







## Evaluation of environmental impact manifestations of electric power transmission projects



## Evaluación de las manifestaciones de impacto ambiental de proyectos de transmisión de energía eléctrica

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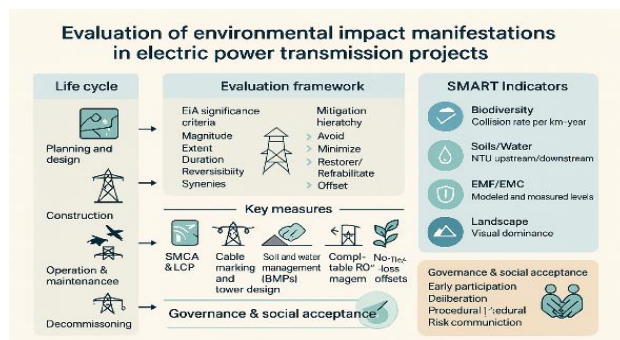


### Abstract

The environmental impact of electrical transmission lines and substations is analyzed throughout their life cycle, from planning to decommissioning. Evaluation criteria and mitigation hierarchies are addressed, enabling cost-effective and socially legitimate decisions, integrating Environmental Impact Assessment [EIA] frameworks, valuation, and risk analysis. The approach includes the participation of project teams, local stakeholders, and life cycle considerations, with an emphasis on climate footprint and electrical losses. In addition, practical guidelines are proposed on aspects such as biodiversity, landscape, soil, water, and electromagnetic compatibility, promoting more robust EIAs for projects in contexts of accelerated energy transition.

### Resumen

Se analiza el impacto ambiental de las líneas y subestaciones de transmisión eléctrica a lo largo de su ciclo de vida, desde la planificación hasta el desmantelamiento. Se abordan criterios de evaluación y jerarquías de mitigación que permiten decisiones costo-efectivas y socialmente legítimas, integrando marcos de Evaluación de Impacto Ambiental [EIA], valoración y análisis de riesgo. El enfoque incluye la participación de equipos de proyecto, actores locales y consideraciones del ciclo de vida, con énfasis en la huella climática y pérdidas eléctricas. Además, se proponen lineamientos prácticos en aspectos como biodiversidad, paisaje, suelos, aguas y compatibilidad electromagnética, promoviendo EIAs más robustas para proyectos en contextos de transición energética acelerada.



### Evaluación de impacto ambiental, líneas de transmisión, biodiversidad



### Environmental impact assessment, transmission lines, biodiversity

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## Introduction

Achieving deep decarbonisation of electricity systems requires not only rapid growth in low-carbon generation, but also a major expansion and modernisation of transmission networks that can transport energy from resource-rich areas to load centres, balance variability and improve system resilience. In practice, the deployment of overhead high-voltage lines and selective undergrounding presents a complex portfolio of biophysical, landscape and socio-environmental externalities distributed throughout the project life cycle, from planning and routing to construction, operation and decommissioning.

A robust environmental assessment must therefore anticipate cumulative, cross-cutting and often synergistic effects, rather than treating projects as isolated interventions. This perspective is increasingly present in recent research on linear infrastructure and its impact at the landscape scale [Teo et al., 2019; Morgan, 2012; Jones, 2016].

Conceptually, Environmental Impact Assessment [EIA] has established itself as a structured, evidence-based process that integrates assessment and scoping with baseline characterisation, impact prediction, analysis of alternatives, and the design of mitigation and monitoring plans. Best practices emphasise transparent significance criteria: magnitude, extent, duration, reversibility, probability, uncertainty, and possible synergies, and require that alternatives be justified with traceable criteria and explicit trade-offs.

The mitigation hierarchy [avoid, minimise, restore/rehabilitate, and compensate] should guide decisions throughout the project cycle and is increasingly framed within outcome-based and ‘net-zero loss’ biodiversity objectives [Glasson & Therivel, 2012; Morgan, 2012; Arlidge et al., 2018].

In this context, the literature on external costs offers complementary tools for internalising environmental damage when comparing technological options and routing alternatives under conditions of uncertainty. Classic and updated reviews highlight how valuation methods, both monetary and non-monetary, can reduce information asymmetries in decision-making, while cautioning that results are sensitive to assumptions, spatial boundaries, and dose-response functions.

