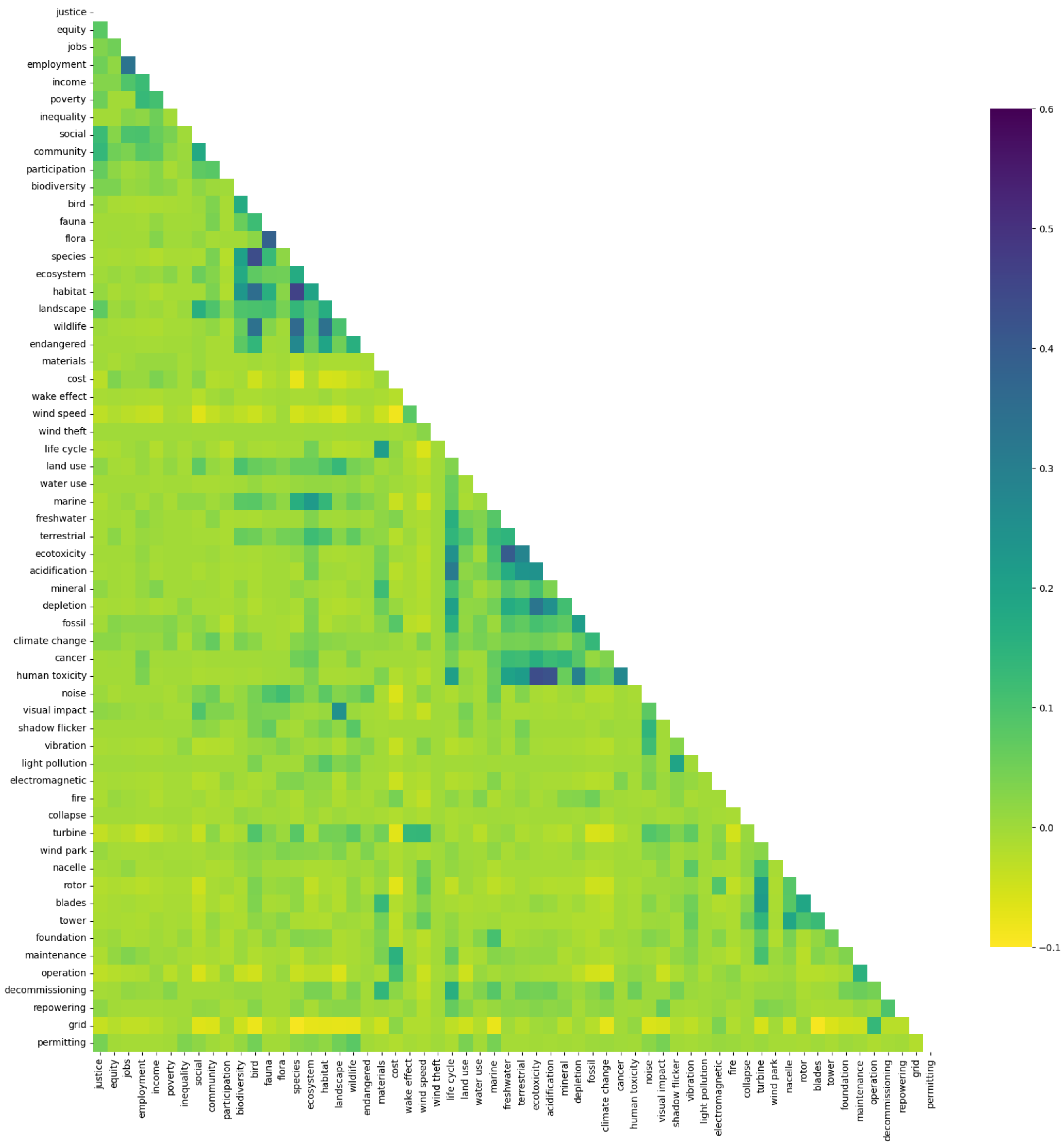
