SMART SITING GUIDE:

Portugal

Balancing energy, conservation, and community priorities in developing ground-mounted solar and onshore wind on low-conflict sites.

January 2026

zero.

The Nature Conservancy

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Acknowledgments

The authors would like to thank the following people for their logistical and coordination support; their help in data gathering; and their feedback on the study's methodology, results, and relevance to the Portuguese context and national processes:

From The Nature Conservancy: Rob McDonald, Louise Combret, Jeffrey Evans, Julia Boverhoff. From ZERO: Ricardo Filipe, Mafalda Antunes, Pedro Nunes, Francisco Ferreira, Acácio Pires, Paulo Castro, Vera Pinho, Susana Fonseca. From LNEG: Juliana Barbosa, Sofia G. Simões, Paula Oliveira, Teresa Simões, Carlos Rodrigues. From APREN: Susana Serôdio, Mariana Cruz de Carvalho, Diogo Carvalheda, Sara Freitas, Pedro Amaral Jorge. From SPEA: Hany Alonso, Julieta Costa. Siddharth Sareen (University of Bergen), Ana Caetano Buchadas (UCLouvain), Luisa Brázia (Silves Municipality).

The authors also extend special thanks to Janet Dalziell and Cristina Gouveia for their facilitation and planning support, and the following participants in the study's stakeholder and expert engagement process, who represented a total of 68 entities at the Portuguese and European level. These included 16 NGOs, 32 renewable energy companies and associations, 9 academic and research institutions, 3 consultancies, and 8 national and international public institutions.

Alice Fonseca, Alexandre Coelho Rezende, Ana Catarina Marcos Henriques, Ana Cristina Antunes, Ana Delicado, Ana Horta, Ana Isabel Guerreiro, Ana Isabel Ruiz Casas, Ana Marinho, Ana Rita Antunes, Ana Rita Justino, Ana Rita Martins, André Joel De Jesus Alves, Bianca Mattos, Bruno Rodrigues, Bruno Silva, Carla S. Pimentel, Celso Xavier, Cosimo Tansini, Cristóvão Santos, Daniel Tavares, Diana Lopes, Diogo Teixeira, Domingos Leitão, Domingos Patacho, Elaine Santos, Elsa Santos, Emanuel José Valpaços Dos Santos, Fernando Ascensão, Filipa De Jesus Gouveia, Filipa Magalhães, Filipe Miguel Moreira Alves, Filipe Pinto, Francisco Godinho, Francisco Manuel Ribeiro Ferraria Moreira, Francisco Parada, Gonçalo Brotas, Gonçalo Vicente, Helena Rio-Maior, Hugo Paz, Inês Bem, Inês Campos, Inês Subtil, Joana Soares, João A. Marques, João António Ferreira Marques, João Galamba, João Joanaz Melo, João Lopes, João Orvalho, João Paulo Silva, João Tomaz, Jonathan Bonadio, Jorge Palmeirim, José Carlos Matos, José Ferreira, José Lino Costa, José Luis Monteiro, José Paulo Gonçalves Martins, José Pereira, Julieta Silva, Júlia Seixas, Justina Catarino, Kaya Schwemmlein, Luis Fazendeiro, Luis Moreno, Luis Rosa, Luiz Eduardo Rielli, Luís Fialho, Luís Silva, Luísa Schmidt, Madalena Santos, Margarida Magina, Maria Do Carmo Figueira, Maria Fernanda Gomes, Maria João Gonçalves Pedreira, Maria Teresa Ponce Alvares, Matilde Azevedo, Manuel Silva, Manuela Fonseca, Miguel Ferreira, Miguel Luz, Miguel Macias Sequeira, Miguel Marques, Miguel Mascarenhas, Miguel Repas Gonçalves, Miguel Tavares, Nuno Carvalho Figueiredo, Nuno Costa, Nuno Jorge, Nuno Ribeiro Da Silva, Oriana Brás, Patrícia Neto, Pedro Almeida Sousa, Pedro Cardoso, Pedro Fernandes, Pedro Ferreira, Pedro Horta, Pedro Miguel De Almeida Fernandes, Ramon Silva Rey, Raquel Brito, Rita Castro, Rodrigo Duarte, Ross Wallace, Rui Daniel De Oliveira, Rui Manuel Cleto Morgado, Rui Oliveira, Rui Pestana, Samuel Infante, Sara Sacadura Cabral, Saturnino De Almeida, Seda Orhan,, Sílvia Mesquita De Oliveira Gonçalves, Sofia Ribeiro, Soraia Duarte, Susete De Jesus Placido Patricio, Teresa Leonardo, Teresa Maria Veloso Nunes Simões Esteves, Tiago Alexandre Da Palma Veigas, Tiago Guimaraes, Timóteo De Jesus Pimenta Monteiro, Vasco Alves Machado, Vasco Vieira, Vera Ferreira, Yevgeniya Afanasenko.

Finally, the authors express their sincere gratitude to `LPN - Liga para a Protecção da Natureza, WWF Portugal, Quercus, GEOTA - Grupo de Estudos de Ordenamento do Território e Ambiente, and SPEA - Sociedade Portuguesa para o Estudo das Aves for the valuable contributions and suggestions provided during the drafting and review stages of this report. The final content and conclusions are the sole responsibility of the authors and do not necessarily reflect the official position of the organizations mentioned.

Suggested Citation: Girolamo-Neto1, C. D.; Oakleaf2, J. R.; Bhattacharjee3, A.; Sochi2, K.; Pontonio1, M.; Gündüzyeli1, E.; Kiesecker2, J. M. 2026. Smart Siting Guide: Portugal - Balancing energy, conservation, and community priorities in developing ground-mounted solar and onshore wind on low-conflict sites. The Nature Conservancy. DOI: 10.5281/zenodo.18242867

1. The Nature Conservancy, Europe Renewable Energy Programme.
2. The Nature Conservancy, Global Protect Oceans, Lands and Waters.
3. The Nature Conservancy, Global Tackle Climate Change.

Contents

Abbreviations & Acronyms

APA	Portuguese Environment Agency
DIA	Declaration of Environmental Impact
DSO	Distribution system operators
DGEG	Directorate-General for Energy and Geology
E-REDES	Portugal's main distribution network operator
EIA	Environmental Impact Assessment
EU RED	European Union Renewable Energy Directive
GET	Grid-enhancing technologies
GTAER	Working Group for the Definition of Renewable Energy Acceleration Areas
HMI	Human Modification Index
IBA	Important Bird Area
INCF	Institute for Nature Conservation and Forests
KDE	Kernel density estimation
LNEG	National Laboratory of Energy and Geology
mTPI	Average multi-scaled topographic position index
NBSAP	National Biodiversity Strategy and Action Plan
NECP	National Energy and Climate Plan
NRP	National Restoration Plans
NRR	Nature Restoration Regulation
NUTS	Nomenclature of territorial units for statistics
PPGIS	Public Participation Geographic Information System
PV	Photovoltaic solar
PVOUT	Photovoltaic power output
RAAs	Renewable Acceleration Areas
REF	Reference method
REN	Redes Energéticas Nacionais (Portugal's national transmission system operator)
RNAP	National Network of Protected Areas
RNT	Rede Nacional de Transporte (Portugal's high-voltage transmission network, overseen by REN)
SDGs	United Nations Sustainable Development Goals
SEA	Strategic Environmental Assessment
SLOSS	Single large or several small
TSO	Transmission system operators
UNCBD	United Nations Convention on Biological Diversity

Executive Summary

Portugal has made a bold commitment to generate 93% of its electricity from renewable sources by 2030 as part of efforts to urgently address the global climate crisis. Expanding wind and solar energy at this scale requires a thoughtful, science-based approach to deciding where and how to build, taking into consideration the lasting impacts on landscapes, communities, and ecosystems.

This Smart Siting Guide posits an approach that emphasizes the identification and development of areas where there is a high potential for wind or solar power and where renewable energy can be developed with minimal risk to biodiversity and social values. It argues that such low-conflict, high-development-potential sites should be prioritized as Renewable Acceleration Areas (RAAs). Besides RAAs, with appropriate and science-based mitigation measures in place, the careful development of moderate-conflict areas, locations where some risks exist, can also be considered for deploying nature-inclusive ground-mounted solar and onshore wind projects.

This guide uses a clear, evidence-based method to identify the best places for renewable energy development. First, it maps areas with strong technical potential for wind and solar. Then, it applies two critical filters: biodiversity and social values. Biodiversity mapping combines ecosystem and species data, while social mapping highlights landscapes important for communities. Finally, these layers are combined to pinpoint sites with minimal environmental and social risk and high development potential for renewable energy. Stakeholder input was integrated throughout the entire process to ensure transparency and local relevance.

This guide thus offers a practical roadmap for decision makers, renewable energy actors and civil society for spatial considerations of a renewable energy future. It brings together the best available science, policy context, and local knowledge to answer a central question:

"How can Portugal accelerate renewable energy while protecting biodiversity and respecting social values?"

Key Findings

1. Solar Energy

Mainland Portugal has more than five times the low-conflict land needed to meet its 2030 goal for ground-mounted solar. This surplus gives policymakers and developers flexibility to choose sites that work best for both energy and the environment.

2. Wind Energy

Up to 70% of the onshore wind energy target can be met on low-conflict sites. The rest can be achieved by upgrading existing wind farms (e.g., repowering/overpowering) only if enough precautions are put in place and the mitigation hierarchy is implemented correctly, and, adopting strong mitigation measures for development in moderate-conflict areas.

3. Moderate-Conflict Zones

These areas are not off-limits. With careful planning and stakeholder engagement, they offer a strategic reserve for future expansion, with potential biodiversity net-gain co-benefits through nature-inclusive project development as technology and policy evolve.

4. Grid Expansion

Smart siting data can guide where to invest in grid upgrades, focusing on regions with high renewable energy potential and low conflict. This helps avoid unnecessary impacts and supports efficient energy delivery.

5. Social Inclusion

Social value mapping and introduction of participatory community engagement methods highlight the importance of taking into account aesthetic values, listening to communities, ensuring projects reflect people's priorities and deliver lasting benefits.

Policy Relevance

Portugal's approach aligns closely with the European Union's Renewable Energy Directive (RED III), which calls for RAAs, streamlined permitting, and mitigation rulebooks. The Smart Siting Guide provides the spatial evidence needed to:

- Designate RAAs that prioritize low-conflict zones with high development potential.
- Support faster permitting while maintaining environmental safeguards.
- Inform the Strategic Environmental Assessment (SEA) process for the RAA designation.
- Inform permitting authorities for project level screening and Environmental Impact Assessments
- Inform renewable energy developers and transmission and distribution grid operators as they make deployment and upgrading decisions.
- Embed stakeholder engagement and community benefit-sharing processes into national frameworks.
- Adopt holistic spatial plans that address renewables acceleration, grid enhancement, and nature restoration needs.

By integrating these elements, Portugal can meet its National Energy and Climate Plan (NECP) targets while setting a precedent for nature-positive energy development across Europe.

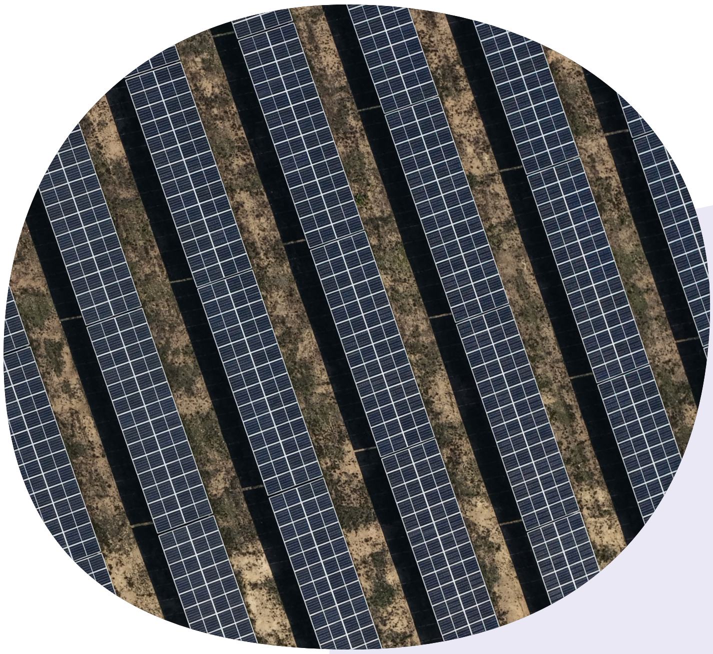
Key Recommendations

No analysis is perfect, and all analyses are dependent on the availability of quality data. This guide acknowledges gaps in fine-scale biodiversity and social data, as well as limitations in grid infrastructure information. In order to strengthen future work, the authors offer the following recommendations:

- Improve access to more detailed ecological and social datasets, as well as up-to-date information on grid locations and grid capacity, through collaboration with national and regional agencies, NGOs, and academic institutions.
- Expand stakeholders to include local communities and specific groups identified through conflict mapping and prioritize engagement efforts where local input is most critical.
- Establish robust monitoring of biodiversity impacts, community responses, and permitting timelines as well as feedback mechanisms to enable iterative improvements to the siting methodology and adaptive management over time.
- Integrate grid expansion modeling into the smart siting analysis and explore advanced modeling, such as co-location of technologies and rooftop solar.
- Improve analysis of the environmental and social impacts of repowering/overpowering existing wind power facilities to better understand the potential benefits and risks.

The Bottom Line

The Portugal case shows that climate ambition and nature protection are not mutually exclusive. By combining rigorous science, transparent mapping, and genuine engagement, the country can meet its energy goals while safeguarding what matters most. The Smart Siting Guide should be read as a blueprint for responsible, inclusive, and forward-looking energy planning, taking a holistic spatial planning approach that considers multiple interests in land use. The tools and lessons here offer a replicable model for balancing climate action with nature and people.



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BOX 1: SMART SITING GUIDE AT A GLANCE

Chapter 1: Introduction

- Frames the urgency of balancing climate action and nature protection.
- Explains the rationale for smart siting.
- Presents Portugal's unique opportunity to align rapid energy expansion with ecological and social priorities.

Chapter 2: The Smart Siting Process

- Explains the technical foundations of the analysis, including modeling renewable development potential and mapping conservation and social values.

Chapter 3: The Potential for Smart Siting in Portugal

- Presents the main quantitative findings, broken down by region.

Chapter 4: How Siting Outcomes Can Aid Portugal's Energy Transition

- Interprets the siting outcomes to assess the practical realities of implementation.

Chapter 5: Insights into Further Action: Beyond RAA Designations

- Shows how spatial data and stakeholder input can inform a variety of real-world decisions and support Portugal's energy transition.
- Provides actionable guidance for infrastructure planning, community engagement, and mitigation strategies.

Chapter 6: Recommendations

- Describes the study limitations.
- Provides recommendations for improving data availability, stakeholder engagement, and monitoring and feedback mechanisms.
- Offers suggestions for future astudies.

Chapter 7: Conclusion

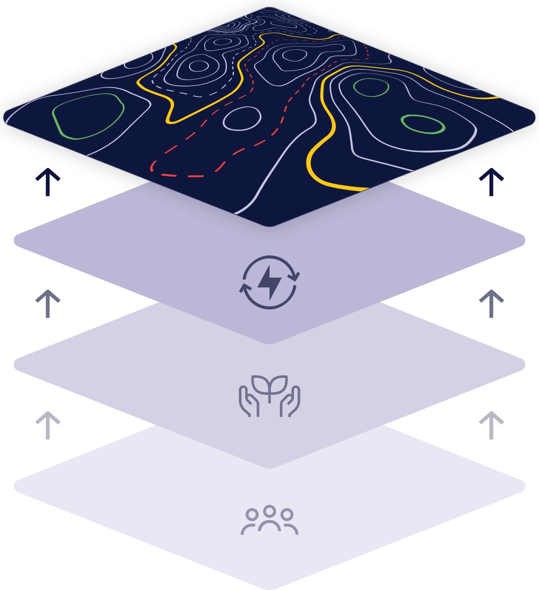
- Presents main takeaways and the broader implications for grid expansion, social inclusion, and EU policy alignment.

Supplements I-VII

- Provide additional technical details, supporting tables and maps, and lessons learned.

Summary of Methodology and Findings

Mapping Methodology:



Map Combination
Layers are combined to identify low-conflict, high-development-potential sites: places with strong technical potential for renewable energy development that pose minimal risk to nature and communities.

Energy Potential Layer
A predictive modelling approach that blends technical criteria and real-world constraints to identify areas where wind and solar projects have the highest likelihood of successful deployment.

Biodiversity Layer
A "coarse-filter/fine-filter" approach that combines ecosystem-level data with species-level information.

Social Value Layer
Landscape aesthetics, cultural heritage, and coastal sensitivity are mapped using national datasets and innovative proxies such as geotagged social media photos.

Key findings and results:

- **Solar Energy:**
  Mainland Portugal has more than five times the low-conflict land needed to meet its 2030 goal for ground-mounted solar.
- **Wind Energy:**
  Up to 70% of the onshore wind energy target can be met on low-conflict sites. The rest can be achieved by adopting strong mitigation measures for upgrading existing wind farms.
- **Grid Expansion:**
  Smart siting data can guide where to invest in grid upgrades, focusing on regions with high renewable energy potential and low conflict.
- **Social Inclusion:**
  Participatory mapping and viewshed analysis highlight the importance of listening to communities. Projects that reflect local priorities are more likely to succeed and deliver lasting benefits.
- **Moderate-Conflict Zones:**
  With careful planning and stakeholder engagement, these zones offer a strategic reserve for future expansion with nature restoration co-benefits, especially as technology and policy evolve.

5X
the low-conflict land needed to meet the **2030 target**.

70%
of onshore **wind** energy target can be met on low-conflict sites.

1.514 km² Total land identified as low-conflict and high-development-potential for **solar**.

267 km² Total land identified as low-conflict and high-development-potential for **wind**.

1. Introduction

An urgent response to the global climate crisis requires a rapid and responsible transition from a fossil-fuel-based energy system toward a renewable-energy-based one, without compromising land conservation or biodiversity protection. Given the spatial demands of renewables, this may seem to pose a contradiction, but both goals can be achieved with a strategic, integrated approach to upfront land use planning. Smart siting of solar and wind infrastructure that optimizes energy supply and demand can help balance the goals of climate mitigation, energy equity, and the preservation of natural heritage. Such an approach can even promote nature-positive outcomes on land degraded by other uses.

Though renewables require more land area per unit of energy than conventional fuels, this is far outweighed by the severe toll that conventional fuels take on the climate, public health, and energy sovereignty. Still, the competition for land use across various sectors makes it challenging to secure the amount of land necessary to transition to renewables at the speed and scale demanded by the climate crisis. Moreover, the rapid expansion of renewable energy infrastructure has sometimes triggered public opposition, not only due to changes in land use, but also as a result of persistent failures to adequately engage the local community and uphold community and land tenure rights.

Beyond the environmental and social consequences, nature degradation poses a systemic economic and financial risk. Extreme weather events, biodiversity loss, and resource scarcity are perceived as top long-term risks for the global economy and sustainable development.[1] In Europe, 19% to 36% of Gross Value Added relies on functioning ecosystems[2] while nature-positive transitions across food, land, ocean use, infrastructure, and energy systems could generate $10.1 trillion in annual business value and create 395 million jobs by 2030.[3]

Portugal has an opportunity to lead this transition by coupling renewable energy development and conservation planning with stakeholder engagement in a way that recognizes the deep interconnections[4] between climate change and biodiversity loss. This document aims to guide readers through a smart siting approach to the acceleration of ground-mounted solar and onshore wind on mainland Portugal in a way that is both actionable and reproducible for policymakers, planners, and stakeholders. (Decentralized solar, including rooftop PV, and offshore wind, as described in Box 6, present significant additional opportunities not included within the main scope of this study.) It emphasizes the development of renewable energy on sites that are in low conflict with biodiversity and social values.

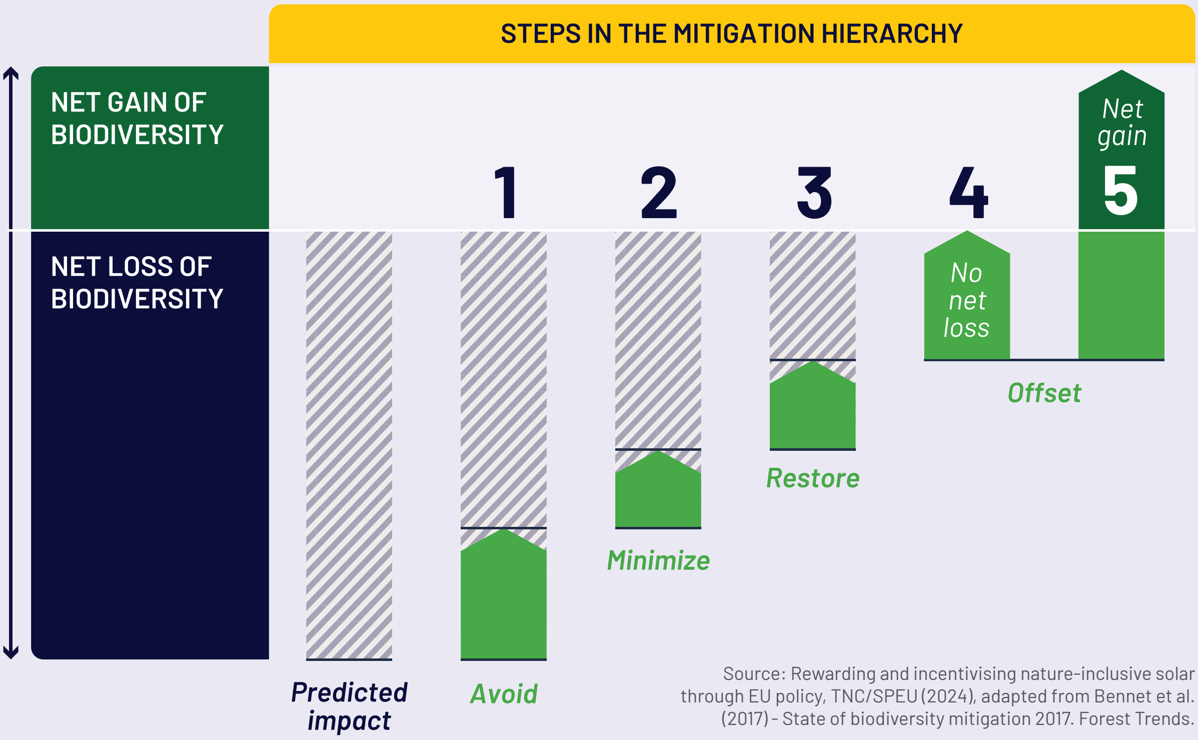
A low-conflict site is defined as a location where renewable energy development is expected to pose minimal risk of significant negative impacts on biodiversity, landscape values, or local communities.[i] These sites are identified through science-based spatial analysis, overlaying areas of low biodiversity and social sensitivity. Building on this, a low-conflict site with high development potential refers to those areas that not only meet the criteria for low-conflict but also demonstrate strong technical feasibility for renewable energy generation, making them priority zones for responsible and efficient project development. Thus, these are the sites that can be considered for future iterations of what have been termed Renewable Acceleration Areas (RAAs).

Critically, low-conflict does not mean "no conflict" and the approach used in this project does not focus on artificial areas or rooftops, but rather on new, non-artificial lands where responsible renewable energy deployment is most feasible and least likely to cause ecological or social harm. Such an approach is in line with Portugal's 2030 climate commitments, against the backdrop of European and global efforts to balance climate mitigation, energy equity, and the preservation of natural heritage.

Our analysis indicates that Portugal can achieve up to 70% of its 2030 target for onshore wind energy by focusing on these low-conflict, high-development-potential areas. Mainland Portugal also has more than five times the low-conflict, high-development-potential land needed to meet its 2030 goal for ground-mounted solar. Projects currently in the pipeline and the repowering/overpowering of existing wind farms can reduce the need to site additional renewables capacity on new land, should they be planned with strong environmental mitigation measures.

[i] The concept of low-conflict siting is technology-neutral and universally applicable to all forms of renewable energy. Rooftop solar and other artificial-area technologies may be considered within the low-conflict framework if suitable data for spatial modeling becomes available.

BOX 2: THE MITIGATION HIERARCHY



Source: Rewarding and incentivising nature-inclusive solar through EU policy, TNC/SPEU (2024), adapted from Bennet et al. (2017) - State of biodiversity mitigation 2017. Forest Trends.

1. **Avoid adverse impacts**, including the consideration of project alternatives.
2. **Reduce impacts** that cannot be avoided.
3. **Restore or rehabilitate damaged ecosystems** or species populations on the site of development.
4. **Offsets** can be used either on-site or off-site as a last resort to minimise residual impacts and achieve no net loss.
5. **Net gain in biodiversity:** offsets can also be used to achieve a net gain in biodiversity.

Repowering involves replacing older, less efficient turbines with modern, higher-capacity models, while overpowering refers to the installation of additional power capacity on existing wind farms, by leveraging untapped network capacity at the existing connection point.[5] Finally, with targeted and science-based mitigation measures, transitional landscapes classified as moderate-conflict zones with high-development-potential represent a strategic reserve of land for wind and solar expansion, offering substantial opportunities to bridge capacity gaps.

This guide details how a smart siting approach, including integrated spatial planning, early and inclusive stakeholder engagement, and robust mitigation measures in line with the mitigation hierarchy (Box 2) can serve as a practical tool for policy, planning, and development. This tool is useful not only for designating and developing RAAs (Chapters 3, 4) but also for a wide range of other applications (Chapter 5), including: guiding potential expansion of the country's power grid; integrating community values into siting decisions; shifting mitigation efforts from fragmented, project-level interventions to coordinated, landscape-level planning; and informing the development of mitigation rulebooks, project level screening and Environmental Impact Assessments (EIAs), Strategic Environmental Assessments (SEAs), and stakeholder engagement frameworks required by EU legislation.

In addition to a thorough explanation of the smart siting methodology in the main guide, an extensive set of supplements allows interested readers to dig deeper into the analysis. These supplements break down potential renewable energy development sites in Portugal by region and conflict level, offer resources for enhancing stakeholder engagement, and provide a framework for blending landscape-level planning with the mitigation hierarchy, among other topics.