For transmission planning, these approaches are useful when evaluating packages of measures such as selective burial in sensitive sections, alternative tower topologies, or intensified bird diversion programmes [Sundqvist & Söderholm, 2002]. Methodologically, transmission projects are paradigmatic linear infrastructures whose main ecological risks include habitat loss and fragmentation, connectivity disruption, edge effects, bird collisions and electrocutions, and disturbances during construction. A systematic review of biodiversity impacts associated with power lines shows consistent evidence of risks to birds and calls for a more robust approach to cumulative effects and improved monitoring designs [Biasotto & Kindel, 2018]. In parallel, a state-of-the-art synthesis indicates that the effectiveness of collision mitigation devices depends on the species, context, and study design, underscoring the need for before-and-after control [BACI] impact monitoring approaches and standardised carcass search protocols [Bernardino et al., 2018; Barrientos et al., 2012].

From a planning perspective, early-stage multi-criteria spatial analysis [MCSAs], together with least-cost route analysis, have proven valuable for corridor definition and micro-routing, jointly optimising engineering feasibility and environmental performance. Empirical applications integrate biodiversity layers, land use conflicts, visual exposure of key receptors, and proximity to sensitive social infrastructure, thus operationalising the ‘avoid’ step of the landscape-scale mitigation hierarchy [Bagli et al., 2011; Biasotto et al., 2022].

During the construction phase, well-documented impact pathways include soil erosion and sediment mobilisation from access roads and foundations, as well as dust and noise affecting nearby communities. Good management practices and event-based turbidity thresholds are recommended to address episodic heavy rainfall. Vegetation clearance in rights-of-way [ROWs] warrants compatible vegetation strategies and native revegetation to accelerate ecological recovery and maintain connectivity. Emerging evidence further suggests that properly managed ROWs can support pollinator diversity and other taxa, reframing residual ROWs as potential ecological assets when herbicide use is minimised and structural heterogeneity is conserved [Glasson & Therivel, 2012; Russo et al., 2021].

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During operation and maintenance, three issues recur across jurisdictions. First, avian risk management must combine context-specific line marking, selective line burial in highly sensitive sections, and adaptive monitoring, recognising that average effectiveness masks substantial interspecific variation [Barrientos et al., 2012; Bernardino et al., 2018]. Second, public exposure to low-frequency [50/60 Hz] electric and magnetic fields is governed by geometry, phase, and distance; international guidelines establish basic restrictions and reference levels for general public exposure, and EIA documentation should transparently report modelling assumptions, distances to receivers, and risk communication strategies [ICNIRP, 2010].

Thirdly, audible noise and radio interference related to the coronavirus, under certain climatic conditions, require predictive assessment to avoid exceedances near sensitive receivers [Glasson & Therivel, 2012; ICNIRP, 2010].

From a life cycle perspective, while the largest climate contribution from the electricity sector occurs in generation, transmission and distribution [T&D] contribute additional loads through materials [steel, aluminium, concrete], insulating gases [in particular SF<sub>6</sub>], construction, losses and end of life. Peer-reviewed life cycle assessments [LCAs] of grid components consistently show that electrical losses predominate in many impact categories, with SF<sub>6</sub> leaks being a relevant factor in cases where gas-insulated equipment is numerous.

Typical T&D contributions to the carbon footprint of supplied electricity are in the single-digit range of g CO<sub>2</sub>-eq/kWh, with variations depending on the context.

These results are relevant for decision-making when comparing overhead and underground sections, conductor sizing and tower design, and for justifying selective burial when ecological or social sensitivities warrant it [Jorge et al., 2012; Turconi, 2014; Valheim, 2016].

Furthermore, prospective scenarios involving long-distance high-voltage direct current [HVDC] corridors to integrate remote renewable energy require explicit life cycle and systems analyses, so that additional material requirements and the impact of converter stations can be weighed against potential system-level benefits, e.g., reduction of constraints and flexibility. Recent studies on HVDC technologies and long-distance interconnectors support this systems approach and call for the integration of LCA with techno-economic planning models [Irnawan et al., 2024; Acaroğlu et al., 2022].