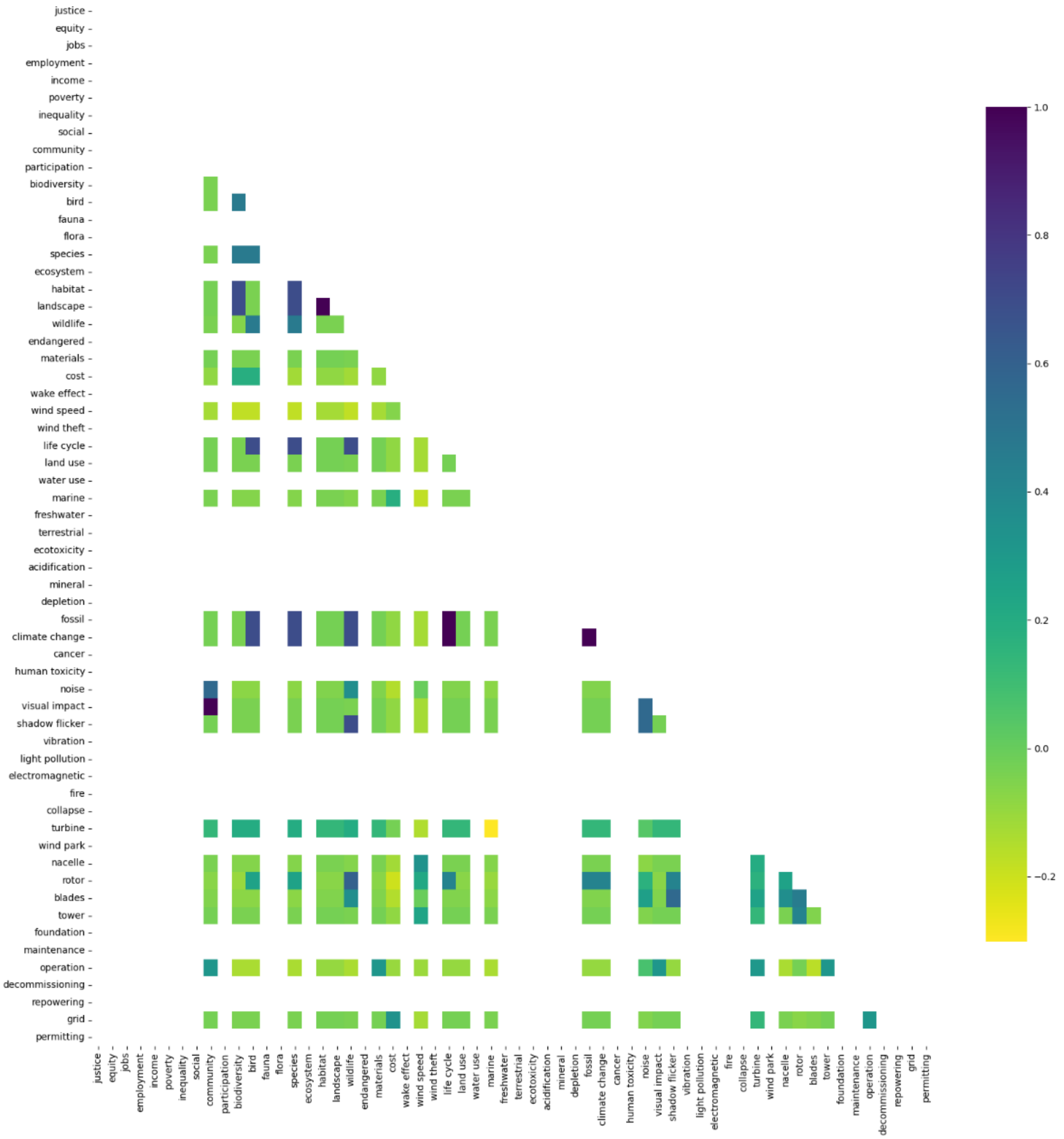