In summary, this smart siting approach developed for Portugal exemplifies how integrated spatial planning, stakeholder engagement, and innovative mapping can accelerate the renewable energy transition while respecting nature and communities. By leveraging the country's available low-conflict land, responsibly developing moderate-conflict zones, and aligning grid investments with environmental and social priorities, Portugal is well-positioned to meet its National Energy and Climate Plan (NECP) targets and contribute to the EU's broader decarbonization and biodiversity goals. The lessons and tools developed here offer a replicable model for other countries and regions seeking to balance climate action with conservation and social justice.

1.1 Integrating Energy, Nature Protection, and Restoration Agendas

As demands on land intensify, encompassing climate resilience, biodiversity, and space for renewable energy production, a holistic, cross-sectorial approach is vital to integrate these goals. Smart siting is a critical part of this approach, guiding the expansion of new renewable energy to low-conflict areas, while at the same time protecting high-biodiversity-value areas and investing strategically in restoration to complement biodiversity conservation. Moving beyond simple land allocation, spatial planning policies must adopt landscape-level strategies that recognize the mitigation hierarchy and ensure that renewable energy investments remain competitive enough to replace fossil fuels.

To achieve the 2030 global biodiversity targets, Europe must deliver its fair share by restoring 30% of all degraded ecosystems and conserving 30% of all lands, waters, and seas.[6] In 2020, the EU adopted its National Biodiversity Strategy and Action Plan (NBSAP) to 2030 in order to deliver on the commitments from the bloc and its Member States as parties to the United Nations Convention on Biological Diversity (UNCBD).[7] NBSAPs are the principal instruments through which countries implement the UNCBD.[6] Under the Kunming-Montreal Global Biodiversity Framework adopted in 2022, all parties are required to develop, update, and implement NBSAPs that align with global biodiversity targets. In Europe, NBSAPs are becoming essential tools for aligning renewable energy deployment with biodiversity goals as Member States are required to integrate biodiversity safeguards into energy sector planning.

The EU's NBSAP aims to protect natural resources in line with the UNCBD targets and implement national strategies and action plans to achieve this. As part of its plan to deliver for the 2030 biodiversity targets, the EU adopted the landmark Nature Restoration Regulation (NRR)[8] to reverse biodiversity loss and restore degraded terrestrial and marine ecosystems. It sets a binding target to restore at least 20% of the EU's land and sea areas by 2030 and all ecosystems in need of restoration by 2050, while mandating that Member States develop National Restoration Plans (NRPs) that outline how these targets will be met.[8]

Existing examples in Europe and globally show the feasibility and benefits of incentivizing nature-integrated renewable energy development on degraded lands with low biodiversity value.[9] A smart siting approach thus sits at the nexus of energy transition and ecological conservation, supporting the competitiveness agenda by de-risking projects and streamlining permitting processes to avoid unnecessary delays.

1.2 Legal Frameworks for Renewable Energy in Portugal

Legal Frameworks for Renewable Energy in PortugalUnder International agreements, including the Paris Agreement, have set the goal to limit global warming to a maximum increase of 1,5°C by 2030.[10] Achieving this target requires a rapid acceleration of the renewable energy transition. In parallel, the United Nations Sustainable Development Goals (SDGs), particularly SDG7 (affordable and clean energy) and SDG15 (life on land), reinforce the need to expand access to sustainable energy while reversing land degradation.[11]

Portugal's embrace of comprehensive energy and spatial planning has positioned it as an early leader in the field. It is one of the frontrunners in renewable energy deployment in Europe, aiming to generate 93% of its annual electricity production from renewable sources by 2030, compared to 61% in 2023.[5] The revised target reflects Portugal's commitment to become one of the leading EU countries in renewable energy integration, aligning with the bloc's broader decarbonization and energy independence goals. In May 2025, 77% of the country's electricity consumption was supplied by renewable energy sources, with solar energy accounting for 17%, the highest monthly share ever recorded for this technology, according to national transmission system operator Redes Energéticas Nacionais (REN).[12] In order for Portugal to achieve its ambitious goals, the country needs to be flexible in tackling the challenges around optimizing available land and energy infrastructure.

National legal frameworks shape this process. Under Decree n.° 72/2022,[13] municipalities may reject projects on landscape-heritage grounds if renewable occupancy exceeds 2% and the project lacks a favorable Declaration of Environmental Impact (DIA).

“The overall goal of this Smart Siting Guide is to provide national and local authorities, developers, and other key stakeholders with actionable insights to drive policy and implementation dialogue for both renewable energy acceleration and nature conservation.”

This mainly affects smaller projects (less than 100 hectares), as large projects typically require a DIA that overrides municipal disapproval. Recent regulatory changes[14] further streamline permitting by exempting solar projects under 100 ha outside sensitive areas from Environmental Impact Assessment (EIA) requirements and allowing wind farm repowering without environmental authority input unless within protected zones. While these measures aim to accelerate deployment, the shortened consultation periods risk leaving high-biodiversity-value areas unprotected. Without a closer look at the project areas through the mitigation and spatial planning lens, this puts the renewables acceleration at risk while raising concerns about nature conservation.[15]

Following the national entry into force of the revised amendments to the European Union's Renewable Energy Directive (EU RED),[16] the government of Portugal formally established the Working Group for the Definition of Renewable Energy Acceleration Areas (GTAER) in December 2023, coordinated by the National Laboratory of Energy and Geology (LNEG).[17] The group published in March 2024 a third edition of the original Renewable Go-To Areas map developed by LNEG in 2022, which outlines the most recent suitable locations for onshore renewable energy.[18] The areas identified in this third edition are assessed through a SEA that started in late September 2025, with the goal of creating a draft version of a renewable energy sectorial plan by April 2026, which will strictly define the RAAs as well as the implementation guidelines for each area.

Moreover, the National Strategy for Nature Conservation and Biodiversity 2030[19] is currently undergoing public consultations as part of the transposition process of implementing the EU NRR.[20] In parallel to the process around final designation of RAAs, these national transposition processes provide a unique opportunity for Portugal to pioneer a holistic, landscape-level approach to upfront spatial planning and mapping that aligns rapid renewable energy expansion with land planning, ecological restoration, biodiversity protection, and social equity.

1.3 Study Design and Applications

This guide supports Portugal's climate and energy commitments by introducing a comprehensive spatial planning approach that integrates several innovative elements: **i)** modeling of energy development potential for solar and wind, **ii)** a coarse-filter/fine-filter biodiversity mapping framework, and **iii)** social values mapping including a viewshed analysis. By combining these methods, the guide expands upon traditional siting approaches with the aim of complementing their use cases by various actors to responsibly and efficiently deploy renewable energy.

Building on GTAER's report,[21] this study moves beyond existing approaches by integrating energy development potential models for both solar and wind directly into spatial planning. Though this study could not address the grid congestion issues in Portugal, these models account for a wide range of other technical and energy resource constraints, while also integrating feasibility measures to ensure that only areas with high development potential are selected. This avoids the common pitfall of designating sites that lack the technical or resource viability needed for economically sustainable renewable projects, thereby providing developers and policymakers with a more reliable and actionable foundation for decision-making.

Additionally, the application of a coarse-filter/fine-filter approach to biodiversity mapping enhances the siting process by integrating both ecosystem-level and species-level data. Rather than simply excluding areas from development, this method supports informed decision-making by identifying where mitigation measures may be necessary, allowing for more responsible and context-aware renewable energy siting. Additionally, the biodiversity approach can further enrich the SEA process and form the backbone of a future Mitigation Rulebook, to be attached to the final RAAs of Portugal (Supplement VI) under EU RED policy mandates.

Social values mapping, including the use of viewshed analysis, is a novel addition to renewable energy planning in Portugal. By identifying landscapes sensitive to tourism and visual aesthetics, planners can anticipate and address potential social resistance, facilitating community acceptance and better project outcomes.

The analysis in this guide further advances spatial planning by also identifying moderate-conflict zones where development could occur in certain circumstances, guided by the Mitigation Hierarchy framework (see Box 2). This expanded approach provides site-specific guidance for responsible renewable energy deployment, enabling planners and developers to address potential challenges through targeted mitigation and restoration measures.

The overall goal of this Smart Siting Guide is to provide national and local authorities, developers, and other key stakeholders with actionable insights to drive policy and implementation dialogue for both renewable energy acceleration and nature conservation.

The spatial data presented can guide mitigation recommendations for future projects, can be integrated with municipal spatial planning, and can inform other cross-cutting land use and land-conversion processes, including:

- **National-level renewable energy spatial planning and RAA iterations:** This guide supports ongoing SEA processes in alignment with national energy targets, equipping authorities to screen projects for RAA deployment. Developers are empowered to de-risk their investments by anticipating permitting challenges and identifying optimal sites (Chapters 3, 4).

- **Solar and wind opportunities beyond the low-conflict, high-development-potential lands:** Apart from strictly protected areas (as per RED III), we highlight regions with high energy development potential where there may be conflicts with biodiversity or social values. These do not automatically represent complete exclusions; rather, they require sophisticated planning, stakeholder engagement, and robust mitigation measures. This data can be used to inform mitigation rulebooks. Developers can use spatial data to anticipate and address potential conflicts with biodiversity values through micro-siting and tailored mitigation/restoration plans, supporting a nuanced and case-specific approach aligned with national and EU permitting frameworks (Section 4.1).

- **Guiding power grid expansion opportunities:** This guide provides methodologies of using low-conflict maps coupled with resource potential models to strategically identify zones poised for current and/or future development, contingent on current infrastructure capacity and potential upgrades. Both national and local methodologies are presented, with a focus on targeting where expansion planning can occur to help incentivize development in low-conflict lands (Section 5.1 and Supplement II).

- **Viewshed analysis for landscape sensitivity:** By mapping visibility from locations with significant aesthetic or sociocultural importance, the viewshed analysis helps planners assess potential social resistance due to visual impacts (Chapter 3). Early adjustments to siting and project design can reduce conflict and facilitate community acceptance, as shown in a pilot participatory mapping exercise in Silves, where local stakeholders identified areas of cultural, agricultural, biodiversity, and tourism value (Section 5.2 and Supplement V).

- **Guiding a national-level mitigation framework:** Biodiversity and social data can inform strategies for offsets and restoration, maximizing return on investment for ecological outcomes. This is particularly relevant for progressive developers, renewable energy procurement processes, and future auctions that include non-price criteria.[22] The data can also support coalitions for nature-positive development (e.g., act4nature[23]) and inform the debate around Portugal's National Strategy for Nature Positive Spatial Planning (Section 5.3 and Supplement IV) and discussions around introducing nature credits.[24]

2. The Smart Siting Process

The smart siting methodology is structured around four innovative core components[25,26] on which the structure of this chapter is based:

i) Modeling wind and solar development potential: Describes the workflow for generating probabilistic development potential maps for wind and solar, including data sources, modeling techniques, and validation.

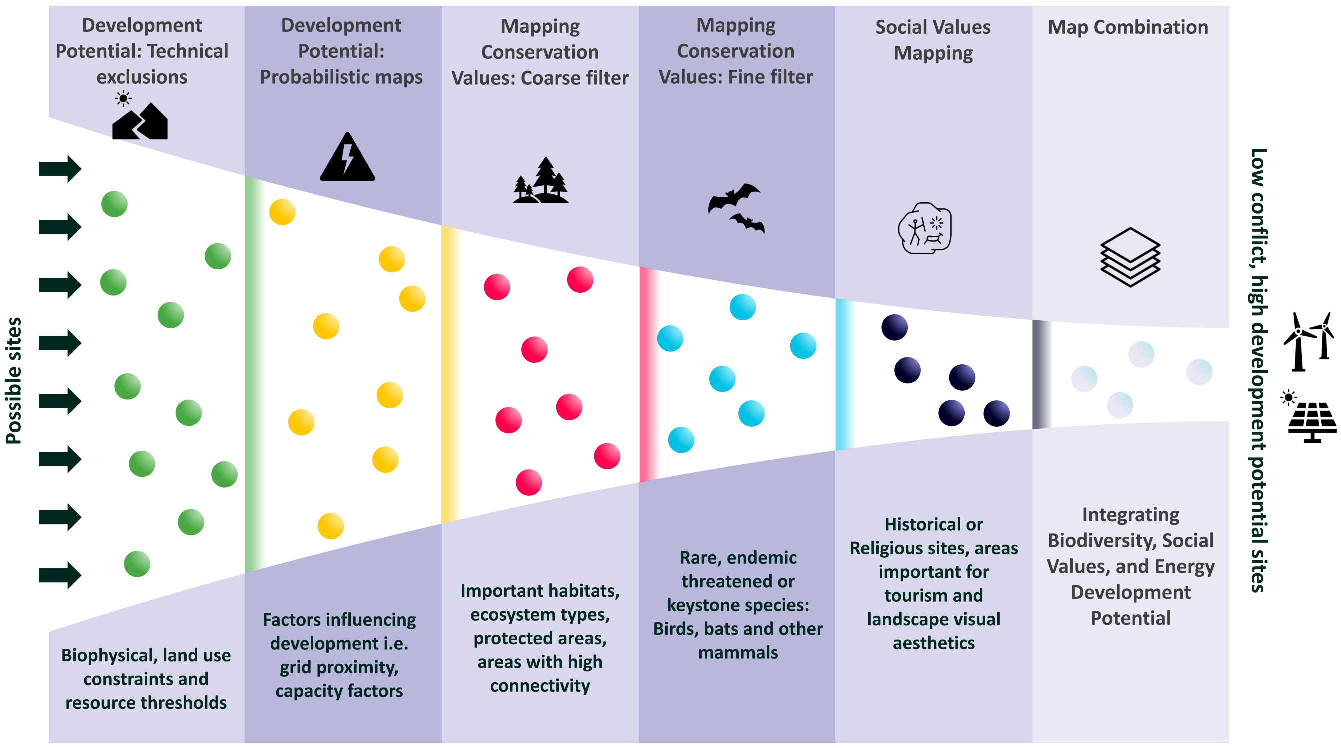
ii) Mapping conservation values through a coarse-filter/ fine-filter framework: Details the methodology for mapping biodiversity values, combining ecosystem-level and species-level data to identify areas of ecological importance.

iii) Social values mapping, including viewshed analysis: Explains the integration of selected indicators (identified in our study as visual aesthetics, sociocultural features, and coastal sensitivity zones) to map areas of social value and potential conflict.

iv) Map combination: Outlines the process for overlaying the three core layers to identify low-conflict, high-development-potential sites for renewable energy, and describes the framework for conflict-sensitive planning.

By combining the first three methods in this final step, the guide moves beyond traditional siting approaches, offering actionable insights for responsible and efficient renewable energy deployment (Figure 1).

FIGURE 1: The Smart Siting Process



“Early and inclusive engagement helps identify values that require spatial representation, builds trust, and reduces the risk of opposition or project delays.”

Stakeholder engagement is a foundational element of the smart siting approach, ensuring that renewable energy planning is both scientifically robust and socially legitimate. By involving a diverse range of stakeholders, including public authorities, industry, civil society, academia, and members of local communities, throughout the process, we were able to gather critical data, validate spatial priorities, and integrate local perspectives into technical analyses. Early and inclusive engagement helps identify values that require spatial representation, builds trust, and reduces the risk of opposition or project delays. In contrast, late or one-sided consultations often result in backlash, project cancellations, and reputational harm, ultimately slowing the energy transition. In Supplement IV, we show the variety of formats used, key outcomes, lessons learned, and recommendations for future engagements.

All data used (Table 6) or produced for this smart siting analysis are available in open data formats compatible with any GIS software and can be downloaded from the TNC website, including a technical annex with the detailed methodology.

2.1 Modeling Wind and Solar Development Potential

Our energy modeling analysis focuses on creating probabilistic development potential maps to predict future locations of onshore wind turbines (wind) and ground-mounted photovoltaic solar farms (PV) across mainland Portugal. These maps assign a relative likelihood of development to each location, ranging from 0 (highly unlikely) to 1 (highly likely), and are instrumental for anticipating where potential impacts from renewable energy expansion may occur.[27]

Using publicly available mapped locations of past and current developments, our methodology combined spatial processing with advanced spatial statistical modeling.[28-32] We selected the non-parametric, probabilistic Random Forest algorithm[33] and applied this bootstrapped Classification and Regression Trees approach for modeling both wind and PV development potential. This modeling technique required three key data products: 1) a map of current wind and PV development; 2) a map of technically suitable lands where development can go in the future; and 3) a suite of spatial parameter maps representing known drivers of renewable energy siting. The step-by-step methodology is summarized in Box 3.

Initial draft wind and PV development potential maps were presented to an expert working team in September 2024 and then to key Portuguese stakeholders (LNEG and APREN) in December 2024 and February and July 2025. During the PV model validation, we observed that the drivers of development differed between small-scale (less than 10 hectares) and large-scale (more than 10 hectares) PV projects. This data-driven insight led us to split the PV modeling by size class, using a 10 hectares threshold, which was determined by the median size of all solar farms in our dataset and closely aligns with the 5 MW capacity cutoff commonly used to define utility-scale solar projects.[40] This increased accuracy measures associated with our PV model and provided opportunities to compare different development scenarios.

Due to high grid saturation and congestion in Portugal, two additional models were developed: one that excluded substation parameters, and another that excluded all power-grid-related parameters. These versions helped to identify development drivers beyond grid infrastructure and offered insights into where grid expansion might be needed to meet long-term renewable energy targets (Section 5.1 and Supplement II). In total, our modeling effort produced nine intermediate development potential maps (three for wind, three for large-scale PV, and three for small-scale PV). These were used to generate one final wind development potential map and two final PV development potential maps (split by size). From these, we identified technically suitable areas with high development potential (greater than or equal to 0,65) for each technology. These binary maps were then integrated with biodiversity and social value layers as part of the smart siting analysis for Portugal.

To ensure our energy modeling aligns with Portugal's renewable energy targets, we performed a capacity gap analysis (Section 3.2) based on the NECP.[5] This involved comparing the projected installed capacities for onshore wind and centralized solar in 2030 with the expected capacities in 2025, allowing us to quantify the additional capacity needed for each technology. By establishing these benchmarks, we can determine how much new renewable energy must be sited and can correlate these numbers with the areas identified by our modeling efforts (Chapter 4).

BOX 3: NINE-STEP PROCESS TO ULTIMATELY PRODUCE EACH DEVELOPMENT POTENTIAL MAP

1. **Map existing development:**
   Create validated maps of current wind and PV installations across mainland Portugal.

2. **Identify technically suitable lands:**
   Map areas suitable for future wind and PV development by applying technical exclusion criteria.

3. **Generate presence/absence data:**
   Derive point locations for existing (present) and non-developed (absent) renewable energy sites to support predictive modeling.

4. **Map influential parameters:**
   Identify and map spatial parameters known to influence wind and PV development (e.g., slope, grid proximity, capacity factors).

5. **Build training dataset:**
   Assign parameter values to all present and absent locations to create a comprehensive training dataset.

6. **Select key parameters:**
   Use the rfUtilities package in R to remove highly correlated variables and select the most significant predictors for the model development.[34-38]

7. **Run Random Forest models:**
   Apply the ranger package in R to build ensemble Random Forest models for wind and PV development potential.[39]

8. **Validate model performance:**
   Assess model accuracy using metrics like log loss, Cohen's Kappa, and AUC/ROC to ensure reliability.

9. **Generate development potential maps:**
   Apply the final models across technically suitable lands to produce probabilistic maps of future wind and PV development potential.

2.2 Mapping Conservation Values

Mapping biodiversity values is a key step to ensure that renewable energy development avoids ecologically sensitive areas and long-term conservation goals. The methodology adopted in Portugal builds on the coarse-filter/fine-filter framework, a widely accepted conservation planning approach.[26,41,42]

The **coarse filter** is designed to represent broad ecological patterns by capturing entire ecosystems and habitat types. The underlying principle is that by protecting representative examples of these systems, such as forests, wetlands, or grasslands, most species and ecological processes will also be conserved. In Portugal, the coarse filter was constructed by integrating three spatially explicit ecological parameters: extent, connectedness, and rarity (Box 4).

BOX 4: THE COARSE FILTER LAYERS

Extent:

This layer quantifies the distribution and composition of land-cover types favorable to biodiversity (e.g., based on capacity to sustain ecological functions), using national land use and land-cover maps.[43,44] Expert consultation was essential to assign biodiversity favorability scores to each class, ensuring these reflect the overall ecological context of Portugal.

Connectedness:

This layer assesses the structural connectivity of favorable habitats, supporting ecological processes such as species movement, gene flow, and climate adaptation.[45] This was derived from the extent layer using moving window analyses, emphasizing landscape-scale function and resilience under climate and land use change.[46]

Rarity:

This layer identifies areas of elevated conservation importance that may not be fully captured by extent or connectedness alone. This layer combines protected areas (e.g., Natura 2000, Ramsar wetlands, National Network of Protected Areas/RNAP) with ecologically significant features such as Important Bird Areas (IBAs) and riparian vegetation buffers. Expert inputs expanded this scope to include areas under forestry regimes and bioenergetic reserves, reflecting the biodiversity potential of managed landscapes. The Human Modification Index (HMI) was used to adjust biodiversity scores based on the degree of anthropogenic disturbance.[47]

The **fine filter** complements the ecosystem-level perspective of the coarse filter by focusing on species that may not be adequately protected through broad-scale habitat representation. It targets rare, endemic, threatened, or keystone species and their critical habitats. In Portugal, fine-filter sensitivity maps were developed for three major taxonomic groups: birds, bats, and other mammals, using two primary datasets (Table 6): National Atlas data[48-53] and Area of Habitat models.[54]

For both filters, statistical analyses and expert knowledge were used to define three conflict categories: low, moderate, and high. For the coarse filter, this involved identifying key transitions in habitat quality, connectivity, and rarity representation. For the fine filter, the process focused on how different levels of species presence translate into ecological risk, ensuring that areas with higher concentrations of threatened species were appropriately flagged. The final step involved combining both filters into a unified biodiversity conflict classification. This was done by cross-referencing the categorical outputs of each filter into a matrix of nine possible combinations. Each combination was grouped into five conflict categories: low, moderate-low, moderate, moderate-high, and high (Table 1).

TABLE 1: Descriptions of combined biodiversity conflict categories for the biodiversity conflict map

LOW-CONFLICT

Areas where both filters agree on minimal biodiversity sensitivity, making them strong candidates for renewable energy development with reduced ecological risk. These areas are typically characterized by low species presence, poor habitat connectivity, and absence of rare or protected habitats.

MODERATE-LOW CONFLICT

Areas where ecosystem-level sensitivity is moderate, but species-level sensitivity remains low. These landscapes may support broader ecological functions but do not host species of high conservation concern. These areas may be suitable for development with minimal ecological risk, provided that appropriate safeguards are in place.

MODERATE-CONFLICT

Areas where species of conservation interest are moderately present, and ecosystem-level sensitivity is also evident but not dominant. While not classified as critical, they warrant careful planning and ecological review.

MODERATE-HIGH CONFLICT

Areas with high species-level sensitivity that are not flagged as ecologically critical by the coarse filter. These zones often lie adjacent to protected areas and may serve as important corridors or buffer habitats, supporting species movement and ecological connectivity. Their elevated fine-filter values indicate the presence of sensitive or threatened species, making them ecologically significant despite moderate or low ecosystem-level indicators. These areas require careful planning consideration to avoid unintended impacts on biodiversity.

HIGH-CONFLICT

Areas with elevated conservation value as identified by the coarse filter, regardless of species-level sensitivity. These zones include protected areas, rare habitats, and landscapes with high ecological connectivity, all of which are essential for maintaining ecosystem integrity. Due to their critical role in biodiversity conservation, development in these areas is strongly discouraged.

2.3 Social Values Mapping

Mapping social indicators is a critical component for assessing renewable energy projects. In our study, we identified landscape aesthetics (viewshed layer), cultural heritage (sociocultural values layer), and coastal dynamics (coastal sensitivity layer) as important values to consider when ensuring socially sensitive development in Portugal. Each serves as a coarse filter to identify areas of potential social conflict or heightened community value.

The **viewshed layer** is based on a national-scale visibility analysis anchored in a "landscape value" dataset derived from geotagged social media content, primarily from Flickr. This innovative method leverages the spatial distribution of user-generated photographs to map areas of perceived scenic, recreational, or cultural value. By identifying locations with greater concentrations of uploads, we pinpointed key viewpoints that are likely to influence social sensitivity to land use change. Our viewshed analysis also used a digital surface model and established buffer distances to delineate zones where renewable energy infrastructure would be most visible and potentially contentious. This approach provides a data-driven proxy for public perception of landscape value, complementing traditional, resource-intensive methods such as surveys or participatory mapping.

The **sociocultural values layer** synthesizes authoritative national datasets of cultural heritage and archaeological sites, including classified monuments, protection zones, documented archaeological sites, and public interest trees. These datasets were harmonized and merged into a single binary raster, highlighting areas of concentrated cultural or archaeological significance. The resulting layer captures both formally protected sites and broader zones of societal importance, ensuring that spatial planning for renewables accounts for Portugal's rich cultural landscape.

The **coastal sensitivity layer** was developed to flag areas along the Portuguese coastline and adjacent islands that are particularly vulnerable to landscape change and dynamic coastal processes. Using a relatively conservative approach, this layer applies a 2 km buffer inland from the shoreline, encompassing both natural and cultural assets that may be affected by renewable energy development. The coastal sensitivity zone is especially relevant for projects near the sea, where visual, ecological, and economic impacts often intersect.

To provide a comprehensive and precautionary screening tool for social conflict, we integrated these three layers into a single social values map. All layers were rasterized at 100 m resolution and clipped to the study area, ensuring spatial alignment and comparability. The integration followed a logical union approach: any cell flagged as sensitive in at least one layer, whether due to visual prominence, cultural heritage, or coastal protection, was classified as a social conflict zone on the final map. This method captures all potential sources of social sensitivity, prioritizing a precautionary approach.

2.4 Map Combination: Integrating Biodiversity, Social Values, and Energy Development Potential

A central objective of the Portugal smart siting project was to identify areas where renewable energy development potential can be maximized with minimal ecological and social conflict. This was achieved through the integration of the three core layers described in this chapter: biodiversity, social values, and energy development potential. In addition to identifying low-conflict sites, the results of the combined maps also reveal areas with moderate-conflict. The steps to map combination are described below:

1. Identifying low-conflict, high-development-potential sites

To strategically guide renewable energy development, we first constructed a unified low-conflict map by overlaying biodiversity sensitivity and social value layers. A location qualifies as low-conflict only if:

- It is identified as low-conflict in the biodiversity layer, and
- It is not flagged as high-conflict in the social value layer.