Crucially, social acceptance and governance dynamics are often decisive for transmission location and timing. Deliberative studies in affected communities show that perceptions of fairness, visual intrusion, communication of EMF risk, and the credibility of alternative analysis, e.g., undergrounding options, influence acceptance more than simple “NIMBY” approaches suggest. Transparent and iterative participation, integrated from the outset in the choice of routes and technologies, has been linked to greater legitimacy and fewer delays [Cotton & Devine-Wright, 2013; Lienert et al., 2015; Lienert et al., 2018].

Therefore, this article proposes and applies an assessment framework for the environmental impact statements of electricity transmission projects, explicitly based on the life cycle, which considers cumulative effects and is decision-oriented. The framework integrates [i] EIA significance criteria and mitigation hierarchy, [ii] the assessment of externalities to compare packages of measures under conditions of uncertainty, and [iii] SMART monitoring indicators by component [biodiversity, soil and water, electromagnetic fields, landscape, and life cycle performance]. In doing so, it seeks to bridge the persistent gaps between compliance-oriented assessments and preventive and adaptive management, aligned with the imperatives of decarbonisation and community well-being [Glasson & Therivel, 2012; Morgan, 2012; Jones, 2016; Arlidge et al., 2018].

## Review methodology

A focused narrative review of indexed literature and reference texts was conducted. The following inclusion criteria were prioritised:

## Article

- a) EIA manuals and reference books.
- b) Peer-reviewed articles on impacts on linear infrastructure and mitigation measures.
- c) Life cycle studies of electricity networks.
- d) Methodological contributions to risk assessment.

Impact statements were coded by life cycle phase, and assessment criteria, measures, and monitoring metrics were extracted. The selection includes [Glasson & Therivel, 2012], [Sundqvist & Söderholm, 2002], [Teo et al., 2019], [Barrientos et al., 2012], and [Turconi, 2014; Valheim, 2016].

### Impact manifestations and life cycle phase

#### - Route planning and design

The definition of the corridor and micro-route determines habitat fragmentation, ecological connectivity, and bird collision risks. Therefore, multi-criteria analysis of alternatives with strata of biodiversity, land use, and the presence of sensitive receptors [schools, homes, health centres] is crucial from the outset of the scoping study. Landscape-scale assessment, including protected areas, wetlands and migratory routes, guides early solutions to avoid collisions [Glasson & Therivel, 2012; Teo et al., 2019].

Visual perception and landscape integration should be considered with simulations from key receptors to select types of supports, heights, finishes and alignments that reduce visual intrusion, especially in scenic and tourist environments [Glasson & Therivel, 2012].

Electromagnetic compatibility [EMC] and radio interference require design analysis [phase configuration, distances, shielding] to avoid disturbances to nearby equipment in urban and peri-urban corridors [Senapati & Ojha, 2017].

#### - Construction

Impacts on soils, erosion and sediments arise from access roads, earthworks and foundations. Evidence recommends best management practices [BMPs] [sediment barriers, temporary drainage, temporary stabilisation] and torrential rain management plans with turbidity thresholds and rapid response [Glasson & Therivel, 2012].

In terms of air quality and noise, dust control, fleet maintenance and scheduling noisy activities outside sensitive hours reduce impacts on nearby communities [Glasson & Therivel, 2012].

Strip clearing affects vegetation and habitat; right-of-way approaches based on compatible vegetation and revegetation with native species reduce residual effects and facilitate biological corridors [Teo et al., 2019].

Finally, when information is scarce, prioritising environmental risks based on the construction team's judgement, e.g., unstable soils, fires, watercourse crossings, allows for the targeting of prevention and contingency resources.

#### - Operation and maintenance

With regard to bird collisions and electrocutions, controlled studies with BACI design show that cable marking [deflectors] reduces mortality in a small but significant way: [Barrientos et al., 2012] estimated a 9.6% reduction after marking 72.5 km of transmission and distribution lines, with variability by species, reinforcing the need for contextualised design and post-implementation monitoring.