Figure S. 2. High resolution metric correlation matrix for airborne technologies



ANNEX III. LIBRARY OF ES CLASSES AND THEIR IMPLEMENTATION IN INDICATORS

Table S. 1. Variables to be used in ecosystem service definition of metrics: Provisioning services

ecosystem service	value class	example indicator	unit
Wind energy	Importance of the resource	Social perception of energy provision	% of respondants considering it important
	Need for the resource	Reduce the dependency on non-renewable abiotic energy sources	kW h -1
		Energy for all purposes (electric power, transportation, etc.)	thermal enery units; kilojoule
	Capacity of the resource	*wind speed*	*m s -1*
	Energy potential	*expected electricity generation*	*MWh*
Wild marine animals used for nutritional purposes	Benthic species and biogenic habitats	Coral size and substrate cover	
	Biomass/abundance	Wild fauna	tonnes ha -1
	Economic value	Value of landed fish	€
	Employment/jobs	Employment in fisheries	No. of employees
	Extent of MPAs/no take zones	Area of marine protected areas	km2
	Food web structure	Food web structure and robustness	
	Habitat extent	Areas to support seafood production	ha
	Harvest/catch/landings	Commercial and artisanal fish and shellfish landing	tonnes yr -1
	Importance of the resource	Social perception of fisheries	% respondents considering it important
	Need for the resource	Fish demand	Megatonne yr -1
	Perceived benefit	Perceived benefit from commercial fishing	Words used most frequently
	Presence/distribution of larvae/fry	Distribution of fish or larvae	No. of species km2 -1
	Quality of the biomass/species/resource	Quality of the fish, shellfish	Species composition, age profile, length profile, % affected by disease, mortality rates
	Replacement costs	Replacement cost with fishery restoration projects	€ ha-1 year-1
	Sales/earnings/income	Financial income from fisheries	€ ha-1 year-1
	Use of the resource	Depletion in the number of viable (non-collapsed) fisheries	%

Table S. 2 Variables to be used in ecosystem service definition of metrics: Cultural services

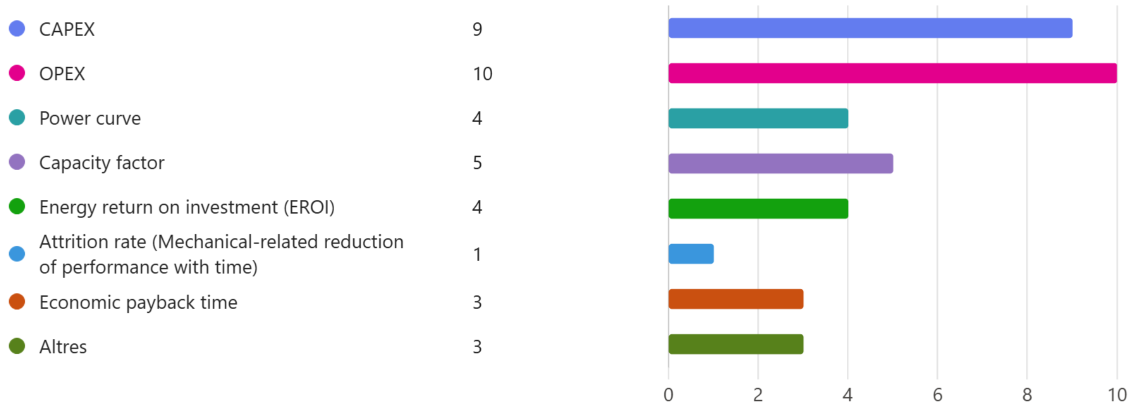
ecosystem service	value class	example indicator	unit
	human activity	*time spent*	*hrs.*
	Fine arts and cultural events	No. of movies and broadcasts in the area	No. km-2
	Importance of the benefit	Importance and specificity of cultural heritage based on expert knowledge	scores 0-3
Elements of living systems that are resonant in terms of culture or heritage	Perceived benefit	Cultural narrative	words used most frequently
	Presence of habitats/species/seascapes	# of households that consider an area or aspects of an area as cultural heritage	No.
	Amount of visits/trips/tourists	Recreational fishing interest	No. of fishing licenses, fishing trips, fishing days
	Economic value	Economic impacts by and expenditures associated with	€
	Employment/jobs	Jobs linked to recreational fishing	No.
	Harvest/catch/landings	amount or catch rate of target species	tonnes yr -1
	Importance of the benefit	Importance and specificity of recreation and tourism based on expert knowledge	scores 0-3
	Participation in recreational activities	Recreational fishing activities, yearly participation rate in recreational activity	tonnes year-1, % of country population
Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Perceived benefit	Perceived benefit from recreational fishing	words used most frequently
	Presence of habitats/species/seascapes	Extent of marine protected areas, presence of iconic species	km2
	Revealed/stated preference valuation	Willingness to pay; importance and specificity of aesthetic values based on expert knowledge	€
	Sales/earnings/income	Local annual income linked to recreational fishing	€
	Visitor expenditure	Visitor expenditure related to angling, diving and marine mammal watching	€