Such areas represent zones where the risk of biodiversity disruption and social opposition is minimal, making them suitable candidates for further analysis. Building on this foundation, we identified sites with both low conflict and high development potential for renewable energy.

This was achieved by combining the low-conflict map with energy development potential maps, applying a threshold (development potential greater than or equal to 0,65) to define high potential.

A site is classified as low-conflict, high-development-potential if:

- It is identified as low-conflict in the unified map (both biodiversity and social criteria), and
- It is classified as high-development-potential in the energy maps.

This process was conducted separately for solar and wind technologies, resulting in distinct sets of priority areas for each. The outcome is a targeted selection of sites where renewable energy projects can proceed with minimal ecological and social risk, and with strong technical feasibility.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"Together, these steps create a transparent, science-based framework for conflict-sensitive renewable energy planning."

2. Estimating land requirements

Following the low-conflict, high-development-potential map and using the capacity gap analysis (Section 3.2), we estimated the land requirements needed to meet Portugal's 2030 energy targets. This calculation uses two power density assumptions for each technology, a conservative value (low power density) and an optimistic value (high power density), reflecting different scenarios for renewable energy efficiency. For wind, we considered an additional value of power density recommended by Portuguese energy experts.

By multiplying the additional capacity required by the power density assumptions, we derived estimates of land need for both wind and solar. We also calculated the estimated repowering/overpowering capacity (Box 5) for wind turbines in Portugal and all projects (wind and solar) that are in the pipeline (either under construction or pursuing approvals; Box 5).

We used these numbers to reduce the land requirements and establish alternative development pathways based on current and planned renewable energy infrastructure.

3. Final smart siting results

Together, these steps create a transparent, science-based framework for conflict-sensitive renewable energy planning. In addition to highlighting low-conflict, high-development-potential sites, the map combination process also reveals areas with moderate conflict, where development may still be feasible if guided by mitigation hierarchy principles and enhanced safeguards. Such areas offer opportunities for responsible expansion, especially when paired with additional mitigation measures or cultural heritage preservation strategies. This integrated approach supports both the acceleration of renewable energy deployment and the protection of Portugal's ecological and social values.

3. The Potential for Smart Siting in Portugal

The quantitative and spatial outcomes of the smart siting analysis, showing how much and where land in Portugal is suitable for renewable energy development when biodiversity, social, and technical criteria are taken into consideration, show great potential for accelerating the energy transition in Portugal.

The findings show that sites with high-development-potential for wind comprise 2.223 km^2 (2,5% of mainland Portugal), concentrated in the North and Center regions, which contain approximately 67% of the total land in this category. When it comes to solar energy, 15.594 km^2 of land (17,5% of mainland Portugal) has high-development-potential, led by the Alentejo region with 43% (approximately 6.758 km^2) of the high solar development potential land.

Meanwhile, the low-conflict mapping process shows that areas with low potential for conflict based on social and biodiversity criteria comprise 11.355 km^2 (12,7%) of mainland Portugal. Thus, the priority zones for renewable energy development – those that are both low-conflict and high-development-potential – total 1.514 km^2 for solar and 267 km^2 for wind.

3.1 Low-Conflict and High-Development-Potential Sites

Our analysis finds that 2.223 km^2 (2,5% of mainland Portugal) has high development potential for onshore wind (development potential greater than or equal to 0,65), after applying all technical exclusions (Figure 2a). These areas are predominantly concentrated in the North and Center NUTS II regions, which together account for nearly 1.495 km^2 (more than 67% of all land with high development potential for wind in Portugal). Other regions, such as the Algarve and the West and Tagus Valley, also feature significant high-development-potential zones, with 259 km^2 and 236 km^2, respectively. For ground-mounted solar, the final development potential map identifies 15.594 km^2 (17,5% of mainland Portugal) as having high development potential for new projects (Figure 2b). More than 43% of high-development-potential land for solar, or 6.758 km^2, is located in the Alentejo region. An additional 44,5% of such areas is well distributed among the Center, West and Tagus Valley, and Algarve regions, with approximately 6.938 km^2 of high-development-potential sites for solar PV.

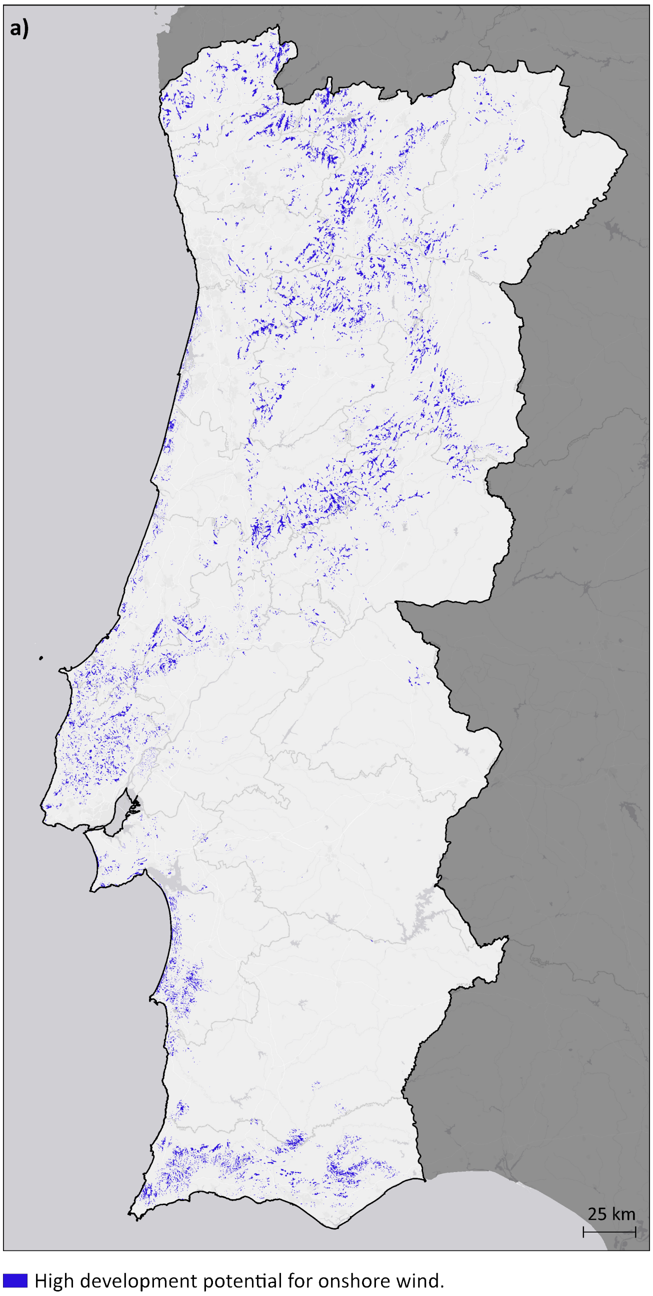
The integrated biodiversity conflict map shows that low-conflict sites cover 12.073 km^2 (Figure 3a), representing approximately 13,6% of the country's mainland, while moderate-low conflict sites account for 5.672 km^2 (6,4% of the country). Moderate-conflict sites comprise 27.308 km^2, or 30,6% of mainland Portugal, and moderate-high conflict sites total 9.894 km^2 (11,1% of the country). High-conflict areas, which indicate strong conservation priorities, encompass 34.154 km^2, making up 38,3% of the national territory.

For the social values mapping, the viewshed analysis identified approximately 1.260 km^2, representing about 1,4% of mainland Portugal, as having high visual/aesthetic sensitivity. The sociocultural values layer highlights zones of concentrated cultural or archaeological significance covering approximately 4.556 km^2. The coastal sensitivity layer identifies 1.846 km^2 of land as sensitive to landscape and coastal dynamics. The final combined social conflict map, where at least one source of social sensitivity is present, identifies 7.269 km^2, approximately 8,2% of mainland Portugal as high social conflict zones (Figure 3b).

The final step of this study was the creation of a unified low-conflict map for Portugal, which reveals that 11.355 km^2, or 12,7% of mainland Portugal, are classified as low-conflict, primarily concentrated in the Center (6.282 km^2) and West and Tagus Valley (2.577 km^2) regions.

Building on the unified low-conflict map, we developed low-conflict, high-development-potential maps for both technologies. This process was conducted separately for solar and wind, resulting in distinct sets of suitable sites for each technology. As identified in Table 2 and Figure 4, a total of 1.514 km^2 of land was identified as both low-conflict and high-development-potential for solar, while for wind, the corresponding area was 267 km^2.

FIGURE 2: High-development-potential sites for a) onshore wind and b) ground-mounted solar.



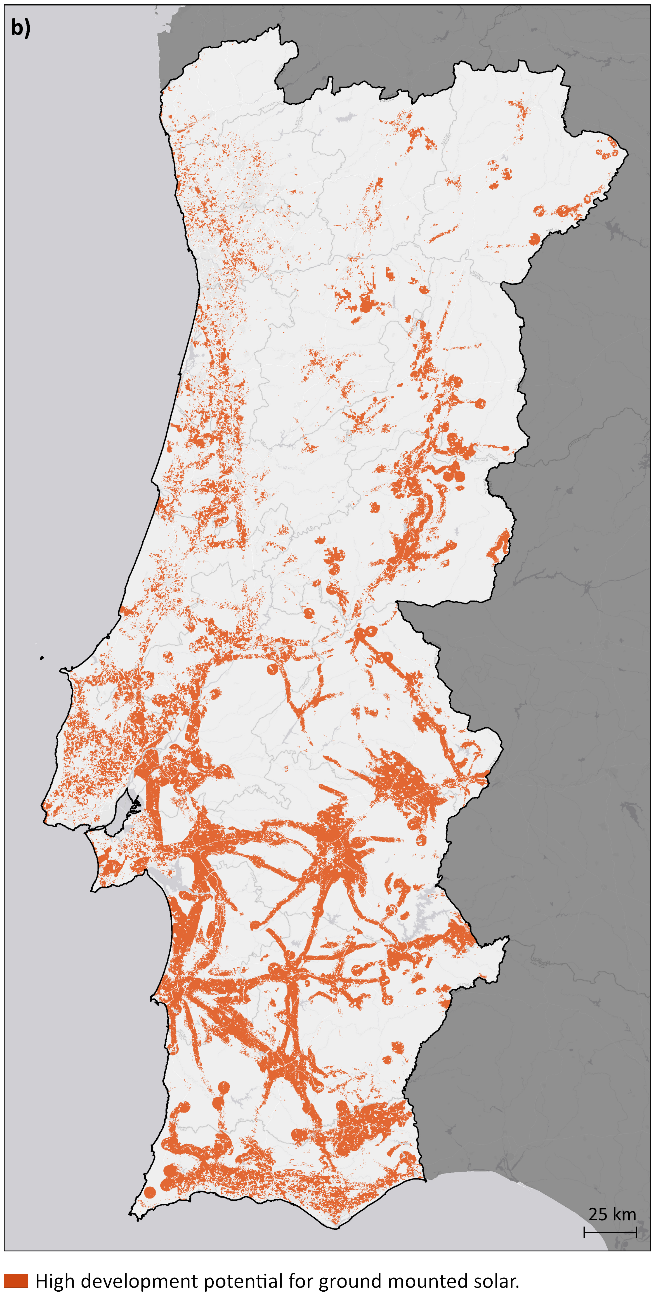
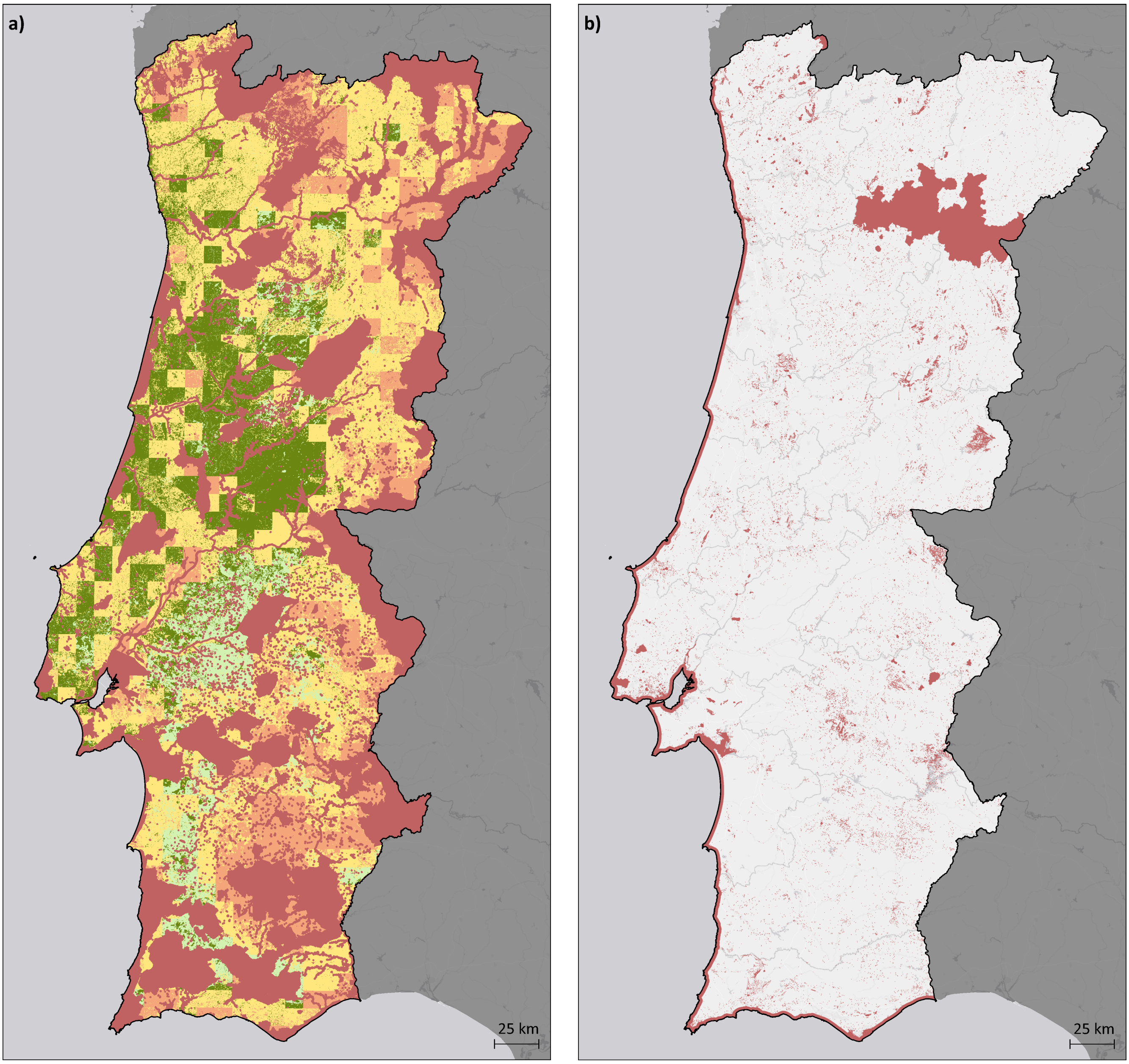


FIGURE 3: Conflict mapping for a) biodiversity and b) social values.



Biodiversity conflict map: Low | Moderate-low | Moderate | Moderate-high | High

Social high conflict sites.

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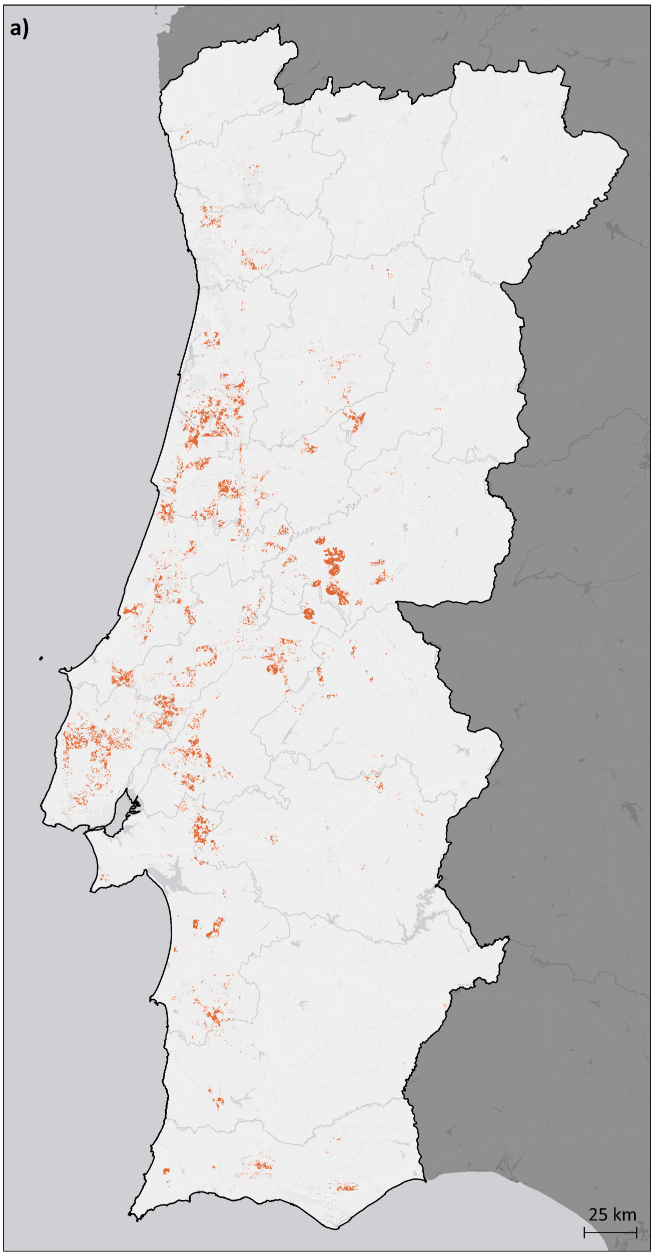
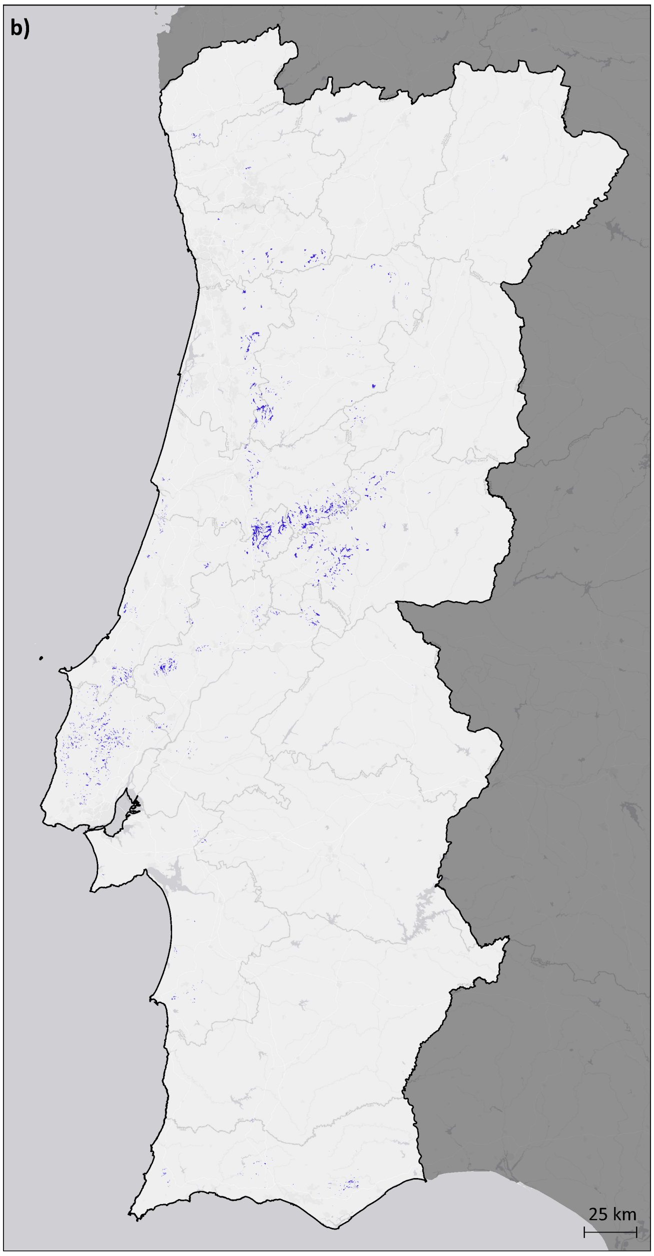
FIGURE 4: Low-conflict, high-development-potential sites for a) ground-mounted solar and b) onshore wind.



Low conflict, high development potential sites for ground mounted solar.



Low conflict, high development potential sites for onshore wind.

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TABLE 2: Land area results in km^2 from the Smart Siting for Portugal[ii] study for all the NUTS II regions, where high-development-potential refers to a value greater than or equal to 0,65

NUTS II	Wind High-Development-Potential	Solar High-Development-Potential	Biodiversity Low-Conflict	Social High-Conflict	Combined Low-Conflict on Biodiversity + Social Maps	Wind Low-Conflict, High-Development-Potential	Solar Low-Conflict, High-Development-Potential
Alentejo	145,69	6.758,37	602,13	1.176,22	588,74	2,83	154,16
Algarve	259,46	1.930,95	124,36	613,70	111,07	6,52	48,65
Center	688,61	2.865,58	6.449,79	1.249,73	6.282,63	158,24	659,14
Greater Lisbon	58,45	381,56	362,61	357,75	284,98	9,34	49,33
North	806,56	966,78	1.688,42	3.142,12	1.369,38	24,24	59,78
West and Tagus Valley	236,02	2.141,86	2.686,05	412,49	2.577,02	65,45	493,53
Setúbal Peninsula	28,37	548,63	160,08	317,31	141,19	0,67	50,27
Portugal	**2.223,16**	**15.593,73**	**12.073,44**	**7.269,32**	**11.355,01**	**267,29**	**1.514,86**

3.2 Assessing Additional Capacity to Meet the NECP Targets

Finally, we assessed the energy capacity gaps for Portugal by quantifying the additional capacity required to meet the 2030 targets set out in the revised NECP.[5] For centralized solar, the NECP establishes a 2030 target of 15,1 GW, with an estimated 6,1 GW expected to be installed by the end of 2025. This leaves a gap of 9 GW for solar that must be deployed within the next five years. Similarly, for onshore wind, the 2030 target is 10,4 GW, compared to a projected 6,3 GW by 2025, resulting in a need for an additional 4,1 GW of new wind capacity. The estimated needs for new capacity, however, should also consider the projects that are in the process of licensing or construction and so, currently in the pipeline, which account for additional 4,74 GW of solar and 0,53 GW of wind (see box 4). Although all this capacity is still uncertain, not installed and may not have followed a smart siting approach, it is important to consider it in the estimations of the capacity needed to meet NECP targets.

In order to assess whether the mapped low-conflict, high-development-potential areas are sufficient to meet Portugal's renewable energy targets, two power density scenarios were assumed for each technology: a conservative (low power density) scenario and an optimistic (high power density) scenario. For solar, the conservative power density is 30 MW/km^2, while the optimistic scenario sets a figure of 69 MW/km^2. Using these assumptions, meeting the additional 9 GW solar target would require approximately 300 km^2 of land under the conservative scenario, or just 131 km^2 for the optimistic scenario.

For wind, with a conservative power density of 7,1 MW/km^2 and an optimistic scenario of 19,8 MW/km^2, the 4,1 GW target translates to a land requirement of 577 km^2 or 207 km^2, respectively. Following feedback received during expert meetings, Portuguese stakeholders established that the power density of 11 MW/km^2 is a good average value to be used across the country. Using this stakeholder-guided value, 372 km^2 of new land would be needed for wind energy.

ii For all spatial calculations in this study, the total area of Portugal is considered as 8.910.214 hectares (or 89.102 km^2), corresponding to the numbers provided by the shapefile obtained from DGT (Direção Geral do Território).

To refine these estimates, we also accounted for capacity contributions from repowering or overpowering existing wind farms (Box 4), which could contribute up to 0,96 GW of wind. Subtracting these values from the NECP capacity gaps significantly reduces the amount of capacity needed until 2030, thus providing a clearer picture of the remaining spatial demands for new development within the NECP framework. Further development will be required to achieve full carbon neutrality, as laid out by the RNC2050[iii]; however, this goes beyond the scope of this study.

BOX 5: ESTIMATING CAPACITY FROM REPOWERING/OVERPOWERING AND PROJECTS IN THE PIPELINE

Repowering and overpowering:

To evaluate how repowering/overpowering could contribute to Portugal's wind energy goals, we used APREN's 2024 Wind Farms in Portugal[55] as our main dataset. Wind farms with more than 15 years of operation by 2030 were considered candidates for repowering/overpowering, as older installations generally gain the most efficiency from upgrades. Commissioning dates were approximated using the parameter grid connection data, and projects post-2015 were excluded to avoid counting recent expansions. A fixed power density of 11 MW/km^2 was applied for consistency and we considered a capacity increase of up to 20%, based on Portuguese law.[56] The results show a **repowering/overpowering potential of 0,96 GW**, which could significantly reduce the need for new land development. Priority should be given to existing wind power plants located in areas with minimal environmental and social conflicts. Where currently installed power plants are in moderate-conflict zones, robust mitigation measures must be adopted in accordance with the mitigation hierarchy framework. Considering the 2024 GTAER report[21], which identifies 0,69 GW of repowering capacity in reduced conflict zones, it becomes evident that some of the potential for repowering may overlay on moderate to high-conflict zones, in which cases a detailed, transparent and rigorous case-by-case environmental assessment shall be required.