Exposure to 50/60 Hz electric and magnetic fields decreases with distance and is managed through design and regulatory compliance; the recommendation in the EIA is to document modelling, distances to recipients, and risk communication strategies, avoiding both alarmism and unfounded minimisation [Senapati & Ojha, 2017]. Corona discharge can cause noise and visual effects in certain weather conditions and should be modelled to avoid exceedances near sensitive receptors [Glasson & Therivel, 2012]. Management of buffer strips oriented towards compatible vegetation, minimal and selective use of herbicides, and monitoring of soils and water bodies reduce residual pressures [Teo et al., 2019].

#### - Dismantling and closure

The removal phase requires management plans for metal waste, foundations, and access roads, with geomorphological restoration and revegetation to restore connectivity and ecosystem functions. EIA guidelines recommend scheduling this phase from the project design stage [Glasson & Therivel, 2012].

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### Climate dimension and life cycle perspective

In terms of climate change, the electricity sector's largest contribution comes from generation. However, transmission and distribution add charges for materials, construction, operation [losses] and decommissioning. Studies on European and Nordic networks place transmission and distribution emissions in the order of a few grams of CO<sub>2</sub> per kWh supplied, with differences depending on the technological and geographical context.

For Denmark, [Turconi, 2014] reports that distribution infrastructure alone contributes ~2 g CO<sub>2</sub>-eq/kWh, and [Valheim, 2016] estimates 2.5 g CO<sub>2</sub>-eq/kWh for the entire network [development, operation and decommissioning], focusing on the role of materials [steel, aluminium, concrete], SF<sub>6</sub> and electrical losses.

These figures, although lower than those for fossil fuel generation, are relevant when comparing design alternatives, for example, selective burial, and when justifying investments according to comprehensive environmental performance criteria [Turconi, 2014; Valheim, 2016].

Complementarily, long-distance transmission scenarios using HVDC highlight the importance of evaluating international electricity bridges in terms of life cycle, considering the increase in materials and the potential systemic benefit of integrating remote renewables.

### Results

The most effective measure is to avoid corridors through critical habitats and flight paths, applying a multi-criteria analysis with environmental and social variables from an early stage and considering technological alternatives [support height, geometric configuration, partial burial in sensitive sections] [Glasson & Therivel, 2012; Teo et al., 2019].

When avoidance is not feasible, cable marking reduces collisions, although its effects vary depending on the species and context. It is recommended to combine this with accurate micro-monitoring in wetlands, floodplains and wildlife crossings [Barrientos et al., 2012].

In CEM/CEM, minimisation is addressed through distances, shielding and optimised conductor configurations [Senapati & Ojha, 2017].

Revegetation with native plants, soil management, and post-construction drainage restoration reduce residual effects, with indicators of success and maintenance over several years [Teo et al., 2019].

In cases of unavoidable significant impacts on biodiversity, e.g., loss of habitat for sensitive species, net zero loss schemes and outcomes-based offsets require clear metrics and independent monitoring [Glasson & Therivel, 2012].

The assessment of externalities allows evidence-based comparisons of combinations of measures [markers vs. selective burial vs. redesign of supports] and supports decision-making under conditions of uncertainty. However, the literature recommends caution regarding assumptions and parameter sensitivity [Sundqvist & Söderholm, 2002].

Methods based on the judgement of the project team when robust series are not available facilitate environmental risk matrices [probability × consequence] that are useful for allocating resources to critical controls and contingencies.

#### - Monitoring metrics and indicators

To operationalise the EIA for transmission, SMART indicators are proposed for each component, with thresholds and actions:

1. Biodiversity/Avifauna: collision rate per km·year, search effort and correction for carrion removal and detection [to avoid bias], seasonal and species variation; success of measures, e.g., percentage change in post-marking [Barrientos et al., 2012].
2. Soil/Water: NTU at upstream/downstream points during construction and first rains, slope stability [safety factor], compliance with BMPs [percentage of verified effective measures] [Glasson & Therivel, 2012].