Table S. 3. Variables to be used in ecosystem service definition of metrics: Regulation services

ecosystem service	value class	example indicator	unit
Abiotic regulation of chemical composition of atmosphere and oceans	*Climatic conditions*	*wind speed*	*m s -1*
	Pelagic conditions	*stratification duration*	*days*
	Chemical/hydrodynamic conditions	Rates of tidal and wind-driven currents	m3 s -1; turbidity (mg m-3 or NTU)
Abiotic maintenance and regulation by inorganic natural chemical and physical processes of fresh or salt waters	Chemical/hydrodynamic conditions	Rates of tidal and wind-driven currents	m3 s -1; turbidity (mg m-3 or NTU)
	Importance of the benefit	Importance and specificity of air quality regulation based on expert knowledge	score 0-3
	Oceanic uptake of GHG and pollutants	Air-sea and sediment-water fluxes of carbon and CO2	mg C m-2 d-1, mg CO2 m-2 d-1
Regulation of chemical composition of atmosphere and oceans	Assimilative/bioremediation capacity	Assimilative and recycling capacity	
	Benthic species and biogenic habitats	Microbial breakdown and deposit feeders activity in the sediments	
	Biomass productivity	Leaf litter production	tonnes DW ha-1 year-1
	Carbon stock/sequestration	Primary production (PP)	tonnes C year-1 km-2
	Economic value	Net value added: primary production valued by the emission permits market	€
	Importance of the benefit	Importance and specificity of climate regulation based on expert knowledge	score 0-3
	Nutrient transformation/ storage/ transport	Denitrification	tonnes year-1
	Dis-service	Harmful algal bloom outbreaks	No. km-2
	Sequestration potential	Carbon sequestration potential	gC year-1
Maintaining or regulating feeding grounds	Benthic species and biogenic habitats	Presence of suspension feeders	tonnes ha -1
	Extent/quality of nursery areas	Structural complexity, nursery and feeding areas	Abundance m-2 and species diversity
	Food web structure	Connectivity, diversity, trophic composition	levels/ratios/no. of sensitive species
	Spill-over effects	Amount of fish caught outside an area	tonnes yr -1
	Economic value	Value of ES or habitat	Benefit transfer (EUR ha-1 year-1)
	Dis-service	Presence of alien species	No. km-2
	Importance of the benefit	Importance and specificity of the habitat based on expert knowledge	score 0-3