Pipeline projects:

To estimate the contribution of renewable energy projects currently in the pipeline, we accessed the Global Energy Monitor database for wind[57] and solar[58] installations. We filtered for projects located in Portugal, selecting "onshore" for wind and "PV" or "assumed PV" for solar. Only projects classified as construction (equipment installation underway) or pre-construction (actively pursuing approvals, land rights, or financing) were included, as these represent high-probability developments. Summing up installed capacities yielded **4,74 GW of solar and 0,53 GW of wind currently in the pipeline**, providing a clear snapshot of near-term development potential and Portugal's progress toward its 2030 targets. It is important to consider where these pipeline projects are being built, ensure they comply with all legal permitting processes and that they follow mitigation hierarchy principles to minimize environmental and social impacts.

iii Roadmap for carbon neutrality 2050

4. How Siting Outcomes Can Aid Portugal's Energy Transition

"It is therefore essential that repowering and overpowering projects are accompanied by robust environmental monitoring and stakeholder engagement."

The results of our spatial analysis provide a robust foundation for evaluating the feasibility of Portugal's renewable energy targets within the context of responsible siting. By comparing the mapped low-conflict, high-development-potential areas to the land requirements derived from NECP capacity gaps and power density scenarios, we move beyond theoretical potential to assess the practical realities of implementation.

Notably, the available low-conflict, high-development-potential area for solar (approximately 1.514 km^2) exceeds the land needed to meet Portugal's 2030 targets, even under conservative power density assumptions. Considering that only approximately 300 km^2 are required to deliver the additional 9 GW of solar capacity set out in the NECP, Portugal has more than five times the necessary land available for ground-mounted solar. This surplus, spread across a wide geographic area (Supplement I) not only ensures that the 2030 targets can be met, but also provides developers and policymakers with a high level of flexibility to select project locations that best align with technical, environmental, and social priorities. This supports the integration of local community preferences, allows for the optimization of grid connections and infrastructure, and provides a buffer to accommodate unforeseen constraints or changes in land use, further de-risking the permitting process and supporting a more resilient energy transition.

For wind, the situation is more nuanced. The mapped low-conflict, high-development-potential area (approximately 267 km^2) falls short of the conservative land requirement, but reaches a sufficient level under the optimistic power density assumptions. For further analysis, we consider the stakeholder-recommended average power density presented in Section 3.2. Under this assumption, the land requirement is 372 km^2. This value provides a more realistic benchmark for planning, reflecting both technical feasibility and local experience. These findings highlight that wind energy may require targeted mitigation, repowering/overpowering, grid expansion, and/or the inclusion of moderate-conflict areas to fully realize national goals.

With additional and science-based mitigation measures, repowering and overpowering existing wind farms has the potential to design effective strategies for minimizing the land footprint of new wind energy development. According to our estimates (Box 5), repowering and overpowering could contribute up to 0,96 GW of additional wind capacity by 2030. This means that new land requirements could be reduced by nearly a quarter (approximately 87 km^2 or 23%), demonstrating that a substantial portion of the required new wind capacity can be delivered without expanding into new, potentially higher-conflict areas.

On the other hand, repowering intensifies the impacts on the current site and can lead to a concentration of environmental and social effects in areas that have already experienced significant development. While this approach avoids the need to convert new land and can streamline permitting by leveraging existing infrastructure and grid connections, it may also increase the cumulative impacts on local biodiversity, landscape values, and communities. For example, replacing older turbines with larger, higher-capacity models, often by building new foundations and dismantling the older ones, can alter the visual profile of the landscape, increase noise levels, and potentially affect local wildlife differently than the original installations. Additionally, the process of dismantling, upgrading, and constructing new turbines can temporarily disrupt habitats and local activities.

It is therefore essential that repowering and overpowering projects are accompanied by robust environmental monitoring and stakeholder engagement. Adaptive management strategies should be implemented to mitigate any intensified impacts, such as scheduling construction to avoid sensitive periods for wildlife, enhancing habitat restoration efforts, and ensuring transparent communication with affected communities. In some cases, opportunities may arise to improve the overall environmental performance of the site, for instance, by decommissioning turbines in the most sensitive locations, restoring habitat in buffer zones, or implementing new mitigation technologies.

In addition to repowering/overpowering, the pipeline of wind projects that are already under construction or in advanced stages of permitting must be considered when calculating the required areas to meet national targets. Our analysis (Box 5) indicates that approximately 530 MW of wind capacity is currently in the pipeline, which corresponds to roughly 48 km^2, if implemented. When both repowering/overpowering and pipeline projects are factored in, the additional wind capacity that must be sited on new land is significantly reduced.

For solar, the projects in the pipeline account for an even more pronounced capacity. The current pipeline includes approximately 4,74 GW of solar capacity, which represents more than half of the additional capacity required to meet the 2030 NECP target. If we consider these projects in the pipeline, then the actual land requirement for new solar development may be even lower than the conservative scenario suggests if they were planned in the low-conflict areas. Given that several of these projects were planned before the design of RAAs and that the conflict level of the land where these pipeline projects may intersect with high-conflict areas, it is important to ensure that these projects follow all legal permitting processes and that they adhere to mitigation hierarchy principles to minimize environmental and social impacts. Given the abundance of mapped low-conflict, high-development-potential land for solar, and the flexibility this provides for site selection, Portugal is exceptionally well-positioned to meet and even exceed its solar targets without encroaching on high-conflict or sensitive areas.

Taken together, these findings underscore the importance of a multi-pronged approach to renewable energy deployment. By combining new development on mapped low-conflict, high-development-potential sites with strategic repowering/ overpowering and the realization of pipeline projects on low-conflict lands, Portugal can minimize land use conflicts, accelerate permitting, and make efficient use of existing infrastructure. Moreover, the spatial analysis of our results highlights the potential for hybrid or dual-use sites in municipalities that have both wind and solar low-conflict, high-development-potential areas (Supplement I). Developing such sites can further optimize land use and grid integration, though it may also require careful management of cumulative impacts. Additional considerations for other technologies that were not part of this study (e.g., decentralized PV and offshore wind) are described in Box 6.

BOX 6: ADDITIONAL NECP TARGETS: DECENTRALIZED SOLAR AND OFFSHORE WIND

Portugal's renewable energy strategy includes commitments for decentralized solar and offshore wind. These segments present significant opportunities to accelerate the energy transition while leveraging existing infrastructure and untapped resources.

Decentralized solar PV:

Portugal's NECP sets a 2030 target of 5,7 GW for decentralized solar, compared to a projected 2,8 GW by 2025, leaving a gap of 2,9 GW. Studies[59] show that the technical potential for rooftop solar in artificialized areas is substantial, estimated at 23,33 GW. Within this potential, development of industrial sites represents an opportunity of 3,73 GW in capacity. Other segments such as residential and mixed-use buildings (8,89 GW) and isolated single-family homes (6,73 GW) also offer considerable potential, but industrial rooftops stand out for their large surface areas and proximity to demand centers, enabling rapid deployment and cost efficiency.

Offshore wind:

The NECP target for offshore wind is 2 GW by 2030, while installed capacity is expected to remain minimal at just 0,03 GW by 2025. This leaves an almost complete gap of 1,97 GW to be filled in the coming years. According to LNEG, Portugal's technical potential for offshore wind is vast, with 2 GW available for fixed-bottom installations and an impressive 36 GW for floating offshore technology. This highlights a major opportunity for Portugal to leverage deep-water resources and complement onshore wind limitations, positioning floating offshore wind as a key long-term renewable energy strategy. However, it is important to ensure a smart siting approach for offshore wind as well, including cohesive and robust territorial management methodologies, favoring low-conflict zones, while promoting early-stage communication and benefit-sharing efforts with local communities and considering non-price criteria in the energy tenders.

4.1 Identifying Additional Opportunity Zones

Provided that enhanced safeguards, including careful planning, robust mitigation, and stakeholder engagement measures, are applied, renewable energy siting may be feasible in transitional landscapes classified as moderate-conflict zones with high development potential, adding to the low-conflict, high-development-potential areas. Once other options are exhausted, such zones represent a strategic reserve of land for wind and solar expansion, offering substantial opportunities to bridge capacity gaps and accelerate Portugal's energy transition while still avoiding high-conflict areas. The results in this section are based on the biodiversity and energy development potential maps. Sociocultural and visual landscape values were considered on the discussion but not used as exclusion criteria, allowing for a broader identification of feasible areas.

Across Portugal, these kinds of moderate-conflict zones with high development potential cover a significant portion of the territory. For wind energy, the combined area of moderate-low conflict, moderate-conflict, and moderate-high conflict zones totals approximately 790 km^2, with the highest concentrations found in the *North* and *Center* regions. For solar energy, these three categories span over 9.100 km^2, indicating a vast landscape where responsible solar development could be pursued with appropriate safeguards. The geographical distribution of these zones is detailed in Box 7 and also in Supplement I.

These zones are particularly relevant in the context of Portugal's 2030 renewable energy targets, as they help bridge the gap between technical potential and ecological feasibility. While low-conflict, high-development-potential zones are ideal, they are limited in spatial extent, especially for wind. Under the low power density scenario, an additional 310 km^2 would be required to meet the 2030 NECP wind targets. This means developing less than 40% of the moderate-conflict zones with high development potential. Using the power density recommended by Portuguese stakeholders, the required area drops by nearly one-third, leaving about 105 km^2 (or approximately 13% of the moderate-conflict zones with high development potential).

BOX 7: KEY OPPORTUNITY ZONES IN PORTUGAL'S REGIONS

Alentejo: The *Alentejo* region stands out for its extensive moderate-conflict, high-development-potential areas for solar energy. *Central Alentejo* and *Baixo Alentejo* together account for over 1.200 km^2 of moderate-high conflict zones, primarily located around the *Castro Verde* Protected Area, Important Bird Areas near *Évora*, and the corridor between *Alqueva* and *Mourão/Moura/Barrancos* Protected Area. In contrast, *Alentejo Litoral*, already identified as a strong candidate for low-conflict development, contains more than 400 km^2 of moderate-low conflict zones, making it a potential hotspot for solar siting in Portugal.

Center and Algarve: Both of these regions offer a balanced mix of moderate-conflict zones with high development potential for wind and solar. In *Beiras e Serra da Estrela*, over 80 km^2 of moderate-conflict zones for wind and more than 470 km^2 for solar suggest strong potential for hybrid or dual-technology deployment. A similar pattern is observed in the *Algarve*, with more modest wind potential (42 km^2 of moderate-conflict zones) but substantial solar opportunity (605 km^2), reflecting a high solar resource availability typical of Mediterranean climates.

North: This region contains over 280 km^2 of wind-suitable land across the moderate-conflict, high-development-potential categories. The *Douro* region emerges as a hotspot for both technologies, with more than 80 km^2 of wind moderate-conflict zones and 100 km^2 of solar moderate-conflict zones. Additionally, the *Porto Metropolitan Area* offers over 150 km^2 of solar potential in moderate-conflict zones. However, the North is also a biodiversity hotspot, with numerous protected areas and socially significant landscapes along the Douro River. Development in this region must be approached with heightened ecological and social sensitivity.

West and Tagus Valley: This region presents a compelling alternative for development near the *Greater Lisbon* area. It contains more than 110 km^2 of wind and 1.200 km^2 of solar moderate-conflict zones with high development potential in all categories and the proximity to urban infrastructure and demand centers enhances its strategic value.

"Incorporating moderate-conflict zones with high development potential into national and regional siting strategies, may allow Portugal to expand its renewable energy footprint, while avoiding high-conflict zones."

Moderate-conflict zones with high development potential often lie adjacent to low-conflict areas with high development potential or within landscapes previously altered by agriculture or forestry, which may reduce ecological sensitivity. These areas can offer a pragmatic path forward, especially in regions where low-conflict, high-development-potential zones are limited or already saturated with development. Incorporating moderate-conflict zones with high development potential into national and regional siting strategies, may allow Portugal to expand its renewable energy footprint, while avoiding high-conflict zones and, with the necessary precautions and robust evaluation processes, maintaining its commitments to biodiversity conservation and social equity. Data on these additional opportunity zones can provide guidance to a Mitigation Rulebook, as mandated by Article 15c of EU RED, to accompany the RAA maps in Portugal (Supplement VI). A detailed explanation of how the mitigation hierarchy and other relevant safeguards should be applied when developing renewable energy projects in these zones is provided in Supplement III.

5. Insights into Further Action: Beyond RAA Designations

"Smart siting results can directly inform grid expansion strategies at both the local and national levels, something that will become increasingly important as Portugal's renewable energy targets grow more ambitious, towards carbon neutrality."

Beyond identifying low-conflict sites feasible for renewable energy development, the smart siting analysis provides actionable guidance for energy infrastructure planning, community engagement, and mitigation strategies. Smart siting results can directly inform grid expansion strategies at both the local and national level, something that will become increasingly important as Portugal's renewable energy targets grow more ambitious, towards carbon neutrality. Expanding the use of participatory mapping and community engagement can help ensure that renewable energy projects are not only technically and environmentally sound, but also socially legitimate and widely supported. And beyond traditional "no net loss" objectives, a smart siting approach can create opportunities for renewable energy projects to actively contribute to nature-positive outcomes, increasing natural capital and ecosystem services. The following applications demonstrate how spatial data and stakeholder input can inform real-world decisions and support Portugal's energy transition.

5.1 Guiding Power Grid Infrastructure Expansion

Renewable energy deployment is highly dependent on grid access and capacity. In Portugal, grid infrastructure is managed by two systems: the high-voltage transmission network (RNT) overseen by REN, and the medium- and low-voltage distribution network managed by E-REDES. Large-scale projects connect to the transmission grid, while small-scale installations typically use the distribution network. Grid capacity, especially in the RNT, remains a major bottleneck for new developments.

Smart siting results, specifically maps of high-development-potential and low-conflict areas, can directly inform grid expansion strategies. For local distribution, communities and E-REDES can use PV low-conflict, high-development-potential maps to guide the placement of new substations and prioritize line upgrades. At the national level, REN should focus transmission upgrades on west-central Portugal, where demand is high and low-conflict, high-development-potential areas are concentrated. This includes enhancing 220 kV and 150 kV lines and applying grid-enhancing technologies to 400 kV lines. In these regions, low-conflict, high-development-potential areas could support approximately 2,5 GW of wind and 65 GW of solar capacity. For wind, new transmission corridors may be needed to unlock further potential, and intermediate wind models can help identify additional feasible areas for expansion.

Looking ahead, integrating spatial planning with grid expansion will be essential for Portugal's long-term renewable energy targets. Proactive coordination between energy planners and grid operators can ensure that infrastructure investments are directed to areas with the greatest potential for low-conflict, high-impact development. This approach not only accelerates project delivery and minimizes costs, but also helps avoid unnecessary environmental and social impacts by aligning new grid infrastructure with responsible siting principles. The details of this analysis are in Supplement II.

"Proactive coordination between energy planners and grid operators can ensure that infrastructure investments are directed to areas with the greatest potential for low-conflict, high-impact development."

"Expanding the use of participatory mapping and community engagement across Portugal can help ensure that renewable energy projects are not only technically and environmentally sound, but also socially legitimate and widely supported."

5.2 Integrating Fine-Scale Community Values in Siting Decisions

Understanding and mapping social values is essential for responsible renewable energy siting. A pilot participatory mapping exercise in *Silves* municipality engaged local stakeholders in spatially identifying areas of cultural, aesthetic, biodiversity, agricultural, and economic/tourism value. Using the kernel density estimation method, the analysis revealed 11 social value hotspot clusters covering about 13% of *Silves*, with most hotspots overlapping areas also classified as potential conflict zones in national coarse-filter datasets. This alignment demonstrates the value of participatory mapping in refining national-scale assessments and identifying locally significant areas that may warrant special consideration. While most hotspots corresponded to conflict zones, some landscape and aesthetic values fell outside pre-screened areas, highlighting the need for nuanced, context-specific engagement. These insights can help target resources for further engagement, inform local siting decisions, and ensure that community priorities are integrated into planning processes.

Expanding the use of participatory mapping and community engagement across Portugal can help ensure that renewable energy projects are not only technically and environmentally sound, but also socially legitimate and widely supported. By systematically incorporating local knowledge and values into spatial planning, developers and policymakers can better anticipate potential conflicts, design more inclusive benefit-sharing mechanisms, and foster long-term acceptance of renewable energy infrastructure. The details of this analysis are in Supplement III.

5.3 Applying the Mitigation Hierarchy for Landscape-Level Planning

As Portugal accelerates its renewable energy deployment, balancing development with biodiversity conservation is increasingly urgent. This guide recommends integrating the mitigation hierarchy into renewable energy planning, with a focus on landscape-scale conservation. EIAs and licensing processes play a critical role in regulating ecological impacts, while spatial conservation planning guides mitigation decisions to align with broader biodiversity goals.

The smart siting approach presented here goes beyond traditional "no net loss" objectives by supporting the transition toward "nature-positive" renewable energy and biodiversity net gain. By using spatial data to identify low-conflict areas with high development potential, projects can be proactively sited where risks to biodiversity and ecosystem services are minimized from the outset. This not only reduces the need for mitigation and offsets but also creates opportunities for renewable energy projects to actively contribute to nature restoration and enhancement.

For example, the mapping framework enables the prioritization of degraded or low-biodiversity value lands for development, where restoration actions (e.g., habitat creation, improving ecological connectivity, or stewardship of buffer zones) can be integrated into project design. If all low-conflict, high-development-potential sites and other development pathways have been exhausted, moderate-conflict areas can represent a contingency reserve so long as robust mitigation and restoration measures are employed.

By leveraging these spatial tools, mitigation can shift from fragmented, project-level interventions to coordinated, landscape-level planning. This enables sustainable energy development while actively safeguarding and enhancing ecosystems and community values. Ultimately, the smart siting framework and associated maps are not only tools for risk avoidance, but also for guiding and incentivizing nature-positive renewable energy. By embedding biodiversity net gain principles into spatial planning and the mitigation hierarchy, Portugal can ensure that its energy transition delivers lasting benefits for both climate and nature. More details and practical examples of this framework can be found in Supplement III.

"Ultimately, the smart siting framework and associated maps are not only tools for risk avoidance, but also for guiding and incentivizing nature-positive renewable energy."

6. Recommendations

6.1 Study Limitations

While the smart siting analysis provides a robust spatial framework for identifying low-conflict zones for renewable energy development, any such study is limited by crucial gaps in the current best available national datasets.

Biodiversity layer: Not all taxa (e.g., invertebrates, flora) could be considered for species-level occurrence, and most species distribution data were available only at coarse resolutions (e.g., 10x10 km tiles), limiting the precision of habitat suitability models and the ability to capture fine-scale ecological patterns.

Social sensitivity layer: Similarly, the social values mapping, though comprehensive, does not yet include fine-scale community perceptions, evolving cultural landscapes, or local land tenure dynamics, all of which influence project acceptance. In addition, the latest land use and land-cover maps are from 2018, potentially missing recent changes relevant for both biodiversity and social value mapping.

Development potential layer: A lack of available capacity estimates and high-resolution technical data for grid infrastructure, including direct data from developers and the Portuguese TSO, constrains the ability to accurately assess where new projects can be efficiently integrated. The timing of substation development is often unknown, and there is limited information on current or future demand centers beyond population centers. Furthermore, the absence of geospatial data related to plans for transmission expansion introduces additional uncertainty into the spatial modeling of feasible sites.

6.2 Recommendations

In order to refine and update such analyses in the future, the authors recommend several actions, building on the following priorities:

Enhance data quality and granularity through collaboration with national and regional agencies, NGOs, and academic institutions.

- Improve access to more detailed ecological and social datasets, such as updated land use and land-cover maps and higher-resolution species occurrence records.
- Make more detailed and up-to-date information on grid locations and grid capacity publicly accessible to allow for more accurate assessments of sites where new projects can be efficiently integrated.

Broaden and strategically target stakeholder engagement:

- Expand stakeholders to include not only national and regional authorities, industry, and NGOs, but also local communities and specific groups identified through conflict mapping (Supplement V).
- Prioritize the leveraging of spatial analysis, engagement efforts, and participatory mapping where local input is most critical.
- Expand social values mapping to include fine-scale community perceptions, evolving cultural landscapes, and local land tenure dynamics.
- Expand viewshed analysis by incorporating additional data sources (e.g., other social media platforms, trekking routes) and participatory GIS and citizen science platforms.

Establish robust monitoring and feedback mechanisms:

- Monitor biodiversity impacts, community responses, and permitting timelines to enable iterative improvements to the siting methodology and adaptive management over time.

6.3 Suggestions for Future Studies

In addition to the above improvements, future analyses could explore several advanced modeling approaches, including:

- **Technology-specific layers** to map biodiversity impacts unique to either solar or wind.
- **Co-location modeling:** Assessing the potential for co-location of solar and wind projects, as well as floating photovoltaics and other renewable energy technologies, could help optimize land use and infrastructure, reduce costs, and minimize environmental impacts.
- **Distributed solar PV modeling:** Developing more granular models for distributed solar, such as rooftop, industrial, and agricultural applications, would provide a clearer picture of the full potential for decentralized energy generation.
- **Modeling additional technologies** such as offshore wind or geothermal energy.
- **Grid expansion modeling:** Integrating detailed, scenario-based grid expansion modeling would allow for a more realistic assessment of where and how new renewable projects can be connected, taking into account planned transmission upgrades, substation development, and evolving demand centers beyond current population hubs.
- **Exploring impacts of repowering and overpowering** on biodiversity and local communities, including site-specific challenges such as increased turbine height, noise, and visual impacts, as well as potential risks for birds and bats.

7. Conclusion

As Portugal accelerates its transition to renewable energy, strategic spatial planning becomes essential to balance climate goals, biodiversity protection, and social equity. This Smart Siting Guide synthesizes the results of a comprehensive smart siting analysis, demonstrating how science-based mapping, stakeholder engagement, and innovative methodologies can guide responsible solar and wind development. The following conclusions highlight Portugal's capacity to meet its NECP targets, the opportunities and challenges of moderate-conflict zones, and the broader implications for grid expansion, social inclusion, and EU policy alignment.

Solar Energy: Portugal is exceptionally well-positioned to meet and even exceed its solar targets without encroaching on sensitive areas, with more than five times the amount of suitable land needed for its 2030 NECP target for ground-mounted solar (additional 9 GW by 2030). The mapping identifies 1.514 km^2 of land as both low-conflict and high-development-potential for solar. This far exceeds the estimated 300 km^2 required to deploy the additional 9 GW. This surplus of low-conflict, high-development-potential sites provides strong flexibility for site selection, future expansion, and the integration of additional sustainability or community benefit criteria.

Wind Energy: Portugal can meet its wind energy goals while minimizing new land use by taking an integrated approach that prioritizes responsible siting and safeguarding biodiversity and community values. For onshore wind, Portugal's 2030 NECP target requires an additional 4,1 GW of capacity, which translates to about 372 km^2 of new land. Portugal can achieve up to 70% of this goal through the development of mapped low-conflict, high-development-potential sites, which cover 267 km^2. Much of the remaining gap could be bridged through repowering and overpowering existing wind farms, with priority given to those in areas with minimal environmental and social conflicts, and robust mitigation measures adopted for those in moderate-conflict zones.

Contingency Opportunities With Proper Mitigation: After prioritizing the low-conflict, high-development-potential sites and other development pathways, Portugal's mapped moderate-conflict areas for solar (totaling 9.100 km^2) and wind (totaling 790 km^2) represent a significant strategic reserve that could be considered if all preferable lower-risk options have been exhausted. Importantly, the intention is not to promote development in these zones, but to recognize their existence as a contingency. Should their use become necessary, any projects would require rigorous application of the mitigation hierarchy and robust stakeholder engagement to ensure that energy generation is balanced with conservation priorities and biodiversity net gain strategies.

Novel Contributions for Future Use-Cases:

i) Grid expansion: The smart siting data and results provide actionable guidance for grid infrastructure planning. By identifying clusters of low-conflict, high-development-potential sites near existing transmission corridors and demand centers, the analysis supports targeted grid expansion that aligns with both technical feasibility and environmental/social safeguards. This approach enables grid operators to prioritize upgrades in areas where renewable energy development is most sustainable, reducing power loss and avoiding sensitive regions.

ii) Social values and community engagement: A key aspect of this study is the integration of social values into spatial planning, notably through national scale viewshed analysis. The viewshed layer, derived from geotagged social media content, provides a data-driven proxy for landscape sensitivity, complementing traditional methods. A pilot participatory mapping exercise in Silves additionally demonstrates how local community values can be spatially represented and compared with national datasets, enhancing the inclusivity and legitimacy of siting decisions.

iii) Policy implications and EU relevance: The results of this study directly support the implementation of EU policies, particularly the RED III and the designation of RAAs. By providing the spatial mapping of low and moderate-conflict sites, the analysis equips policymakers with the evidence needed to fast-track permitting, optimize land use, and integrate biodiversity safeguards into energy sector planning. The methodology and findings can also inform the development of mitigation rulebooks, SEAs, and stakeholder engagement frameworks required by EU legislation. Moreover, the surplus of low-conflict, high-development-potential land for solar and the strategic use of moderate-conflict zones with high development potential for wind demonstrate that Portugal, and by extension, other EU Member States, can achieve ambitious climate and energy targets without compromising ecological integrity or social equity.

In summary, Portugal's Smart Siting Guide exemplifies how integrated spatial planning, stakeholder engagement, and innovative mapping can accelerate the renewable energy transition while respecting nature and communities. By leveraging the country's abundant low-conflict land, responsibly developing moderate-conflict zones, and aligning grid investments with environmental and social priorities, Portugal is well-positioned to meet its NECP targets and contribute to the EU's broader decarbonization and biodiversity goals. The lessons and tools developed here offer a replicable model for other countries or regions seeking to balance climate action with conservation and social justice.

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Supplement I: Geographical Distribution of Sites in Portugal by Conflict Level

This section interprets the spatial results in the context of Portugal's diverse geographies, integrating technical, ecological, and social perspectives. The analysis draws on both NUTS regions and key municipalities, with Table 3 providing a summary of the main quantitative findings referenced throughout the discussion.

I. Areas With High Development Potential

High-development-potential areas for wind energy are predominantly concentrated in the *Alto Tâmega e Barroso* and *Douro* regions in the *North*, which together offer 386 km^2 of high-development-potential land. In the *Center*, the *Beiras* e *Serra da Estrela* region contributes an additional 231 km^2. These priority areas are characterized by optimal wind resources and favorable topography, particularly ridgetops, making them especially suitable for future wind energy projects.