3. EMF/EMC: Modelled and measured levels at 50/60 Hz at boundaries and installations; reported and resolved interference events; compliance with national and international guidelines [Senapati & Ojha, 2017].
  4. Landscape: Assessment of contrast change and visual dominance through photographic audits by sensitive receivers; social perception [surveys] [Glasson & Therivel, 2012].
  5. Life cycle: Inventory of critical materials [steel, aluminium, concrete], SF<sub>6</sub> and technical losses; estimation of g CO<sub>2</sub>-eq/kWh attributable to T&D and comparison with design alternatives [Turconi, 2014; Valheim, 2016].
- Social and governance considerations

In social terms, the EIA should integrate the mapping of key actors, communication and informed participation mechanisms, with special attention to local communities and indigenous peoples, as well as rights-based easement acquisition processes.

Comparative experience with infrastructure corridors underscores that the legitimacy of the process, transparency in the criteria for selecting alternatives, feedback on results, and collaborative design of measures reduce conflicts and implementation delays [Teo et al., 2019].

- Lessons from analogous sectors: geothermal energy as a methodological case

Although specific, geothermal developments offer extrapolatable lessons: anticipating seismic, emissions and groundwater risks through preliminary EIAs improves the quality of scoping analysis and adaptive monitoring. In this regard, technical reports from geothermal training programmes demonstrate the usefulness of interaction matrices and phased monitoring plans, which can be adapted to linear infrastructure in critical subsections.

- Technical-environmental comparisons: aerial vs. underground

The literature on the life cycle recommends avoiding generalisations: undergrounding reduces visual intrusion and the risk of bird collisions, but increases the complexity of materials, civil works and, in some cases, maintenance; overhead lines, on the other hand, require fewer materials per km, although they generate greater landscape exposure and collision risk.

In cold or humid climates, corona discharge and noise can be significant in high-voltage overhead lines. Multi-criteria assessment, based on life cycle inventories and technical losses of the system, is the recommended approach for deciding on selective undergrounding in sensitive sections [Turconi, 2014; Valheim, 2016; Barrientos et al., 2012].

## Conclusions

The EIA for electricity transmission projects must go beyond formal compliance and operate with a preventive and adaptive approach: avoiding corridors over sensitive habitats, minimising cable marking and micro-routing with proven measures, and restoring and compensating according to net zero loss principles, with independent monitoring and periodic audits.

The assessment of externalities brings economic rationality to the selection of packages of measures under conditions of uncertainty, if assumptions are made explicit and sensitivity analyses are performed. This is particularly relevant in contexts of energy transition with multiple technological alternatives.

The life cycle perspective shows that, even when the climate loads of transmission and distribution per kWh are relatively low compared to generation, they are decisive for design decisions [materials, topologies, selective burial] and for avoiding overlapping impacts.

Informed participation and transparent governance, with mapping of key actors, risk communication and right-of-way agreements, promote social acceptance and the long-term viability of projects, an essential condition for networks that are compatible with biodiversity, the landscape and community well-being.

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## Article

**Declarations****Conflict of interest**

The authors declare that they have no conflict of interest. They have no conflicting financial interests or known personal relationships that could have influenced the work presented in this article.

**Contribution of the authors**

*Aguilar-Marin, Jorge Luis:* Conceptualisation, methodology, writing [revision and editing].

*Cisneros-Villalobos, Luis:* Conceptualisation, methodology, research, supervision.

*Vera-Dimas, José Gerardo:* Conceptualisation, formal analysis, research.

*Gutiérrez-Álvarez, Yair Alejandro:* Conceptualisation, formal analysis, writing [review and editing].

**Availability of data and materials**

The original contributions presented in this study are included in the article. For further information, please contact the corresponding author.

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**Abbreviations**

BACI	Before-After Impact Monitoring
BMPs	Best Management Practices
CO <sub>2</sub> -eq	Carbon Dioxide Equivalents
EIA	Environmental Impact Assessment
EMF	Electric and Magnetic Fields
EMC	Electromagnetic Compatibility
Hz	Hertz
HVDC	High Voltage Direct Current
ICNIRP	International Non-Ionizing Radiation Protection Commission
kWh	Kilowatt-hours
LCA	Life Cycle Analysis
NTNU	Norwegian University of Science and Technology
NTU	Nephelometric Turbidity Units
ROW	Right of Way
SF <sub>6</sub>	Sulphur Hexafluoride
SMCA	Multicriteria Spatial Analysis

SMART	Specific Measurable Achievable Achievable Relevant Relevant Time Limited
T&D	Transmission and Distribution

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## Basics

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