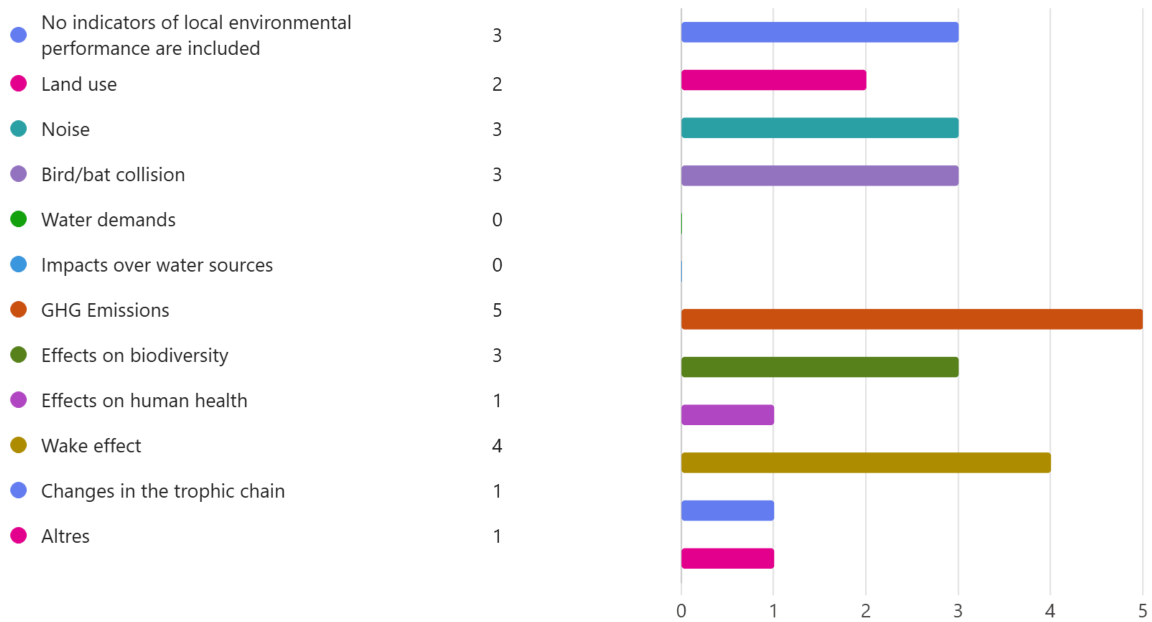
ANNEX IV. CINEA’S CLUSTER SURVEY RESULTS

11. What indicators of technical and economic performance of wind parks are used in your project? Please select all that apply



12. What indicators of **local environmental performance** of wind parks are used in your project? Please select all that a pply

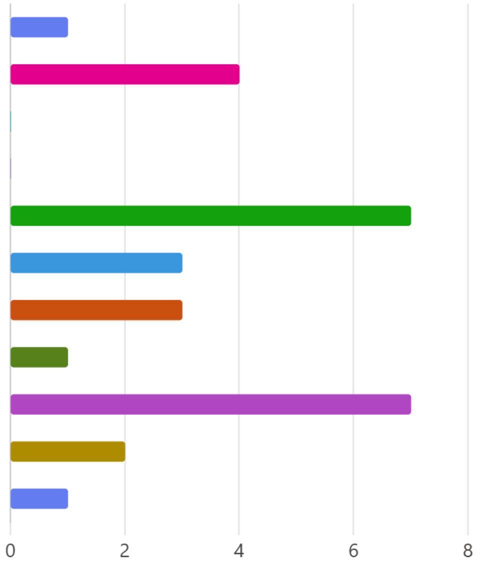
We refer here to impacts onsite, happening usually during the installation or operation of the parks.



13. What indicators of **environmental performance in the life cycle** of wind parks are included in your project? Please select all that apply

We refer here to impacts that are offsite, happening either during the extraction of materials, manufacturing of the te chnology, or for the decommission.

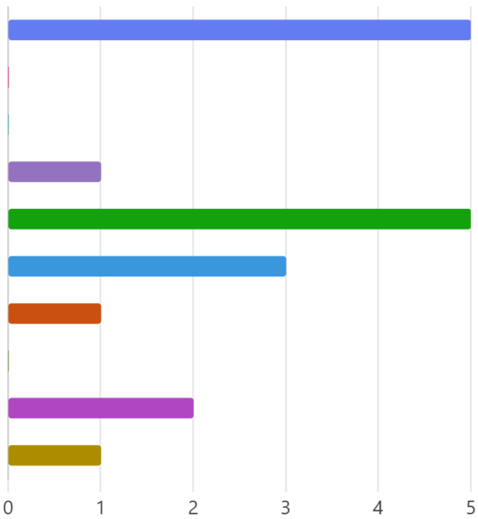
No indicators of life cycle environmental performance are included	1
Land use	4
Water demands	0
Impacts over water sources	0
GHG emissions	7
Cumulative energy demand	3
Effects on biodiversity	3
Effects on human health	1
Material requirements	7
Blade recycling rate	2
Altres	1