The wind modeling consistently identified two key drivers of development potential across all scenarios. The average multi-scaled topographic position index (mTPI) emerged as a critical factor: sites with high mTPI values, typically ridgetops, showed the greatest development potential and closely matched the current distribution of wind turbines in Portugal. Conversely, negative mTPI values, indicative of valleys and low-lying areas, were associated with low development potential. Wind capacity factor was the second major driver, with locations exceeding 2.500 equivalent operating hours per year consistently classified as high-development-potential, while those below 2.200 hours were marked as low development potential.

Additional parameters, such as proximity to substations, transmission lines, and major urban areas, played a moderate role in shaping wind siting outcomes. Importantly, no single parameter alone was sufficient to produce high-development-potential values; rather, high-development-potential was achieved through the combination of favorable conditions, especially where both wind capacity factor and mTPI were high.

For solar energy, high-development-potential areas are mainly located in the *Alentejo* region. Within *Alentejo*, nearly two thirds of this potential is concentrated in the regions of *Alentejo Central* (2.120 km^2) and *Baixo Alentejo* (2.019 km^2), with the remainder distributed across *Alentejo Litoral* (1.713 km^2) and *Alto Alentejo* (904 km^2). The *Algarve* region also stands out, offering 1.930 km^2 of high-development-potential sites for solar PV. These regions correspond to areas with the highest solar capacity factors and favorable proximity to grid infrastructure, making them especially suitable for new ground-based PV installations.

Two additional regions also present considerable opportunities for solar development. *Lezíria do Tejo*, within the *West* and *Tagus Valley*, contains 1.075 km^2 of high-development-potential sites and is strategically located near *Greater Lisbon*, including the municipality of *Alcochete*, where a new airport is planned and could benefit from renewable energy supplied by these sites. *Beiras e Serra da Estrela*, in the *Center* region, offers 896 km^2 of high-development-potential land and is notable for also being highlighted in the wind development potential analysis, suggesting strong potential for hybrid renewable energy projects in this area.

TABLE 3: Land area results in km² from the Smart Siting for Portugal study for all the NUTS II regions, where high-development-potential refers to a value greater than or equal to 0,65

NUTS II	NUTS III	Total Area	Wind High-Development-Potential	Solar High-Development-Potential	Biodiversity Low-Conflict	Social High-Conflict	Combined Low-Conflict on Biodiversity + Social Maps	Wind Low-Conflict, High-Development-Potential	Solar Low-Conflict, High-Development-Potential
Alentejo	Alentejo Central	7.393,46	2,51	2120,9	100,33	375,14	95,9	0,56	28,38
Alentejo	Alentejo Litoral	5.309,41	117,23	1.713,26	220,67	381,50	215,92	2,10	91,89
Alentejo	Alto Alentejo	6.084,34	6,95	904,73	244,35	195,90	240,96	0,02	30,51
Alentejo	Baixo Alentejo	8.542,72	19,01	2.019,48	36,78	223,68	35,97	0,15	3,37
Algarve	Algarve	4.996,79	259,46	1.930,95	124,36	613,70	111,07	6,52	48,65
Center	Beira Baixa	5.252,92	55,86	709,40	1.501,64	186,43	1.484,19	32,57	161,43
Center	Beiras e Serra da Estrela	6.304,95	231,34	896,04	294,08	477,73	278,99	10,83	32,42
Center	Região de Aveiro	1.692,86	43,15	303,32	755,05	146,23	733,62	11,42	111,30
Center	Região de Coimbra	4.335,57	165,32	573,36	1.992,33	241,52	1.920,84	62,78	241,49
Center	Região de Leiria	2.449,13	88,03	255,56	1.015,63	114,11	1.000,59	35,45	92,27
Center	Viseu dos Lafões	3.237,74	104,91	127,90	891,07	83,71	864,39	5,18	20,23
Greater Lisbon	Grande Lisboa	1.389,98	58,45	381,56	362,61	357,75	284,98	9,34	49,33
North	Área Metropolitana do Porto	2.041,27	49,28	229,06	557,63	175,78	482,40	8,04	27,69
North	Alto Minho	2.218,84	140,07	45,19	129,72	221,95	110,66	1,64	4
North	Alto Tâmega e Barroso	2.921,91	193,41	93,54	29,23	88,69	27,38	0	0,51
North	Ave	1.451,36	57,80	45,29	185,35	51,54	176,20	0,62	6,79
North	Cávado	1.245,79	58,08	84,97	140,74	99,67	126,66	0,80	2,65
North	Douro	4.031,58	192,64	212,77	241,14	2.186,16	51,39	2,84	3,67
North	Tâmega e Sousa	1.831,52	78,99	56,85	314,53	70,96	305,94	10,24	14,04
North	Terras de Trás-os-Montes	5.543,60	36,29	199,12	90,09	247,37	88,74	0,06	0,43
Setúbal Peninsula	Península de Setúbal	1.625,25	28,37	548,63	160,08	317,31	141,19	0,67	50,27
West and Tagus Valley	Lezíria do Tejo	4.274,97	45,92	1.075,76	935,67	67,08	925,38	13,52	184,91
West and Tagus Valley	Médio Tejo	2.706,03	35,92	460,71	901,17	83,70	876,99	10,15	126,08
West and Tagus Valley	Oeste	2.220,16	154,19	605,39	849,21	261,71	774,66	41,78	182,54
Portugal		**89.102,14**	**2.223,17**	**15.593,73**	**12.073,44**	**7.269,32**	**11.355,01**	**267,30**	**1.514,86**

Examining the drivers of solar development potential reveals distinct patterns for large-scale and small-scale PV projects. For large-scale PV, the most influential factor is proximity to substations, with sites located within 2,5 kilometers of a substation exhibiting the highest development potential values. Solar capacity factor is nearly as important, with development potential values rising sharply as the solar capacity factor increases from 4.1 to 4.3 kWh/kWp per day and plateauing above 4.5 kWh/kWp. Proximity to major urban areas also plays a significant role, with the highest development potential values found within 25 kilometers of these centers. Other factors, such as distance from power plants and transmission lines, contribute to the model but with less pronounced effects.

For small-scale PV projects, the key drivers shift slightly, reflecting the different siting realities of distributed solar. Distance from all substations remains the most influential parameter, with the highest development potential values found within one kilometer of a substation. Proximity to cities is also highly significant, with high-development-potential values within two kilometers of urban centers. Additional factors such as distance from major substations and transmission lines are also important. Flat land, up to four percent slope, is favored for small-scale PV, but this influence diminishes rapidly as slope increases.

II. Areas With Biodiversity Conflicts

In terms of biodiversity, the *Alentejo* region exemplifies the complexity of balancing conservation and renewable energy expansion. The biodiversity data reveals a mosaic of conflict categories, with high-conflict zones covering nearly 50% of its territory, primarily concentrated around protected areas such as the Vale do Guadiana Natural Park and the Castro Verde Special Protection Area. These landscapes are characterized by extensive steppe habitats and strong ecological connectivity, supporting threatened species such as the little bustard, great bustard, and Iberian lynx. Surrounding these high-conflict areas are broad transitional belts of moderate-high conflict zones, mainly in *Baixo Alentejo* and *Alentejo Central*, which often serve as corridors for species movement and ecosystem resilience.

Conversely, *Alentejo* also contains the largest extent of moderate-low conflict areas in Portugal. These are predominantly located in the eastern part of *Alentejo Litoral* and in fragmented landscapes with lower ecological sensitivity. Such areas, characterized by a reduced presence of rare or threatened species and limited habitat connectivity, are promising candidates for conflict-sensitive renewable energy development. Here, ecological risks can be minimized, and permitting processes may be more straightforward, provided that site-specific assessments confirm the absence of critical biodiversity.

In the *North*, high and moderate-high conflict zones cover almost 11.000 km^2, mainly in *Terras de Trás-os-Montes* (from Montesinho Natural Park to Douro International Park) and *Alto Tâmega* (from Peneda-Gerês National Park to Alvão Natural Park). These landscapes feature extensive protected areas, rugged topography, and strong ecological connectivity, supporting critical habitats for species such as the Iberian wolf, forest birds, and bats. The *North* also has some low-conflict areas, with 1.688 km^2 mainly located in the *Porto Metropolitan Area* and *Tâmega e Sousa* regions.

The *Center* region, despite its complex mosaic of conflict categories, contains the highest number of low-conflict sites in Portugal, around 50% of the national total, approximately 6.450 km^2. These areas are concentrated in the central and eastern *Coimbra* Region, northeastern *Leiria* Region, and western *Beira Baixa*. High and moderate-high conflict zones in the Center are concentrated in *Beiras e Serra da Estrela* and along the mountainous corridors of Serra da Malcata and Serra da Estrela, extending to the Tejo International Reserve in southern *Beira Baixa* and the Douro International Park, forming an important biodiversity corridor with the *North*. These zones are recognized for their rich biodiversity, including habitats for the Iberian wolf, Bonelli's eagle, and several threatened bat species. Particular attention should be brought to these areas when designing international energy connections, since this biodiversity hotspot also borders Spain.

In the *West* and *Tagus Valley* region, biodiversity conflict mapping shows a predominance of low and moderate-low conflict areas. Low-conflict zones (2.686 km^2) are mainly located near the borders of the *Center* region (northeast of *Médio Tejo*) and in the *West* region (north of *Greater Lisbon*), typically exhibiting lower ecological sensitivity and a reduced presence of rare or threatened species. One exception is the corridor between the Serras de Aires e Candeeiros Natural Park and the Alvaiázere protected area, which hosts a high concentration of bat shelters. Moderate-low conflict zones are primarily found in the eastern part of the *Lezíria do Tejo* region, connecting with similar areas in *Alentejo*.

In the *Algarve* region, biodiversity conflict mapping reveals a landscape dominated by high-conflict zones, covering approximately 56% of the territory. These areas are mainly concentrated in the interior, bordering *Alentejo* and near protected areas such as *Monchique*, *Barrocal*, and *Caldeirão*, which are important bird habitats. However, low and moderate-low conflict areas can still be found in specific municipalities such as *Silves*, *Tavira*, and *São Brás de Alportel.*

BOX 8: KEY SPECIES DRIVING HIGH BIODIVERSITY CONFLICT ZONES

The spatial distribution of high-conflict zones in the fine-filter biodiversity map is strongly influenced by the presence of several notable birds, bats, and other mammal species.

Steppe birds:

The little bustard (*Tetrax tetrax*) and the great bustard (*Otis tarda*) are emblematic steppe birds whose populations are concentrated in the *Alentejo region*. Both species are highly sensitive to habitat loss and fragmentation, and their conservation status is a key driver of high sensitivity areas in open agricultural landscapes.

Raptors:

he Montagu's harrier (*Circus pygargus*) is present not only in *Alentejo* but also in the *North* of Portugal, favoring extensive cereal fields and grasslands and contributing to high-conflict scores in these habitats. The black vulture (*Aegypius monachus*), one of Europe's largest and most threatened raptors, is concentrated in areas with extensive woodlands and open landscapes, particularly in the *Beira Baixa* region, where its conservation depends on the maintenance of large, undisturbed habitats.

Other birds of prey:

The Eurasian eagle-owl (*Bubo bubo*) is a large nocturnal raptor highly sensitive to disturbance and renewable energy infrastructure, including wind turbines and power lines. The Bonelli's eagle (*Aquila fasciata*), a flagship raptor for Mediterranean ecosystems, breeds in rugged, forested, and mountainous areas of central and southern Portugal.

Bats:

Notable bat species such as the lesser mouse-eared bat (*Myotis blythii*), Mehely's horseshoe bat (*Rhinolophus mehelyi*), and Geoffroy's bat (*Myotis emarginatus*) are key drivers of high-conflict zones, especially in regions with suitable roosting sites such as caves, old or abandoned buildings, and mature forests. These bats are highly sensitive to habitat disturbance, fragmentation, and changes in land use.

Mammals:

The Iberian lynx (*Lynx pardinus*), one of Europe's most endangered carnivores, and the Iberian wolf (*Canis lupus signatus*) both require large, contiguous habitats and are highly sensitive to human disturbance. The Iberian lynx is primarily found in southern Portugal, with key habitats[60] (e.g., Mediterranean forests and dense shrublands) in the Guadiana Valley and surrounding areas. The interior of *Algarve*, including *Silves* municipality, is particularly important as it hosts the Iberian Lynx Recovery Center.[61] The Iberian wolf, concentrated mainly in northern Portugal, also depends on extensive, undisturbed territories and faces similar threats from habitat loss and human activity.

The presence and conservation needs of these and other species considered in this project underscore the importance of integrating species-specific data into spatial planning for renewable energy. Ensuring that development does not compromise Portugal's most threatened terrestrial fauna is essential for a truly sustainable energy transition.

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III. Areas With Social Conflict

Beyond biodiversity, social values mapping reveals that areas of high social conflict are not evenly distributed across Portugal, but instead cluster in specific geographies with strong cultural, visual, or economic significance. The *Douro* region, and particularly the *Alto Douro Vinhateiro*, stands out as a landscape of exceptional sensitivity.

Recognized as a UNESCO World Heritage Site, this area is defined by its steep terraced vineyards and scenic river valleys, which are highly valued for their cultural heritage and aesthetic appeal. Any land use change in this region, including renewable energy development, is likely to face strong public opposition due to the potential for visual intrusion and impacts on the region's wine economy and identity.

Similarly, the *Algarve*'s coastline emerges as another hotspot of social sensitivity. As one of Portugal's most iconic tourist destinations, the Algarve is characterized by high landscape value, dense recreational use, and a local economy heavily reliant on tourism. The coastal sensitivity layer highlights the vulnerability of this region to changes that could alter coastal views or restrict access. Renewable energy projects in these areas must therefore be planned with particular care, taking into account both the visual landscape and the socioeconomic fabric of local communities.

Other regions also present notable concentrations of potential social conflict. In the *Beiras* and *Serra da Estrela*, as well as in *Alentejo Central* and *Alentejo Litoral*, pockets of high social sensitivity are associated with cultural or archaeological significance, as well as with valued landscapes. These areas, while not as extensive as those in the *Douro* or *Algarve*, still require careful engagement with local stakeholders and consideration of community values in the planning process.

IV. Low-Conflict, High-Development-Potential Sites

Low-conflict and high-development-potential sites for wind

The spatial distribution of the low-conflict, high-development-potential sites for wind energy at the municipal level reveals several distinct geographic clusters (Figure 5 and Table 4).

The most prominent cluster is located in the *Centro* region (Cluster Central), particularly within the districts of *Castelo Branco*, *Coimbra*, and Leiria. This cluster accounts for more than 100 km^2 of low-conflict, high-development-potential sites for wind development (approximately 38% of the total such sites in Portugal). Within this cluster, municipalities such as *Pampilhosa da Serra* and *Figueiró dos Vinhos* stand out, each contributing nearly 48 km^2 of low-conflict, high-development-potential sites, making them the leading municipalities for future wind development in the country.

A second notable cluster emerges in the *West* and *Tagus Valley* region (Cluster West), close to the *Lisbon* metropolitan area. Here, the municipalities of *Torres Vedras*, *Alenquer*, and *Mafra* collectively offer almost 30 km^2 of low-conflict, high-development-potential sites for wind. Expanding this cluster to include nearby municipalities such as *Santarém*, *Caldas da Rainha*, and *Rio Maior* increases the total available area to approximately 47 km^2, further emphasizing the region's significance for wind development.

Another spatial pattern can be observed by following the Central cluster northward. Starting from the northern part of the *Coimbra* region (*Penacova* and *Mortágua*), this Central-North cluster extends through the *Aveiro* region (*Águeda* and *Sever do Vouga*), and reaches the periphery of the *Porto* metropolitan area, including municipalities like *Arouca*, *Penafiel*, and *Baião*. This northward extension highlights the continuity of suitable wind development areas from the *Centro* into the *Norte* region, with a total area of almost 40 km^2 suitable for wind development.

In the *Algarve*, although the overall low-conflict, high-development-potential area for wind is more limited, municipalities such as *Tavira* and *Silves* still account for a combined 4,3 km^2 of suitable sites, indicating that even in regions with higher ecological or social constraints, pockets of opportunity for wind energy siting exist.

FIGURE 5: Clusters of wind development potential at a municipality level in Portugal, with dark blue polygons representing more wind.

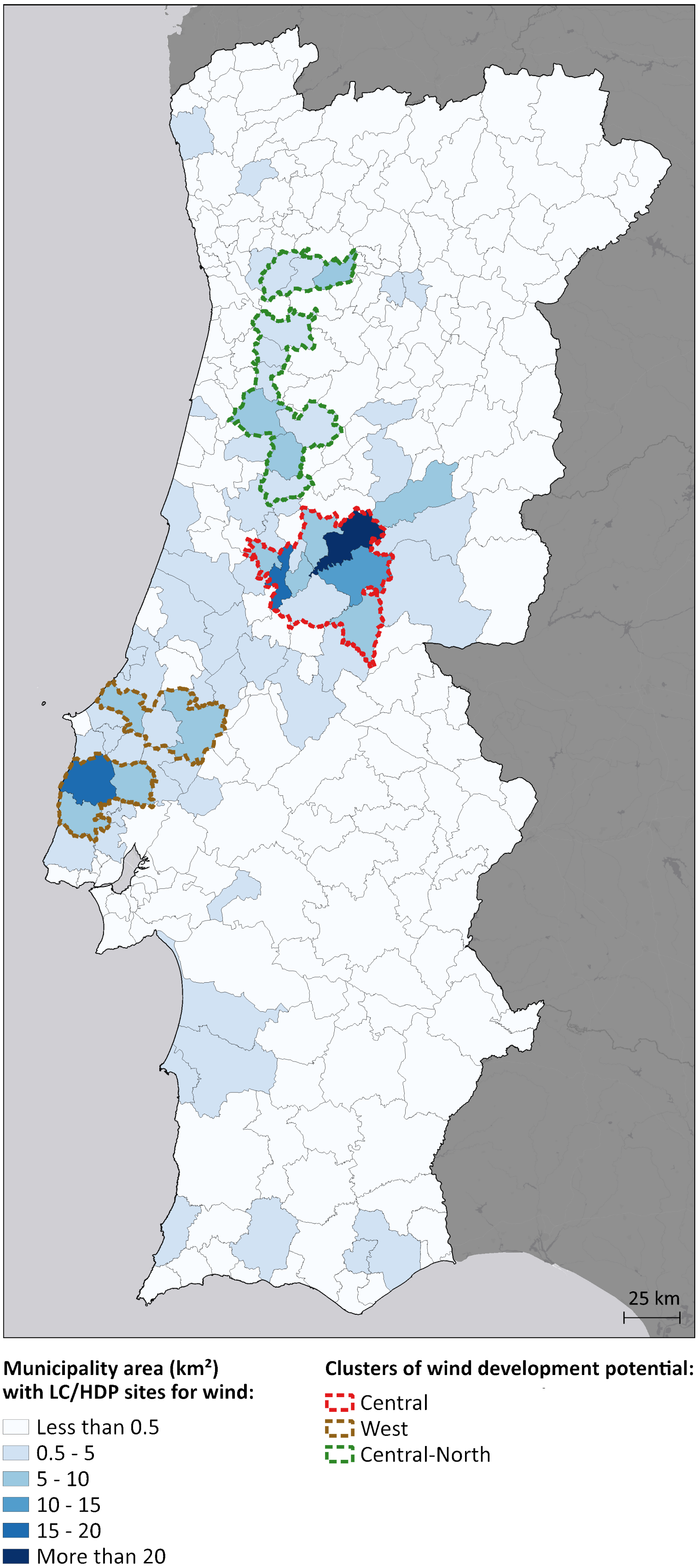


TABLE 4: Results from the Portugal Smart Siting guide with municipality clusters representing best locations for wind development.

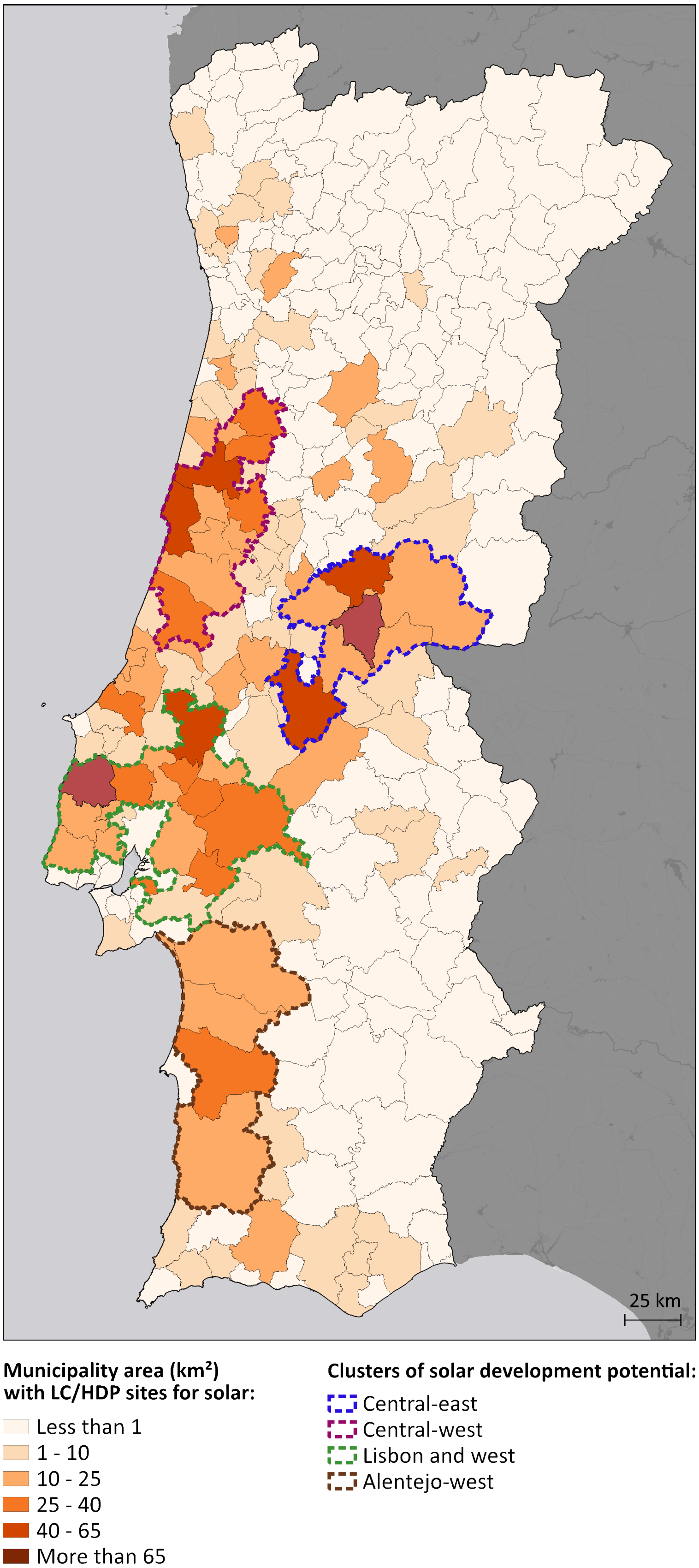
MUNICIPALITY	Area (km²)	Wind Cluster	Wind Low-Conflict, High-Development-Potential (km²)	Wind Low-Conflict, High-Development-Potential (%)
Castanheira de Pêra	66,77	Central	3,09	4,63
Figueiró dos Vinhos	173,44	Central	19,43	11,20
Góis	263,30	Central	9,38	3,56
Oleiros	471,09	Central	14,84	3,15
Pampilhosa da Serra	396,46	Central	28,53	7,20
Pedrógão Grande	128,75	Central	7,37	5,72
Penela	134,80	Central	6,51	4,83
Proença-a-Nova	395,40	Central	9,23	2,33
Sertã	446,73	Central	4,77	1,07
Alenquer	304,22	West	8,64	2,84
Caldas da Rainha	255,69	West	5,83	2,28
Mafra	291,65	West	5,39	1,85
Rio Maior	272,76	West	2,45	0,90
Santarém	552,54	West	8,38	1,52
Torres Vedras	407,15	West	15,76	3,87
Águeda	335,27	Central-North	6,04	1,80
Arouca	329,11	Central-North	1,44	0,44
Baião	174,53	Central-North	5,63	3,23
Marco de Canaveses	201,89	Central-North	0,81	0,40
Mortágua	251,18	Central-North	9,34	3,72
Penacova	216,73	Central-North	2,39	1,10
Penafiel	212,24	Central-North	2,83	1,33
Sever do Vouga	129,88	Central-North	3,69	2,84
Tondela	371,22	Central-North	1,81	0,49
Vale de Cambra	147,33	Central-North	4,48	3,04

Low-conflict and high-development-potential sites for solar energy

An analysis of the spatial distribution of the low-conflict, high-development-potential sites for solar energy reveals a high degree of flexibility for project siting across Portugal's municipalities (Figure 6 and Table 5). This flexibility is particularly valuable for developers, as it allows for adaptation to site-specific assessments and the ability to manage project locations within municipalities to better address biodiversity and social concerns.

One of the most prominent locations is the region *Centro*, which holds two clusters of low-conflict, high-development-potential sites for solar. The first, *Central-East* cluster, is located in the eastern part of this region and overlaps partially with the same wind cluster identified in this area. This cluster encompasses more than 230 km² of feasible land for solar development, including municipalities in the north of the *West* and *Tagus Valley* region. Key municipalities within this area include *Abrantes, Oleiros, Mação, Castelo Branco, Sertã, Vila Velha de Ródão*, and *Proença-a-Nova*. Notably, *Proença-a-Nova* stands out as the municipality with the largest low-conflict, high-development-potential footprint for solar, offering over 73 km² of suitable land for solar development.

FIGURE 6: Clusters of solar development potential at a municipality level in Portugal, with dark orange polygons representing more solar.



The second major cluster is located along the *Centro* region's coastal belt (named *Central-West*), adjacent to the wind *Central-North* cluster that extends towards the *North* region, but in this case not reaching the *Porto* metropolitan area. This Central-West cluster includes municipalities from *Leiria* to *Águeda*, with *Cantanhede* ranking third nationally for low-conflict, high-development-potential solar area, providing more than 60 km^2. The total area encompassed by this cluster is more than 320 km^2, underscoring the strategic importance of the *Central* region for solar energy development.