14. What indicators of **local social performance** of wind parks are included in your project? Please select all that apply

We refer to impacts that happen to the communities near the wind parks

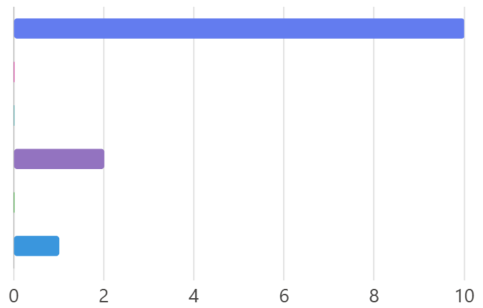
No indicators of local social performance are included	5
Shares of state/regional government, local government, local community, industry, or...	0
Shares of state/regional government, local government, local community, industry, or...	0
Share of local population for/against the park	1
Number of full-time job equivalents in the installation, operation and maintenance of...	5
Number of full-time job equivalents in installations and services related to the park	3
Monetary compensations to local community by industry	1
Evolution of land prices	0
Interference with tourism/agricultural activities	2
Altres	1



15. What indicators of **life cycle social performance** of wind parks are included in your project? Please select all that apply

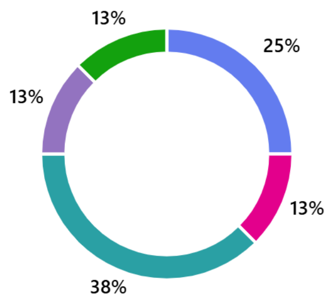
We refer to impacts that happen to the communities around the world during the raw material extraction, manufacturing, transport and decommission of the park.

No indicators of life cycle social performance are included	10
Share of child labor in related industry	0
Salary gaps in related industry	0
Share of community or socially owned companies in related industry	2
Share of mandatory labor overtime in related industry	0
Altres	1



16. What are the main reasons for not including indicators in your project? Please select all that apply

Lack of data	4
Lack of expertise within the project	2
Not a priority for our assessment	6
Not relevant for our stakeholders/shareholders	2
Altres	2



19. Please grab and rank the following indicators under development in the JUSTWIND4ALL project. The higher an indicator is, the more relevant for your project.

Environmental breakeven points of wind power (years): time that new wind parks need to accumulate savings in impacts that equal the impacts created for their construction

Net Environmental performance (impact / net kWh): Accumulated environmental impacts of life cycle by net KWh considering all the energy demand of the life cycle chain.

Local environmental performance (Impact/kWh): Local environmental impacts by KWh produced by the park

Offsite environmental performance (impact/MW): Life cycle impacts that affect places other than the location of the wind park/turbine by the capacity of the park/turbine

Environmental capacity factors (dimensionless): A coefficient that relates how much impact you need to create with wind to save the same impact from the total energy system.

APPENDIX: EC SUMMARY REQUIREMENTS

Changes with respect to the DoA	No changes to report
Dissemination and uptake	Public
Short summary of results (<250 words)	This deliverable (D1.2) of the JUSTWIND4ALL project, we developed a library of metrics for wind energy to aid decision-making and streamline wind power implementation. This library, created through literature reviews, workshops, and case studies, addresses information gaps and prioritizes useful metrics. We identified barriers such as insufficient understanding of impacts, inadequate planning, and data fragmentation. Our WindSES framework, based on the socio-ecosystem concept, integrates these metrics across five analytical energy levels and three ecological levels. The metrics assess feasibility and viability, considering resource demands, ecosystem impacts, and contributions to global change. A pilot study on Cataluya and the Tramuntana offshore wind park demonstrates the framework's application, highlighting the need for detailed resolution and alternative methods for specific aspects.
Evidence of accomplishment	This deliverable and the supplementary file that can be all found in Zenodo. https://zenodo.org/records/15038095