Around *Greater Lisbon*, the spatial pattern for solar low-conflict, high-development-potential sites for solar is even more pronounced than for wind. A broad concentration of municipalities encircles the *Tagus* delta, creating a "ring" of solar opportunity that offers significant flexibility for site selection near the capital and in proximity to key infrastructure projects, such as the planned *Alcochete* airport. This cluster (named *Lisbon* and *West*) includes municipalities within *Greater Lisbon* (*Mafra*, *Sintra*, and *Loures*) and extends to *Torres Vedras*, which ranks second nationally for low-conflict, high-development-potential solar area with more than 70 km^2. This cluster continues north and east to *Santarém* and the southern part of *Lezíria do Tejo* (including *Coruche*, *Benavente*, and *Salvaterra de Magos*) and concludes with *Montijo* in the *Setúbal Peninsula*. This cluster has a total of more than 380 km^2 of low-conflict, high-development-potential sites for wind. Despite its high technical potential, this region also encompasses municipalities of significant tourism and iconic landscapes, as well as important biodiversity areas such as the *Estuário do Tejo* protected area.

Collectively, these three clusters cluster accounts for the majority of low-conflict, high-development-potential sites for solar in Portugal, totaling approximately 935 km^2, or nearly 62% of the national total. However, the *Alentejo* and *Algarve* regions also have some potential to be explored.

In the *Alentejo* region, the complexity of the landscape is reflected in the distribution of the low-conflict, high-development-potential sites for solar, which are concentrated closer to the coastline, creating the *Alentejo-West* cluster. A minor cluster with the municipalities of *Santiago do Cacém, Grândola, Alcácer do Sal*, and *Odemira* together provide more than 90 km^2 of suitable land for solar development, representing almost 60% of the total low-conflict, high-development-potential solar sites in *Alentejo*. For the *Algarve*, the municipalities of *Silves* and *Tavira* again emerge as leaders, offering a combined total of nearly 30 km^2 of low-conflict, high-development-potential sites for solar.

TABLE 5: Results from the Portugal Smart Siting guide with municipality clusters representing best locations for solar development

MUNICIPALITY	Area (km²)	Solar Cluster	Solar Low-Conflict, High-Development-Potential (km²)	Solar Low-Conflict, High-Development-Potential (%)
Abrantes	714,69	Central-East	50,05	7,00
Castelo Branco	1.438,19	Central-East	16,24	1,13
Mação	399,98	Central-East	23,02	5,76
Oleiros	471,09	Central-East	44,53	9,45
Proença-a-Nova	395,40	Central-East	73,58	18,61
Sertã	446,73	Central-East	13,35	2,99
Vila Velha de Ródão	329,91	Central-East	11,23	3,40
Águeda	335,27	Central-West	28,93	8,63
Anadia	216,63	Central-West	31,98	14,76
Cantanhede	390,88	Central-West	60,86	15,57
Coimbra	319,40	Central-West	33,68	10,54
Condeixa-a-Nova	138,67	Central-West	15,42	11,12
Figueira da Foz	379,05	Central-West	42,05	11,09
Leiria	565,09	Central-West	35,65	6,31
Montemor-o-Velho	228,96	Central-West	19,29	8,43
Oliveira do Bairro	87,32	Central-West	16,96	19,42
Pombal	626,00	Central-West	15,63	2,50
Soure	265,06	Central-West	22,01	8,30
Alenquer	304,22	Lisbon and West	30,92	10,16
Almeirim	222,12	Lisbon and West	11,13	5,01
Azambuja	262,66	Lisbon and West	10,44	3,97
Benavente	521,38	Lisbon and West	19,36	3,71
Cartaxo	158,17	Lisbon and West	28,39	17,95
Coruche	1.115,72	Lisbon and West	25,40	2,28
Loures	167,24	Lisbon and West	11,67	6,98
Mafra	291,65	Lisbon and West	20,97	7,19
Montijo	348,62	Lisbon and West	38,53	11,05
Palmela	465,12	Lisbon and West	8,24	1,77
Salvaterra de Magos	243,93	Lisbon and West	33,90	13,90
Santarém	552,54	Lisbon and West	46,40	8,40
Sintra	319,23	Lisbon and West	14,98	4,69
Sobral de Monte Agraço	52,10	Lisbon and West	10,33	19,83
Torres Vedras	407,15	Lisbon and West	70,81	17,39
Alcácer do Sal	1.499,87	Alentejo-West	16,11	1,07
Grândola	825,94	Alentejo-West	23,41	2,83
Odemira	1.720,60	Alentejo-West	16,07	0,93
Santiago do Cacém	1.059,69	Alentejo-West	35,37	3,34

Supplement II: Using Smart Siting Data to Guide Power Grid Infrastructure Needs/Expansion

This section demonstrates how smart siting spatial analysis can inform the planning, optimization, and expansion of Portugal's power grid infrastructure for renewable energy integration. Mapping low-conflict, high-development-potential sites for wind and solar can guide grid upgrades and new substation locations, helping grid operators prioritize investments that support rapid, sustainable renewable energy deployment while minimizing environmental and social impacts.

I. Background

All wind and photovoltaic solar power plants require grid access to deliver power to consumers, and infrastructure costs often limit development to areas near existing connections. Additionally, the power grid must have the capacity required to inject and transport the additional power produced by new power plants. In Europe, grids are divided into transmission and distribution systems, typically managed by separate entities: transmission system operators (TSO) handling the national level grid and distribution system operators (DSO) providing more local and consumer-level support.

In Portugal, REN (*Redes Energéticas Nacionais*) is the TSO responsible for management and maintenance of the high-voltage transmission network (RNT) comprised of 400 kV, 220 kV, and 150 kV lines with E-REDES being the main DSO responsible for the medium- and low-voltage distribution network. Both entities work with renewable energy developers, with large-scale projects requiring connections to the RNT and small-scale projects often connecting to the more local distribution network. Regardless of the grid system, developers of renewable energy projects must currently go through a complex approval process across multiple government agencies before producing any power.[62] This process ensures that adequate capacity exists within the grid to transport power across the system from the connection point of the potential power plant. Power plant connections to the grid usually require step-up substations, typically built by the developer or power producer except in some cases when E-REDES invests in local substations to increase electrical supply to a region. In Portugal, most power producers identify the approval process as the major limitation to continued growth of renewable energy development, though the current lack of capacity within either system, but especially the RNT, comes in as a close second.[63]

Meeting future renewable energy targets and power demand will require REN and E-REDES to expand capacity through new lines, upgrades, and grid-enhancing technologies (GET) such as reconducting with advanced conductors or adding devices like flexible AC transmission systems with cost and time requirements decreasing respectively with each option.[64] Recognizing this need, the Portuguese government has committed over €400 million to modernize grid operations and control systems.[65] Additionally, for local community distribution systems to further meet demand, step-up substations can be built to encourage more local renewable energy development, especially PV. Here we propose how our methodology and products developed can be used to help guide grid expansion and further incentivize more wind or solar in areas showing high development potential but low conflict with biodiversity and social values.

II. Guiding Grid Expansion

Smart siting results: Final spatial data from the Portugal Smart Siting analysis identified where optimal locations for future wind and solar development can occur with minimal likelihood of biodiversity and/or social conflicts. To do so, we modeled wind and solar development patterns and selected those technically suitable areas with high probability for future development potential. We then intersected these results with those areas assessed to have low biodiversity values and no potential social impacts. Ultimately a map is produced for both solar and wind which identifies potential "go-to" areas for each technology having high-development-potential and low-conflicts.

Local distributed system expansion: Local distributed systems are mainly provided power from large-scale renewable energy sites delivered by the national grid but often supplemented by more small-scale and local PV power plants.

When planning for new step-up substations, we recommend local communities and E-REDES utilize the PV low-conflict, high-development-potential map to propose these new substations be located near one or more identified areas. We also recommend, if needed, line capacity to be expanded to meet this additional energy being placed within the distributed grid.

National grid system expansion: As of 2024, Portugal's RNT consists of 3.242 km of 400 kV lines, 3.886 km of 220 kV lines, and 2.533 km of 150 kV lines. Given the range of methods available to increase grid capacity, our first recommendation is to prioritize upgrades along existing lines before building new corridors. To guide this, we combined wind and PV low-conflict, high-development-potential maps into a single layer showing all areas with high development potential and low conflict, regardless of technology (Figure 7).

This combined map reveals that grid expansion should focus on the west-central portion of Portugal to the north of Lisbon and south of Porto, where the country's two largest electricity demand centers are located (Figure 8a). Within this area, opportunities exist to increase voltage on 220 kV and 150 kV lines feeding Lisbon and Porto.

Additionally, applying GET, such as reconductoring or flexible AC transmission systems, to 400 kV lines could further boost capacity. All lines crossing or near low-conflict, high-development-potential areas should be considered for upgrades, with priority given to those intersecting the largest clusters of identified sites.

When analyzing low-conflict areas for wind and PV within this region, PV offers significantly more opportunity than wind (Figure 8b). Approximately 1.298 km^2 of land with high PV development potential could support around 65 GW of additional capacity, compared to 231 km^2 for wind, which could provide roughly 2,5 GW. Regions with overlapping wind and PV potential are concentrated north of Lisbon and in the western part of Castelo Branco district. Expanding grid capacity in these zones would enable sustainable growth for both technologies.

Without creating new transmission corridors, the RNT can be expanded within these focus areas to meet Portugal's solar targets on low-conflict lands. For wind, however, new corridors may be necessary to unlock additional potential. Using our intermediary wind model (which excludes grid parameters) we identified low-conflict, high-development-potential lands that would become feasible if new transmission lines were built (Figure 8c). Implementing this approach within the focus area could potentially double wind capacity. While this method relies on intermediary development potential models for precise expansion planning, other low-conflict areas with moderate development potential values (greater than 0,3 and lower than 0,65) from the final model could also be considered for broader grid development strategies.

While smart siting data helps TSOs prioritize low-conflict areas for transmission upgrades or new corridors, grid expansion itself can introduce additional environmental and social impacts. These may include biodiversity fragmentation, landscape alteration, and community-level concerns such as land use conflicts. Therefore, TSOs should adopt robust mitigation measures aligned with the mitigation hierarchy, ensuring early stakeholder engagement, cumulative impact assessments, and proactive planning to minimize these risks.

III. Final Remarks

Coupling smart siting results with grid expansion planning creates more opportunities for developers to build new power plants sustainably and at lower cost. Identifying regions with the highest concentration of low-conflict, high-development-potential lands provide clear guidance to grid managers on where to prioritize capacity upgrades, while expansions in these areas directly incentivize renewable development.

Aligning these regions with major demand centers, such as Lisbon and Porto, further reduces transmission losses by matching low-conflict sites to nearby consumers. Expanding grid capacity in these zones also helps avoid development in environmentally and socially sensitive areas elsewhere in Portugal. Overall, integrating low-conflict lands into grid investment planning through smart siting, supported by policies that incentivize this approach, ensures future renewable energy growth aligns with environmental and social safeguards.

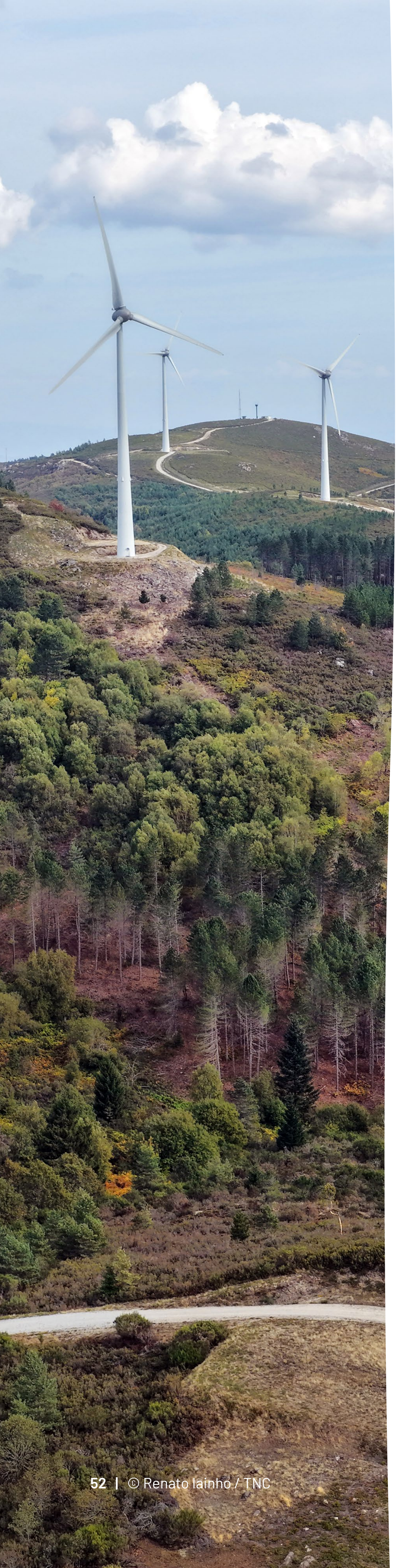


FIGURE 7: Map of current transmission lines within Portugal managed by REN with combined high development potential for wind and solar PV on low-conflict sites.

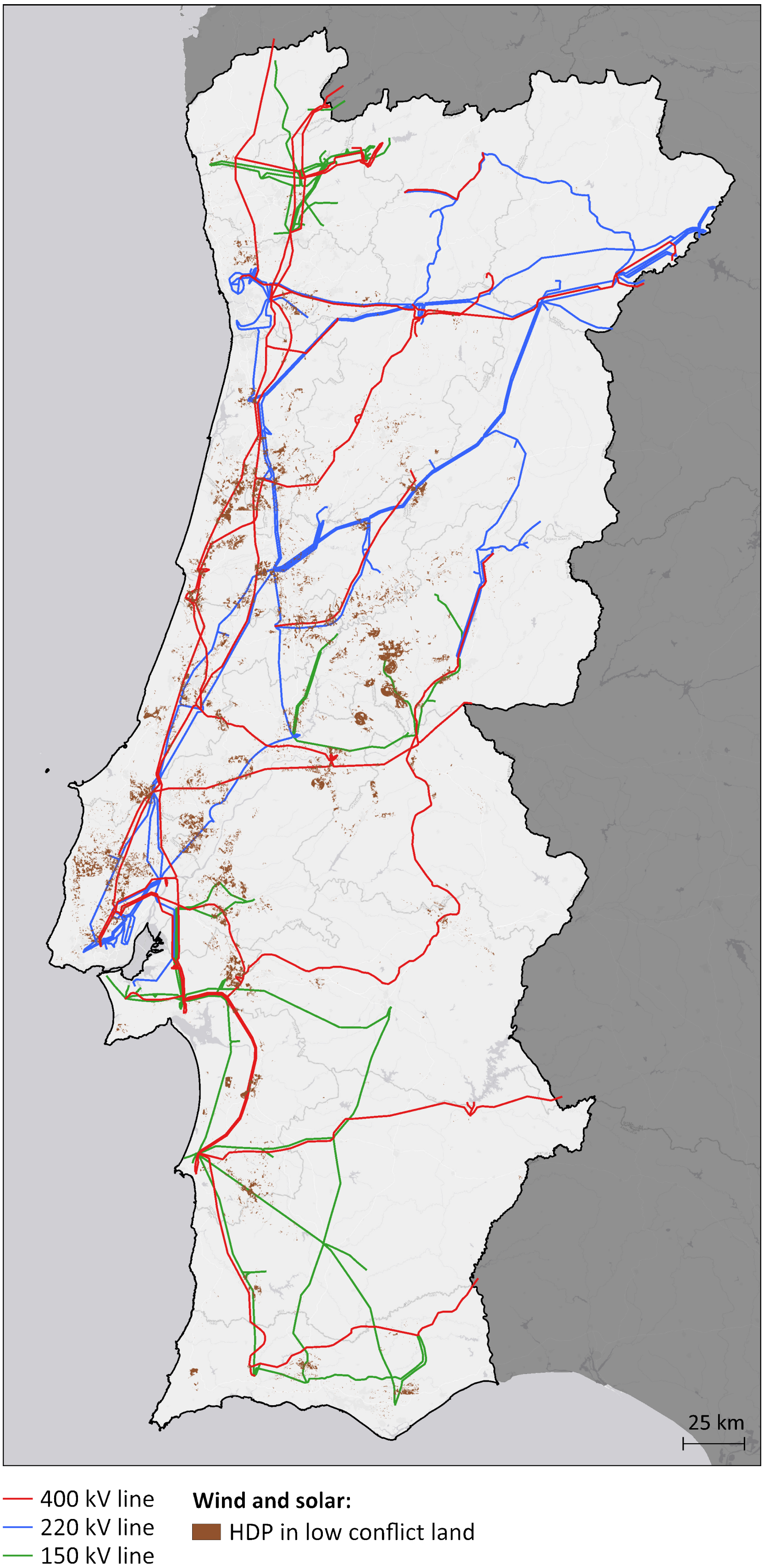


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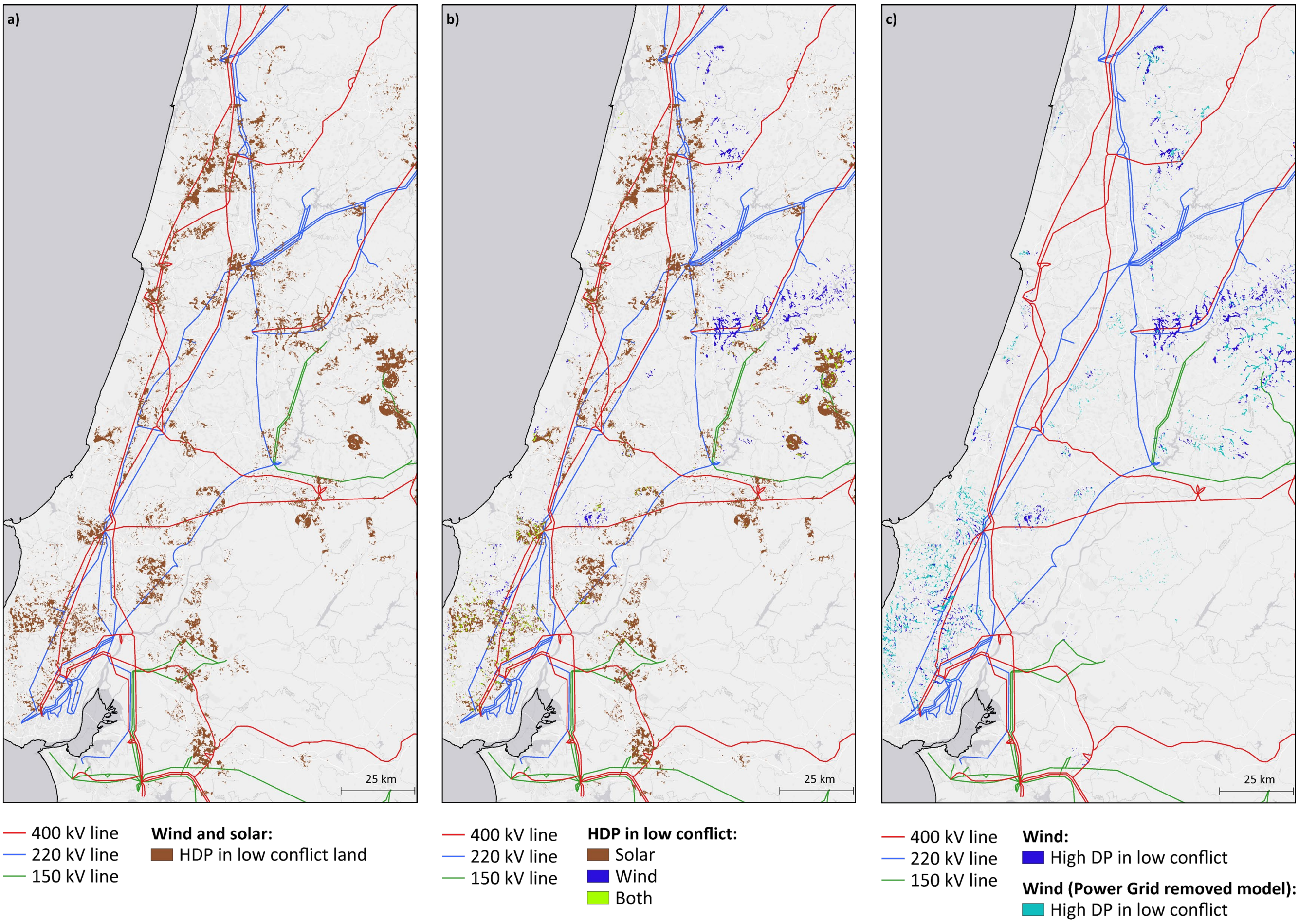
FIGURE 8: Map of current transmission lines within the Portugal national grid managed by REN with combined high development potential for wind and solar PV on low-conflict sites where a) The zoomed area and detailed map highlight a priority area for potential grid expansion; b) with only wind, only solar PV, and overlapping areas for both technologies and c) with combined wind high development potential on low-conflict sites identified by the final wind model and by an intermediary model that excluded all power grid parameters.



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Supplement III: Blending Landscape-level Planning With the Mitigation Hierarchy

I. Introduction

To meet global climate targets and prevent the most severe consequences of climate change, greenhouse gas emissions must be cut nearly in half by 2030 and reach net-zero by 2050. Achieving this rapid transition from fossil fuels to renewable energy demands the thoughtful expansion of wind and solar power, with a strong emphasis on preserving ecosystems and respecting community values. An approach that integrates landscape-scale spatial planning with the mitigation hierarchy enables planners to balance energy expansion with biodiversity conservation.

The scale of the necessary transition is immense: recent studies estimate that the EU will need land-based wind and solar installations covering about 164.789 km^2 by 2030 and expanding to 445.654 km^2 by 2050, roughly the size of Sweden.[32] Depending on the chosen development path, by 2030 solar and wind projects could affect between 4.386 km^2 and 20.996 km^2 of natural land and 65.735 km^2 to 138.454 km^2 of agricultural land. These impacts are projected to grow significantly by 2050, with solar potentially affecting up to 33.911 km^2 and wind up to 399.879 km^2.

Current development trends often target areas with high land use conflict, underscoring the need for strategic planning to balance competing interests, especially in regions with high land demand or limited suitable space. Low-conflict areas offer vast renewable energy potential: up to 6.6 million GWh from solar and 3.5 million GWh from wind. These figures far exceed 2030 targets, offering capacity for eight to 31 times the solar, and three to five times the wind energy goals. After prioritizing low-conflict areas, tailored mitigation strategies can be applied in moderate-conflict zones to support sustainable and policy-aligned project outcomes.

Countries with high emissions and ambitious renewable targets (such as Germany, Italy, Poland, France, and Spain), as well as those with restricted options for low-conflict development (such as Albania, Slovenia, Montenegro, Hungary, Croatia, Serbia, Bosnia and Herzegovina, Finland, Greece, Portugal, and Norway), should be prioritized for tailored strategies that minimize environmental and social disruption.

II. Environmental Licensing

Environmental licensing, particularly Environmental Impact Assessments (EIAs), is a vital tool for regulating how development projects affect the natural world. In most countries, developers must secure an environmental permit before initiating construction or other activities, and EIA legislation is now in place in nearly every nation globally.[66] These permits are typically granted based on how well anticipated environmental harms are addressed or on meeting specific conditions set by regulatory authorities. An EIA is a structured, iterative process designed to evaluate the environmental implications of proposed developments, with a strong focus on forecasting and preventing ecological damage.[67] At the heart of this process is the mitigation of environmental impacts, guided by the mitigation hierarchy of avoid, minimize, restore, and offset.

- **Avoidance** involves proactive steps to prevent harm altogether, such as choosing infrastructure locations and timelines that reduce ecological disruption.
- **Minimization** aims to lessen the severity, duration, or scope of unavoidable impacts.
- **Restoration** focuses on rehabilitating ecosystems that have been degraded or cleared.
- **Offsetting** compensates for residual impacts through actions like habitat restoration, risk reduction, or protection of areas facing imminent biodiversity loss.[66,68]

The use of this hierarchy to meet biodiversity targets has gained global momentum, influencing public policy, financial lending standards, and corporate practices. Leading financial institutions, including the International Finance Corporation (IFC) and over 70 Equator Principles signatories, require funded projects to follow this framework. This means prioritizing the avoidance of harm to biodiversity and ecosystem services, and where avoidance isn't feasible, ensuring impacts are minimized or restored. In ecologically critical areas, projects must deliver net positive outcomes for biodiversity values. Comparable standards are enforced by the European Bank for Reconstruction and Development (EBRD).[69,70]

As these guidelines evolve from voluntary best practice to formal compliance, businesses increasingly integrate them into biodiversity strategies and operational norms, treating them as standard practice.[71]

While biodiversity offsets offer advantages for industry, governments, and conservation organizations, implementation faces conceptual and practical challenges. Key concerns include the assumption that all habitats can be offset, an approach that is not always feasible, and the recurring lack of long-term planning and maintenance funding required to guarantee that the offset efforts reach full ecosystem integration. This raises a critical question: under what circumstances are offsets a suitable solution? As offsets become more widespread, developers must adhere to the mitigation hierarchy on-site, only using offsets for residual impacts.[66] Yet clear quantitative criteria to guide these decisions are often lacking, making consistent application difficult in practice.

In Portugal, the licensing process is conducted by the licensing authority, which for energy projects is the Directorate-General for Energy and Geology (DGEG). Depending on the scale of the project, DGEG is either required to subject the project to an Environmental Impact Assessment (EIA) process (for larger projects, greater than 100 ha or than 50 MW) or has discretionary power to decide whether an EIA is required (for smaller projects). Since 2023, following the entry into force of Decree-Law no. 11/2023, (also known as "environmental SIMPLEX"), a wide range of projects below the thresholds of 100 ha or 50 MW have ceased to be subject to mandatory EIA.

For projects that do undergo an EIA, the process is initiated and mediated by an environmental authority, which is typically the Portuguese Environment Agency (APA) but, in some cases involving more localized impacts, may be the respective Regional Coordination and Development Commission (CCDR). The EIA study, prepared by an environmental consultancy firm, is submitted to an evaluation commission composed of several entities, such as the Institute for Nature Conservation and Forests (ICNF), and chaired by the environmental authority. This commission operates under a tight schedule to analyze the documentation, open a public consultation process, consolidate inputs, and issue a final decision, generally within a timeframe of approximately 50 to 90 days.

This process relies on several key factors that must be ensured in order to establish a robust and credible EIA framework. Environmental consultancy firms must adhere to high standards of scientific rigor, for example through certification by regulatory or professional bodies. Environmental assessment authorities should be supported by adequate legal frameworks and sufficient human resources to effectively analyze projects and approve those that meet environmental requirements. Information should be readily accessible to all relevant stakeholders, in order to reduce redundant data collection, optimize processes, and enhance transparency. Finally, public consultation is critical to preventing future social opposition to projects and should be conducted at early stages of the licensing process.

III. Mitigation Planning: Blending Conservation Planning and the Mitigation Hierarchy

Conservation planning offers a structured method to align mitigation strategies with broader conservation objectives.[72,73] This approach often focuses on preserving large, resilient ecosystems that support both wildlife and human well-being. Integrating the mitigation hierarchy into conservation planning provides several advantages over isolated, project-specific efforts: **i)** It accounts for cumulative effects from existing and future development activities; **ii)** It introduces a regional perspective, guiding decisions on whether to avoid impacts entirely or apply offsets; **iii)** It enhances flexibility in selecting offsets that deliver the greatest conservation value, particularly by directing resources toward the most vulnerable habitats and species.

Landscape-scale conservation planning involves identifying, designing, and managing areas to ensure the long-term survival of biodiversity and other ecological assets.[74] At its core, this approach centers on crafting a clear and comprehensive biodiversity vision that reflects the full spectrum of biological elements, their current distribution, and the minimum conditions each species or ecosystem needs to thrive over time. Developing and executing this vision requires collaboration across sectors, including government agencies, multidisciplinary experts, development partners, and local communities. The aim is to produce a rigorously reviewed conservation strategy with actionable steps that gain broad support and are effectively put into practice by all stakeholders.

IV. Adapting Mitigation Planning for Renewable Energy Development: A Conceptual Example in Portugal

Here, we use the conservation assets selected as priorities (Section 4.1) to illustrate how the mitigation hierarchy can balance conservation objectives with impacts from future renewable energy development. Since only a small portion of Portugal's land falls into the high-conflict category with high development potential, most conflicts can be avoided by redirecting investment toward areas with lower conservation value, thereby minimizing impacts on ecologically sensitive zones (Figure 9).

To illustrate conceptually how to apply the mitigation hierarchy, we examined the intersection between areas with conservation values from moderate-low to moderate-high conflict categories with the high-development-potential category. For wind and solar development, these numbers are approximately 790 km^2 and 9.100 km^2, or respectively 0,9% and 10,2%, of mainland Portugal area. These sites would receive different mitigation recommendations, depending on the nature and distribution of conservation targets that the sites could conserve. In our example, nearly 1.250 km^2 (approximately 1,4% of mainland Portugal) overlap high-development-potential and moderate-low conflict zones, where offsets could mitigate impacts from renewable energy development. These landscapes may support some ecological functions but do not host species of high conservation concern and have a low level of ecosystem-level sensitivity so impacts could be offset.

Moderate-conflict sites overlap with areas of high development potential across nearly 6.200 km^2 (almost 7%) of Portugal's mainland area. These areas contain species of conservation interest and ecosystem-level sensitivity but are not classified as critical; they still require careful planning and ecological review.

Nearly 2.500 km^2 (2,8% of Portugal) falls within the moderate-high conflict category. These areas are not flagged as ecologically critical by the coarse filter but often lie adjacent to protected areas and may serve as corridors or buffer habitats, supporting species movement and connectivity. They also host sensitive or threatened species, making them ecologically significant despite moderate ecosystem-level indicators. These areas require careful planning to avoid unintended impacts on biodiversity. In both moderate and moderate-high conflict sites, the first step is to avoid disturbance to critical species habitats and minimize indirect impacts (e.g., spread of invasive plants). If wind development is proposed and sensitive birds and/or bats are present, developers would need to curtail activity during migration or other seasonal movement events. In areas important for species movement and connectivity, development must ensure it does not create barriers to movement. Secondly, only in the last resort situation of unavoidable impacts to ecological systems present within the site, the environmental authorities should impose offset obligations to the project.

Approximately 6.000 km^2, or roughly 6,8% of Portugal's mainland area, is classified as high-conflict sites that overlap with high development potential and represent areas identified by the coarse filter with elevated values, regardless of species-level sensitivity. These zones include protected areas, rare habitats, and landscapes with high ecological connectivity, all of which are essential for maintaining ecosystem integrity. Due to their critical role in biodiversity conservation, development in these areas is strongly discouraged as it is likely to lead to conflicts and projects delays and cost overruns. In areas where existing renewable energy already exists, developments could be "repowered" to improve efficiencies, only if enough precautions are put in place and the mitigation hierarchy is implemented correctly, since "repowering" is not exempt of significant impacts.

At the sites where conflicts can be resolved, development could proceed with a greater degree of flexibility in applying the mitigation hierarchy, so that residual impacts are managed through the use of on-site minimization, restoration, and offsets (Box 2). For example, a development proposed within sites that would result in residual impacts to widespread ecological systems could be offset. Applying the "no-net-loss" concept to impacts associated with development at this site and offsetting any residual impact would be consistent with the goals of maintaining broad scale conservation. Moreover, this landscape-scale perspective provides the opportunity to maximize offset benefits, for example, by directing offsets at other sites where these ecosystems occur (in-kind offsets) or toward targets of greater conservation value (out-of-kind offsets).

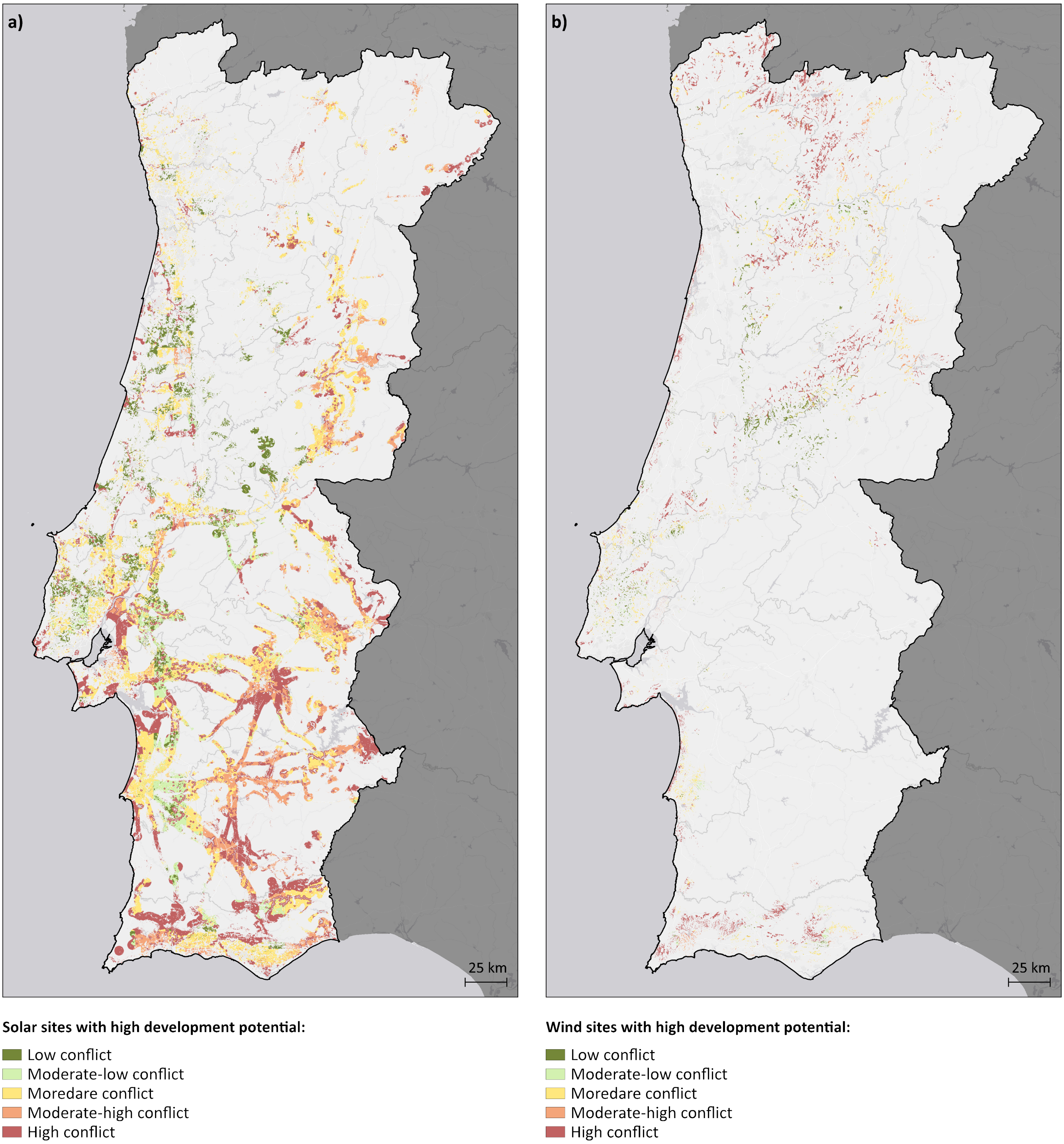
If these systems are widespread, highly conserved, and occur in areas not judged to be at great risk, directing offsets at targets considered to be irreplaceable (e.g. rare and/or under threat of conversion) will result in a higher conservation return. Moreover, if mitigation decisions are better coordinated with broader conservation goals and targets, as we suggest here, they can be used to accomplish other targets, such as nature-positive efforts.

At sites containing irreplaceable targets, however, greater emphasis will be given to avoidance or minimization. This means that avoidance or minimization strategies should be considered in order to maintain viability of the target species. These target species are critical, as they are extremely rare, or face other factors that place them at risk. Because there is limited flexibility in where these target species can be conserved, impacts on such a site would make meeting landscape conservation goals difficult. Proposed developments at these sites would most likely be rejected. Many consider offsets an opportunity to develop projects within areas that should be avoided, but following a landscape-scale vision for the mitigation hierarchy should circumvent those decisions. That said, offsets need both a strong policy and strong implementation to be successful.

V. Conclusions

As renewable energy development scales up to combat climate change, the strain on natural resources will intensify.[32] To reconcile these growing demands with the need to protect biodiversity, a departure from conventional development practices is essential. Integrating a forward-looking landscape strategy with the mitigation hierarchy allows us to move beyond piecemeal, project-by-project planning.

FIGURE 9: High-development-potential sites that overlap that overlap with biodiversity conflict areas for a) solar and b) wind.



This integrated approach involves first avoiding or minimizing harm to critical ecological assets, then restoring affected ecosystems using the most advanced techniques available and finally offsetting any residual damage. Such a framework aligns with the principles of sustainable development. A landscape-level vision is crucial as it ensures that key ecological features remain central to conservation efforts throughout the planning and implementation process. Without it, conservation goals become fragmented, prioritization suffers, and limited resources may be misallocated. While identifying which areas to protect as habitat is a complex task, it is often more straightforward than securing the financial resources needed to maintain them. By embracing this strategy and enforcing the no-net-loss principle,[72] we not only strike a balance between development and conservation but also establish funding mechanisms that reflect the true environmental cost of development.

Supplement IV: Importance of Stakeholder Engagement

I. Introduction

Early and inclusive stakeholder engagement plays a critical role in renewable energy siting and planning, contributing valuable data and insights that can help to identify values that need spatial representation.[75,76] Engaging diverse stakeholders and communities ensures that local priorities, knowledge, concerns, and planning needs are reflected in spatial planning, leading to more equitable and successful renewable energy projects that are accepted by their neighboring communities. This approach stands in stark contrast to the kind of one-sided, inadequate consultations that are deferred to the end of the process, often leading to backlash and opposition.[77,78] Whether local communities are concerned about environmental impacts, aesthetics, or changes in local landscapes, their opposition can cause project delays and cancellations,[79] harming the companies' profitability and reputation, and slowing down the energy transition.

In the preparation of this guide, we engaged stakeholders in an open process of engagement and expert consultation at the national and international level, across different sectors: public administration, renewable energy, civil society organizations, academia, and consulting. The full list of participating organizations, programs, and outcome documents can be provided. Due to time and resource limitations, the project did not conduct a full community engagement process on a national scale. However, a pilot participatory local community meeting was performed in one municipality, which allowed us to formulate clear recommendations for the future (Supplement V).

II. Stakeholder Mapping and Prioritization

A total of 140 experts (78 men and 62 women) were engaged in the study, representing a wide spectrum of stakeholders from the Portuguese and European renewable energy policy, spatial planning, biodiversity, and social sciences fields. The experts were affiliated with 68 entities, including academia and research institutions, environmental and energy consultancies, NGOs and civil society organizations, renewable energy developers and industry representatives, public institutions, and international organizations.

Through a stakeholder mapping exercise, we ensured balanced representation of interests for renewable energy development in Portugal. We collected targeted feedback from the resulting group of experts at strategic study milestones: inception and subsequent progress stages. The pilot local community engagement event took place in the Silves Municipality and involved 19 community members (8 women and 11 men), representing various sectors such as citizen associations, social services, civil society, tourism, sports, cultural organizations, energy cooperatives, agriculture, youth, and the elderly. The majority of the participants were aged 50 to 65.

III. Engagement Methods and Tools

Engagement formats

- **In-person international stakeholder meeting:** An in-person workshop was organized in Lisbon in collaboration with TNC's local partner ZERO. It was held on 22 February 2024, bringing together 56 Portuguese and European international policy and spatial science experts from governmental bodies, academia, decision-making bodies, the renewable energy industry, and civil society. Through a dialogue focused on science and policy, participants discussed and explored common approaches to siting: methodology, governance, and implementation.

- **In-person national events:**
    - *In-person workshop for biodiversity, social science, and energy experts:* Held in Lisbon on 11 September 2024, this in-person event included 29 Portuguese biodiversity, social science, and energy experts from academia, public entities, civil society, and the energy industry. The primary objectives of this workshop were to fill data gaps and to get expert input on the relevance and importance ranking of the data under consideration.

- *Advisory group meeting:* A smaller group of 10 experts was convened to provide ad-hoc advisory feedback, drawing from high-level decision-makers from public authorities, experts, and scientists from the electricity industry, the Portuguese TSO REN, NGOs, and consulting and research centers. The objective was to validate preliminary findings and ensure applicability within the Portuguese context. The meeting was held in Lisbon on 12 September 2024.

- **Expert webinars:** Three webinars were held on 10 July 2024, 11 July 2024, and 12 September 2024, focused respectively on biodiversity, social sciences, and energy. The webinars were attended respectively by 25, 21, and 45 European and Portuguese biodiversity, social science, and energy experts from governmental bodies (including ICNF and APA), academics, decision-makers and Portuguese renewable energy industry representatives (including those from REN). The focus was on data selection and availability, biodiversity values at a country level, definition of social values in the context of renewable energy projects, possible social conflict hotspots in Portugal, renewable energy development constraints, and parameters of development potential modeling.

Community engagement pilot workshop (Silves)

This project included a pilot community engagement meeting, run in collaboration with ZERO. While limited in scope due to resource constraints, the meeting serves as a replicable model for incorporating participatory approaches in renewable energy siting. The information acquired through this event was not used for modeling, but the resulting guidelines could inform local authorities and developers of the best practices for inclusive and transparent engagement. The event was held in Silves in April 2025.

Selecting a target area for community engagement: Using a standardized set of pre-screening criteria, including preliminary results on low biodiversity and social conflict and energy development potential, candidate municipalities were shortlisted and cross-checked with: **i)** a bibliographic review aimed at identifying the main geographical patterns of social conflict related to wind and solar development in Portugal and **ii)** a SWOT analysis, drawing from ZERO's on-the-ground experience and local contacts, incorporating known conflicts and relationship with the community and local authorities. While Silves was the final selection for the pilot activity, we note that the final results of this study ultimately identified significantly more conflict area in the municipality than estimated in our preliminary data layers. Still, our summary insights and participatory mapping activity provide useful information on local-scale dynamics, perspectives, and co-created community value clusters.

Community engagement plan: To characterize the local community and ensure representative sampling, ZERO performed a specific demographic and socioeconomic context analysis. A comprehensive community engagement plan was then drawn up, outlining goals, stakeholder groups, and the purpose of engagement. The primary goals were to: (**i**) validate the smart siting results, based on national-level data, in one "test site", (**ii**) understand local communities' needs and visions regarding renewable energy development, and (**iii**) assess conditions of acceptance, potential benefits, and engagement preferences. The targeted stakeholders included municipal leaders, farmers (including smallholders), local civil society, religious and cultural groups, public servants, youth, tourism, sports and recreational associations, and the academic community.

Facilitation techniques and tools

Breakout groups into areas of expertise: In-person expert workshops included breakout discussion sessions that grouped participants based on their field of expertise, facilitating focused conversations on specific subjects. The groups then reported back to the larger assembly with clear, shared feedback. Topics discussed with this method in the various workshops included siting methodology, local, national, and European policies to guide designation and implementation of RAAs and broader energy spatial planning, the ranking of biodiversity and social indicators by importance in the local context, and the preliminary results of predictive modeling.

Facilitated focus group discussion: In Silves, participants were divided into three groups, each with a mix of individuals selected with a goal of mitigating potential power dynamics. In each group, the facilitators guided the discussion to get insights into local needs, values, and visions regarding solar/wind development, conditions that influence acceptance or resistance to renewable energy projects, preferences for engagement methods and governance/decision-making approaches, previous and ongoing experiences with public consultation processes, and enabling factors for fair benefit sharing. The discussions were recorded and analyzed through thematic coding and latent content interpretation in order to outline the main patterns regarding social value categories, siting/technological preferences, and public participation practices.

Presentations and Q&A sessions: In all in-person and online engagement events, presentations were used to keep stakeholders informed of the methodology development and preliminary results, and to get feedback from local experts about the relevance of modeling results for the national context and processes. Apart from presentations by TNC scientists, these included contributions from external experts from LNEG, SPEA, and the University of Bergen.

Questionnaires: For structured input and feedback, participants in expert meetings were given questionnaires, either in person during the events, or online to give them time to provide complex feedback. This approach was followed for biodiversity value ranking, the identification of social conflicts with renewable energy development, social value datasets, and technical parameters of renewable energy development predictive modeling.

Pilot usage of participatory mapping tools: We used the Public Participation GIS (PPGIS) tool, developed by TNC for participatory mapping of select local values, at the Silves community engagement meeting (Supplement V). Participants individually entered their social values into the platform, pinpointing their areas of interest on their smartphone or tablet. Given the pilot nature of this event, the collected data is not included in the overall social value dataset of the study (Section 2.3). However, it gave TNC valuable qualitative information to contextualize the national-level analysis, and to validate social value mapping outputs, analyzing how local-scale, community values attributed to the landscape differ from (or correspond with) the pre-screened spatial conflict data developed through the national scale, coarse-filter approach.

IV. Key Insights

a) Policy and Governance: Implementation of the EU REDIII is hampered by procedural ambiguities, especially regarding the Strategic Environmental Assessment for RAAs. Portugal's early mapping of RAAs, before completing national energy mapping as required by REDIII, has created additional confusion. Project-level screening criteria remain ill-defined, the definition of "significant impact" is still unclear, and concerns remain as to whether permitting authorities have the capacity to meet RED's ambitious deadlines.

i) *Public participation:* Lack of coordination among authorities and "one-stop-shops" makes stakeholder engagement less effective, and engaging local actors across Portugal's 300 municipalities is resource-intensive. While public participation is valued, authorities struggle with staff shortages and recruitment.

ii) *Mitigation:* Achieving 2030 renewable energy targets will require clear mitigation guidelines and ongoing environmental monitoring, especially as projects expand beyond RAAs.

iii) *Benefit sharing:* Equitable distribution of benefits is key to securing community support for renewable energy projects.

iv) *Artificial areas and dual land use:* Limited data availability and site accessibility remain practical challenges to implementing the broadly supported view that RAAs should prioritize artificial areas and dual land use models such as Agri-PV (agricultural photovoltaics) to minimize land use conflicts.

b) Biodiversity: High-value Mediterranean agricultural landscapes, such as dryland cereal fields and the extensive pastures of Alentejo, play a crucial role in supporting threatened steppe birds. The importance of distinguishing between different land types and management practices in biodiversity assessments, was also highlighted. For instance, native forests like cork oak, stone pine, and chestnut are recognized as more ecologically valuable than monoculture plantations such as maritime pine. Experts recommended broadening the range of datasets used in ecological modeling to include information on invertebrates, birds, bats, mammals, flora, and grid infrastructure. Finally, the integration of ecosystem services, such as water regulation, soil protection, and biomass storage, into renewable energy planning is seen as beneficial for maintaining these environmental functions.

c) Social Values and Justice: Renewable energy development can put pressure on iconic landscapes, agricultural land, and local economies, especially in regions reliant on tourism and farming. While aesthetic impacts are recognized as subjective and variable, ensuring fair distribution of economic benefits and protecting agricultural land are key concerns. Social conflict often arises not from opposition to renewables themselves, but from a lack of transparency, limited opportunities for community participation, and exclusion from decision-making and ownership.

i) *Conflict hotspots:* Experts have identified several conflict hotspots, particularly for solar in the Algarve and Alentejo, and for wind in northern and central Portugal. To improve planning, experts recommend refining data and modeling, including better viewshed analysis and more local context.

d) Energy Development Potential: For wind, experts recommend stricter siting criteria, including higher minimum wind speeds, slope limits, and buffers around existing turbines, while generally excluding artificial surfaces except for industrial zones. For solar, there is consensus on prioritizing flat artificial areas and setting appropriate slope thresholds, but less agreement on using solar irradiance as a constraint. Both technologies require careful calibration using up-to-date production data.

i) *Grid integration:* The availability of grid connections is a critical factor, yet data on grid capacity and expansion plans is often lacking. As a result, development potential appears concentrated in southern Portugal, where grid access is better, while northern and central regions face more constraints despite having lower biodiversity value.

e) Cross-cutting Issues: Renewable energy mapping must be tailored to each technology, as wind and solar projects have different spatial, ecological, and social impacts. Integrating these aspects into a single planning framework is methodologically complex and requires high-quality data and technical expertise. The ongoing debate over whether to prioritize large installations or multiple smaller projects ("SLOSS") remains unresolved, especially given the potential for cumulative impacts.

V. Challenges and Lessons Learned in Stakeholder Engagement

The stakeholder engagement process revealed several important challenges and lessons for future renewable energy planning in Portugal. One of the most significant issues was the limited participation of local administrations in national-level engagement activities. Despite concerted efforts to involve municipalities, national and local engagement processes often remained disconnected, missing opportunities to bridge perspectives and priorities between different levels of governance. Feedback from participants suggests that a lack of financial and human resources, as well as insufficient incentives, hindered the sustained involvement of local institutions. While the pilot engagement event in Silves demonstrated genuine interest and willingness to participate among local institutions and communities, scaling this approach to a broader and more representative sample of municipalities will require additional resources and support.

A persistent challenge is the limited accessibility and quality of key datasets, particularly regarding electricity transmission and distribution infrastructure. Despite the involvement of the Portuguese TSO (REN) in advisory processes, confidentiality and security concerns have restricted access to comprehensive network data, making it difficult to accurately assess current grid capacity or plan for future expansion in a usable format. This limitation undermines the robustness of renewable energy development potential modeling and complicates the identification of suitable areas for deployment. Similar data gaps are evident in other EU Member States and literature recommends that strengthening data collection practices, ensuring regular updates, and improving coordination between national, regional, and local authorities are essential steps to overcome these barriers.[80] Without high-quality, up-to-date, and accessible data, Member States risk misidentifying suitable areas, underestimating grid constraints, and ultimately slowing progress toward renewable energy targets.

VI. Recommendations for Future Engagement

To improve future stakeholder engagement in renewable energy planning, it is essential to begin the process early and maintain it throughout all stages of project development. Early involvement of stakeholders ensures that local priorities and concerns are integrated into decision-making, which helps to build trust and reduce the risk of opposition or project delays. Engagement should be broad and inclusive, involving not only national authorities and industry representatives but also local administrations, civil society organizations, and subject-matter experts. Special attention should be given to municipalities, whose participation is crucial for bridging national and local perspectives.

A variety of engagement formats should be used to reach different audiences and accommodate diverse preferences. In-person workshops, online webinars, surveys, focus groups, and participatory mapping tools can all contribute to a more accessible and effective process. Building local capacity is also important; providing training, resources, and incentives enables community members and local institutions to participate meaningfully and offer informed feedback.

It is also important to tailor engagement strategies to the specific needs and contexts of each community or region. Representative sampling and context analysis can help ensure that local voices are genuinely reflected in planning outcomes. Coordination between national, regional, and local authorities should be promoted to align spatial planning frameworks and stakeholder engagement practices, avoiding disconnects and ensuring that local perspectives inform national policy.

Supplement V: A Pilot Participatory Mapping Exercise in Silves Municipality

To explore how local community values align with national-scale coarse-filter datasets used in renewable energy siting, we conducted a pilot participatory mapping (PPGIS) exercise in the municipality of Silves. The workshop engaged 18 participants who mapped 160 points across five social value categories: cultural (40), landscape/visual aesthetics (38), biodiversity (34), agricultural (31), and economic/tourism (23). Details of the broader stakeholder engagement process can be found in Supplement IV.

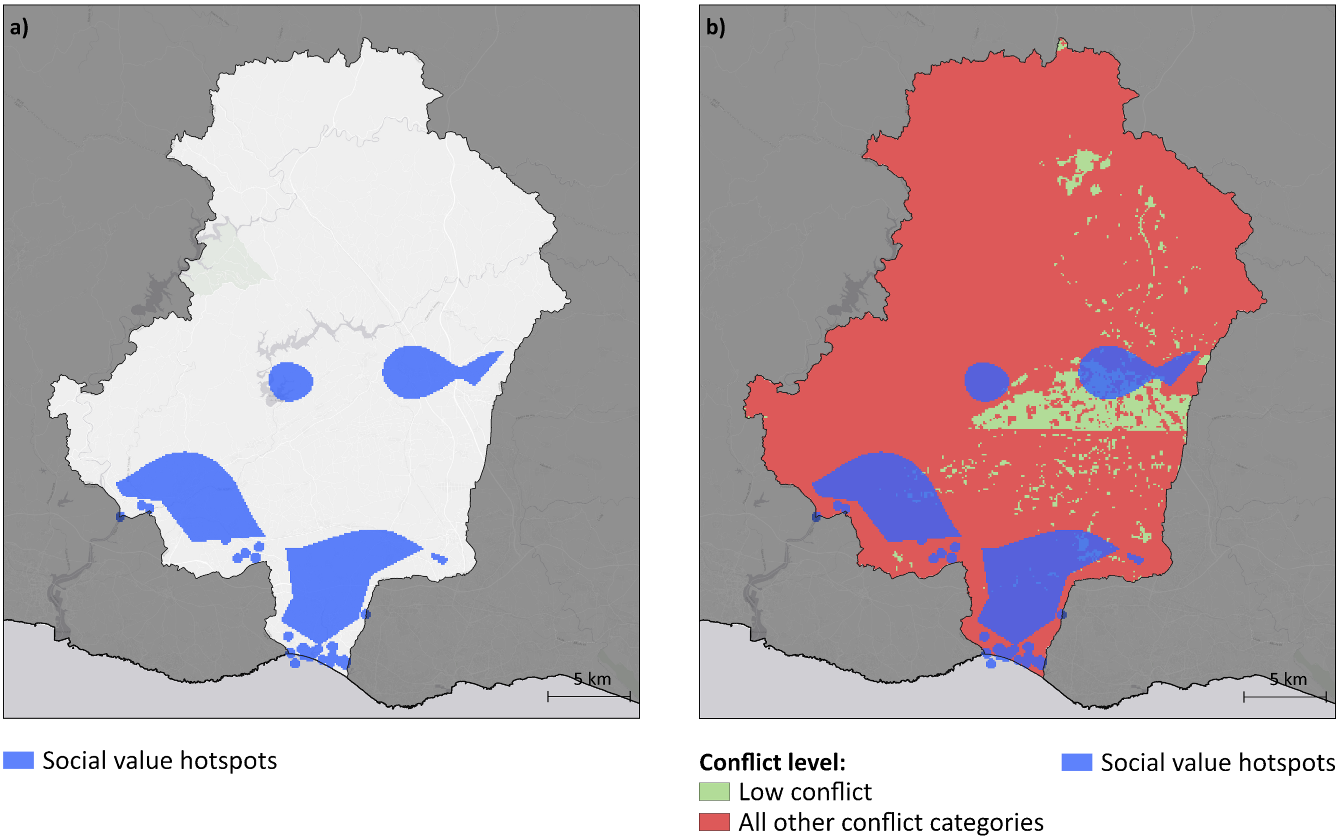
In order to transform these points into spatial maps representing social hotspots, we used kernel density estimation (KDE) with automatic bandwidth selection and scaling for interpretability (REF). Hotspots were extracted by retaining 70% of mapped points within the highest-density KDE cells, producing polygons suitable for visualization and comparison with our coarse-filter outputs.[81] The spatial analysis included a 300 m buffer around the municipality boundary to ensure all mapped points were retained.

The KDE analysis revealed 11 hotspot clusters covering approximately 13% of Silves (roughly 85 km^2), while capturing approximately 70% of all mapped points. The patch sizes from these cluster ranged from 0,3 km^2 to 35 km^2, which indicates that participants concentrated values in specific areas, while also recognizing dispersed landscape importance (Figure 10a).

When compared to our national conflict raster, over 90% of hotspot areas overlapped with zones previously classified as having potential conflict (Figure 10b). This pattern generally aligned with what was expected from the coarse-filter layer, which indicated large portions of the municipality as high-conflict, when combining all the conflict layers. Only 8% of the pooled hotspots fell in "non-conflict" zones, and in most cases those areas were located adjacent to areas of potential conflict. If we consider value-specific hotspots, clusters pertaining to biodiversity and economic/tourism values were almost entirely within areas we had identified as conflict zones (more than 97%). Hotspots for landscape value and visual aesthetics had the greatest representation, with nearly 13% falling outside of known, pre-screened conflict areas. These patterns indicate that in this population sample of public participatory mapping, the local data was well-aligned with the coarse-filter datasets but also provided insight to the relative priorities (social value types) within a blanket "conflict" designation.

These findings highlight the value of participatory mapping in refining national-scale assessments and identifying locally significant areas that may warrant special consideration.

FIGURE 10: a) Pooled social value hotspots in Silves. Participant points are masked to protect exact locations and considering a minimum density threshold that captured approximately 70% of the points and b) Hotspot polygons for pooled social value points overlaid with lands classified as "conflict" per environmental and social data.



Supplement VI: EU RED Policy Mandates for RAA Designation and Accelerated Permitting

The European Union's Renewable Energy Directive (EU RED) [16] has become the cornerstone of the continent's push to accelerate renewable energy deployment in response to geopolitical shocks, most notably the Russian invasion of Ukraine. This crisis prompted the EU to urgently reduce its reliance on imported natural gas by increasing its renewable energy target for 2030 to at least 42,5%, and aiming for 45%. To meet this goal, Member States will need to install an additional four to 15 times the installed capacity of solar by 2030 and more than double wind production, ultimately tripling clean energy capacity, by 2030.[82] Science shows that if policy and implementation prioritizes low-conflict areas, the EU has enough low-conflict land to achieve its 2030 targets.[32]

EU RED also compels Member States to fast-track permitting for renewables through a suite of RED articles and supplementary guidance.[83] It sets out explicit mandates and deadlines for coordinated spatial mapping and Renewable Acceleration Areas (RAAs), and the designation of grid-dedicated areas, emphasizing a coordinated approach to land use and energy planning.

The following text summarizes key articles of EU RED that are relevant to this process and how this guide aims to steer the implementation of those articles in Portugal:

Article 15b: Member States are required to spatially map all technically suitable areas for renewable energy deployment to achieve their 2030 targets under their National Energy and Climate Plans (NECPs). For the purpose of identifying these areas, this article asks Member States to take into account resource availability, technology-specific feasibility potential, projected energy demand, and availability of relevant energy infrastructure, including grids, storage, and other flexibility tools, or the potential to create or upgrade such grid infrastructure and storage. The deadline for this exercise was 21 May 2025. Chapter 3 of this Smart Siting Guide presents the results for the spatial modeling for wind and solar, identifying areas that are feasible for renewable energy development and can directly support Member States in fulfilling the mapping requirements outlined in the EU Renewable Energy Directive. The data on available low-conflict land with assumed grid infrastructure can guide upgrades to existing grid infrastructure.

A part of the RAA maps is a "**mitigation rulebook**," that, according to Article 15b, outlines rules for ensuring effective mitigation of environmental impacts that a specific renewable energy technology might have in a particular RAA.[84] Member States are asked to adopt mitigation rulebooks targeted to the designated area, technologies, and identified environmental impacts. Where appropriate, those measures should ensure compliance with requirements of environmental regulation. Supplement III of this guide, which not only outlines the integration of landscape-level planning with the mitigation hierarchy, but also illustrates a conceptual example for Portugal, can directly provide insights in the development of the mitigation rulebooks.

Article 15c: Member States are mandated to enable the designation of RAAs within the mapped areas of Article 15b by 21 February 2026 using transparent and science-based spatial mapping. RAAs are introduced as fast-track permitting zones, a subset of the national spatial maps designed under Article 15b, where projects would be exempted from EIAs but the proposed RAAs would go through a SEA process before developers can apply for those fast-track permits. The projects that apply for permits would then go through a project-by-project screening process by the permitting authority in a short amount of time. Chapters 3 and 4 of this guide can contribute to the adoption of final RAAs in Portugal, as the current proposal will go through a Strategic Assessment, by integrating energy potential, land use, biodiversity, and social value layers. Moreover, Supplement IV shares insights on how systemic stakeholder engagement could be applied, as well as lessons learned and recommendations.

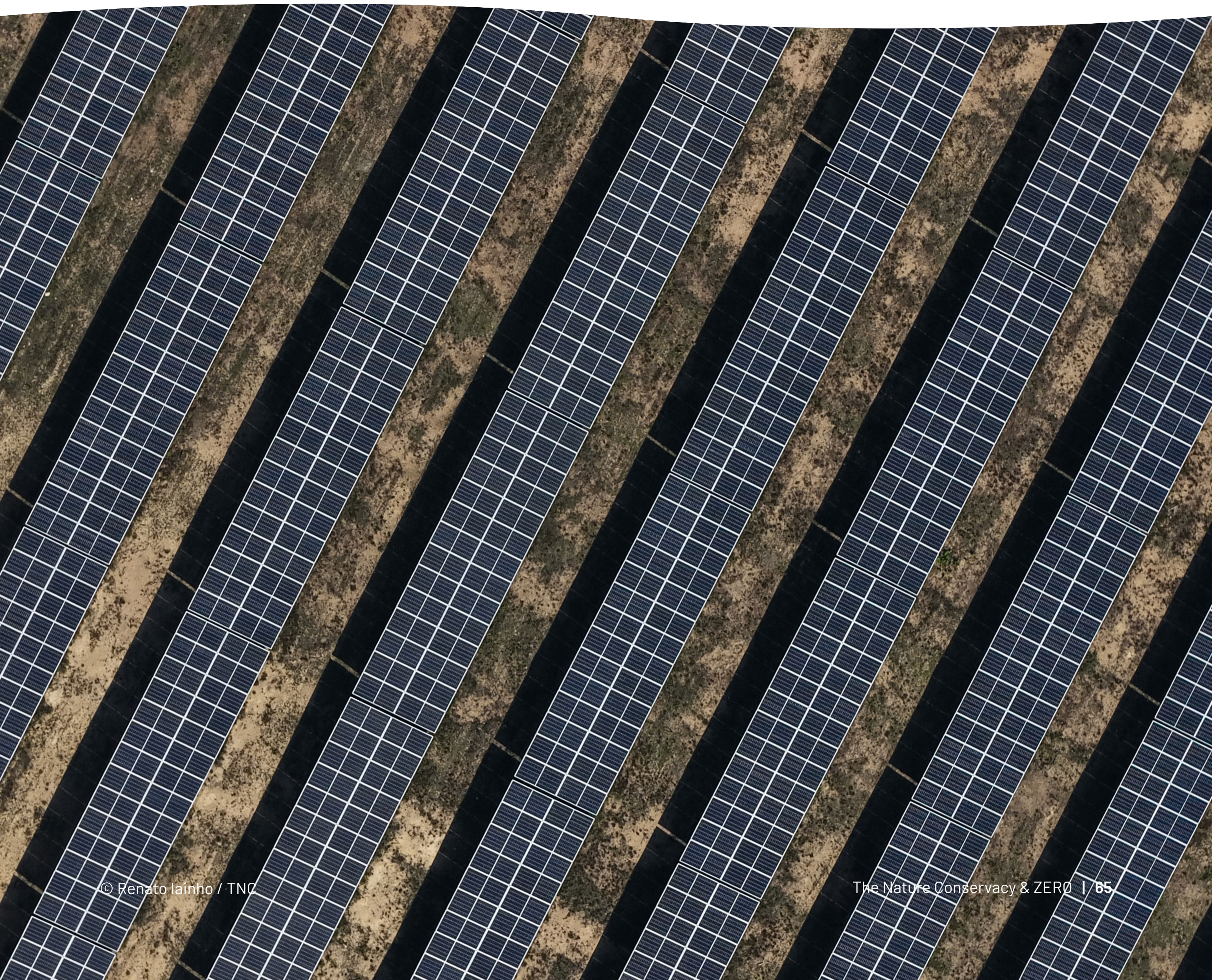
Sections 3.1 and 3.2 of this paper, particularly the discussion on energy capacity gaps and development on moderate-conflict zones, respectively, guide the implementation of this article by providing data and results about development potential on moderate-conflict zones to ensure limiting EIA to two years. Repowering capacity is mentioned in Box 5.

Article 15d: Member States are required to ensure public participation regarding plans that designate renewables acceleration areas, including identifying the public affected or likely to be affected.

This article mandates Member States to promote public acceptance of renewable energy projects by means of direct and indirect participation of local communities in those projects. Section 5.2 of this guide addresses integrating the human dimension in the implementation of this article by showcasing determination of social values and indicators as a preliminary, coarse-filter screening tool for landscape and social sensitivity. In addition to desktop-based assessments that map and quantify social values, this guide emphasizes the importance of participatory approaches to better capture local perspectives. Supplements IV and V introduce methodologies that help bridge the gap between broad landscape-scale planning and meaningful local engagement, including a pilot application of TNC's participatory mapping tool in a Portuguese municipality, with initial insights from that activity.

Article 15e: To complement and support the RAAs, Member States are recommended to adopt one or more plans to designate dedicated infrastructure areas for the development of grid and storage projects that are necessary to integrate renewable energy into the electricity system where such development is not expected to have a significant environmental impact or such an impact can be duly mitigated or, where not possible, compensated for. With the objective to help upgrade and expand grids to support rapid electrification and speed up permitting, the European Grids Package is set to be published in December 2025. Chapter 5 of this guide aims to steer the implementation of this article and the Grids Package by providing examples of where grid development could occur in Portugal, indicating potential low-conflict expansion areas for future grids.

Article 16b: Member States are required to limit permitting times to two years for ground-mounted renewable energy projects located outside renewables acceleration areas. If the need for extended assessment is justified under applicable EU environmental law, Member States may extend those periods by up to six months. The article limits the permit-granting procedure for the repowering of renewable energy power plants, for new installations with an electrical capacity of less than 150 kW and for co-located energy storage, as well as for the connection of such plants, installations, and storage to the grid, located outside renewables acceleration areas, to 12 months, including with regard to environmental assessments where required by the relevant law.



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Supplement VII:
Supporting Tables and Maps

TABLE 6: List of all datasets and parameters used on the energy modeling, biodiversity and social layers.

Parameter Description	Layer	Original Resolution	Original Data Source
Wind capacity factor (no. of equivalent operation hours at nominal power, NEPS v2)	Energy (Wind)	100 m	LNEG, 2025
Solar capacity factor - average daily totals (PVOUT)	Energy (Solar)	1 km	Solar Atlas V2. 2024 [85]
Average multi-scaled topographic position index	Energy (Wind)	30 m	NASA, SRTM 2000 [86]
Average aspect ranking	Energy (Solar)	30 m	NASA, SRTM 2000 [87]
Minimum and average (solar) and (wind) percent slope	Energy (Both)	30 m	NASA, SRTM 2000 [87]
Distance from major substations (size is greater than 2 hectares)	Energy (Both)	Approximately 5 m	OpenStreet Map, 2024 [88]
Distance from all substations (size is greater than ¼ hectare)	Energy (Both)	Approximately 5 m	OpenStreet Map, 2024 [88]
Distance from transmission lines	Energy (Both)	Approximately 5 m	OpenStreet Map, 2024 [88]
Distance from power plants	Energy (Both)	Approximately 5 m	DGEG [89] & GREW [90], 2024
Distance from primary roads	Energy (Both)	Approximately 5 m	OpenStreet Map, 2024 [88]
Distance from all major roads	Energy (Both)	Approximately 5 m	OpenStreet Map, 2024 [88]
Distance from major urban areas	Energy (Both)	1 km	EU-JRC, GHSL GHS-MSMOD, 2025 [91]
Distance from all cities	Energy (Both)	1 km	EU-JRC, GHSL GHS-MSMOD, 2025 [91]
Population density	Energy (Both)	30 m	META, 2024 [92]
COS2018 (LULC map for Portugal)	Biodiversity	1ha	DGT (2018) [43]
CORINE2018 (LULC map for Pan-European region)	Biodiversity	100 m	Copernicus (2018) [44]
Natura 2000 (Protected areas from the Natura 2000 network)	Biodiversity	-	ICNF (2024) [93]
Ramsar Sites (Important wetlands from the Ramsar convention)	Biodiversity	-	ICNF (2024) [94] RAMSAR (2024) [95]

RNAP (Rede Nacional de Areas Protegidas from Portugal)	Biodiversity	-	ICNF (2024) [96]
UNESCO Biosphere reserves	Biodiversity	-	UNESCO (2024) [97] Palliwoda et al. (2021) [98]
IBAs (Important Bird Areas)	Biodiversity	-	SPEA (2024) [99]
Geossítios (Geosites from Portugal with a 500m buffer)	Biodiversity	-	LNEG (2024) [100]
Bioenergetic Zones for Portugal	Biodiversity	-	ICNF (2024) [96]
Areas under forestry regime (REFLOA)	Biodiversity	-	ICNF (2024) [96]
HMI (Human Modification Index)	Biodiversity	300 m	Theobald et al. (2025) [47]
Red Book of Birds for Portugal	Biodiversity	10 km	Almeida et al. (2022) [48]
III Atlas of Breeding Birds of Portugal	Biodiversity	10 km	SPEA (2024) [49]
Red Book of Mammals for Portugal	Biodiversity	10 km	Mathias et al. (2023) [50]
Eurasian eagle-owl additional information (Nesting sites and complementary occurrence data)	Biodiversity	10 km 2 km	SPEA (2024)
Black vulture complementary occurrence data	Biodiversity	10 km	Aegypius return project (2024) [51]
Bonelli's eagle complementary occurrence data	Biodiversity	10 km	SPEA (2024)
Montagu's harrier complementary occurrence data	Biodiversity	10 km	Gameiro et al. (2023) [52]
National wolf census (2019-2021)	Biodiversity	10 km	Pimenta et al. (2023) [53]
Conservation of Key Underground sites: the database (Bat shelters)	Biodiversity	-	Eurobats (2024) [101]
Area of Habitats	Biodiversity	100 m	Lumbierres et al. (2022) [54]
Classified or under classification cultural heritage sites			LNEG (2024) PCIP (2024) [102]
Restriction zones associated with classified or under classification cultural heritage sites			LNEG (2024) PCIP (2024) [102]
Special Protection Zones associated with classified or under classification cultural heritage sites			LNEG (2024) PCIP (2024) [102]
General Protection Zones associated with classified or under classification cultural heritage sites			LNEG (2024) PCIP (2024) [102]
Documented archaeological sites with recommended 150 m buffers			LNEG (2024) PCIP (2024) [102]
Public interest individual trees or groups of trees with `a 150 m buffer			ICNF (2024) [96]

TABLE 7: List of all municipalities in Portugal, their total area in km², and their sites (in km² and as a percentage of total area) with low conflict and high development potential for wind and solar.

Municipality	Area (km²)	Solar Low-Conflict, High-Development-Potential (km²)	Solar Low-Conflict, High-Development-Potential (%)	Wind Low-Conflict, High-Development-Potential (hectares)	Wind Low-Conflict, High-Development-Potential (%)
Abrantes	714,69	50,05	7,00	1,26	0,18
Águeda	335,27	28,93	8,63	6,04	1,80
Aguiar da Beira	206,77	0,01	0,00	0,00	0,00
Alandroal	542,68	0,33	0,06	0,00	0,00
Albergaria-a-Velha	158,82	4,59	2,89	0,00	0,00
Albufeira	140,66	0,96	0,68	0,02	0,01
Alcácer do Sal	1.499,87	16,11	1,07	0,00	0,00
Alcanena	127,33	2,55	2,00	0,67	0,53
Alcobaça	408,14	14,42	3,53	1,49	0,37
Alcochete	128,36	0,00	0,00	0,00	0,00
Alcoutim	575,36	0,24	0,04	0,00	0,00
Alenquer	304,22	30,92	10,16	8,64	2,84
Alfândega da Fé	321,95	0,09	0,03	0,02	0,01
Alijó	297,60	0,00	0,00	0,00	0,00
Aljezur	323,50	6,09	1,88	0,82	0,25
Aljustrel	458,47	0,00	0,00	0,00	0,00
Almada	70,01	0,01	0,01	0,00	0,00
Almeida	517,98	0,00	0,00	0,00	0,00
Almeirim	222,12	11,13	5,01	0,00	0,00
Almodóvar	777,88	0,03	0,00	0,00	0,00
Alpiarça	95,36	0,19	0,20	0,00	0,00
Alter do Chão	362,07	0,07	0,02	0,00	0,00
Alvaiázere	160,48	0,24	0,15	0,48	0,30
Alvito	264,85	0,32	0,12	0,00	0,00
Amadora	23,78	0,34	1,43	0,00	0,00
Amarante	301,33	0,03	0,01	0,00	0,00
Amares	81,95	0,01	0,01	0,06	0,07
Anadia	216,63	31,98	14,76	0,83	0,38
Ansião	176,09	6,28	3,57	1,00	0,57
Arcos de Valdevez	447,60	0,00	0,00	0,00	0,00
Arganil	332,84	0,01	0,00	0,18	0,05
Armamar	117,24	0,70	0,60	0,82	0,70
Arouca	329,11	1,37	0,42	1,44	0,44
Arraiolos	683,75	0,25	0,04	0,00	0,00
Arronches	314,65	0,05	0,02	0,00	0,00

Arruda dos Vinhos	77,96	5,85	7,50	1,47	1,89
Aveiro	197,58	2,71	1,37	0,00	0,00
Avis	605,97	0,02	0,00	0,00	0,00
Azambuja	262,66	10,44	3,97	0,56	0,21
Baião	174,53	0,06	0,03	5,63	3,23
Barcelos	378,90	0,64	0,17	0,12	0,03
Barrancos	168,42	0,00	0,00	0,00	0,00
Barreiro	36,39	0,00	0,00	0,00	0,00
Batalha	103,42	10,98	10,62	0,49	0,47
Beja	1.146,48	0,00	0,00	0,00	0,00
Belmonte	118,76	0,02	0,02	0,00	0,00
Benavente	521,38	19,36	3,71	0,00	0,00
Bombarral	91,29	2,88	3,15	1,53	1,68
Borba	145,19	0,32	0,22	0,00	0,00
Boticas	321,96	0,00	0,00	0,00	0,00
Braga	183,40	1,40	0,76	0,52	0,28
Bragança	1.173,57	0,00	0,00	0,00	0,00
Cabeceiras de Basto	241,82	0,00	0,00	0,00	0,00
Cadaval	174,89	2,04	1,17	0,55	0,31
Caldas da Rainha	255,69	26,08	10,20	5,83	2,28
Caminha	136,52	0,00	0,00	0,02	0,01
Campo Maior	247,20	0,00	0,00	0,00	0,00
Cantanhede	390,88	60,86	15,57	0,00	0,00
Carrazeda de Ansiães	279,24	0,09	0,03	0,07	0,03
Carregal do Sal	116,89	0,39	0,33	0,00	0,00
Cartaxo	158,17	28,39	17,95	1,07	0,68
Cascais	97,40	0,68	0,70	0,00	0,00
Castanheira de Pêra	66,77	0,56	0,84	3,09	4,63
Castelo Branco	1.438,19	16,24	1,13	3,46	0,24
Castelo de Paiva	115,01	0,01	0,01	0,23	0,20
Castelo de Vide	264,91	0,08	0,03	0,00	0,00
Castro Daire	379,04	0,02	0,01	0,21	0,06
Castro Marim	300,84	0,00	0,00	0,00	0,00
Castro Verde	569,44	0,00	0,00	0,00	0,00
Celorico da Beira	247,22	0,80	0,32	0,04	0,02
Celorico de Basto	181,07	0,08	0,04	0,00	0,00
Chamusca	746,01	2,16	0,29	0,11	0,01
Chaves	591,23	0,18	0,03	0,00	0,00
Cinfães	239,29	0,03	0,01	0,33	0,14
Coimbra	319,40	33,68	10,54	1,41	0,44

Condeixa-a-Nova	138,67	15,42	11,12	0,00	0,00
Constância	80,37	4,63	5,76	0,00	0,00
Coruche	1.115,72	25,40	2,28	0,20	0,02
Covilhã	555,60	1,80	0,32	5,51	0,99
Crato	398,07	2,82	0,71	0,00	0,00
Cuba	172,09	0,00	0,00	0,00	0,00
Elvas	631,29	0,09	0,01	0,00	0,00
Entroncamento	13,73	0,02	0,15	0,00	0,00
Caldas da Rainha	255,69	26,08	10,20	5,83	2,28
Caminha	136,52	0,00	0,00	0,02	0,01
Campo Maior	247,20	0,00	0,00	0,00	0,00
Cantanhede	390,88	60,86	15,57	0,00	0,00
Carrazeda de Ansiães	279,24	0,09	0,03	0,07	0,03
Carregal do Sal	116,89	0,39	0,33	0,00	0,00
Cartaxo	158,17	28,39	17,95	1,07	0,68
Cascais	97,40	0,68	0,70	0,00	0,00
Castanheira de Pêra	66,77	0,56	0,84	3,09	4,63
Castelo Branco	1.438,19	16,24	1,13	3,46	0,24
Castelo de Paiva	115,01	0,01	0,01	0,23	0,20
Castelo de Vide	264,91	0,08	0,03	0,00	0,00
Castro Daire	379,04	0,02	0,01	0,21	0,06
Castro Marim	300,84	0,00	0,00	0,00	0,00
Castro Verde	569,44	0,00	0,00	0,00	0,00
Celorico da Beira	247,22	0,80	0,32	0,04	0,02
Celorico de Basto	181,07	0,08	0,04	0,00	0,00
Chamusca	746,01	2,16	0,29	0,11	0,01
Chaves	591,23	0,18	0,03	0,00	0,00
Cinfães	239,29	0,03	0,01	0,33	0,14
Coimbra	319,40	33,68	10,54	1,41	0,44
Condeixa-a-Nova	138,67	15,42	11,12	0,00	0,00
Constância	80,37	4,63	5,76	0,00	0,00
Coruche	1.115,72	25,40	2,28	0,20	0,02
Covilhã	555,60	1,80	0,32	5,51	0,99
Crato	398,07	2,82	0,71	0,00	0,00
Cuba	172,09	0,00	0,00	0,00	0,00
Elvas	631,29	0,09	0,01	0,00	0,00
Entroncamento	13,73	0,02	0,15	0,00	0,00
Espinho	21,06	0,01	0,05	0,00	0,00
Esposende	95,41	0,39	0,41	0,00	0,00
Estarreja	108,17	10,33	9,55	0,00	0,00

Estremoz	513,80	9,13	1,78	0,00	0,00
Évora	1.307,08	0,53	0,04	0,00	0,00
Fafe	219,08	0,08	0,04	0,15	0,07
Faro	202,57	2,51	1,24	0,18	0,09
Felgueiras	115,74	0,13	0,11	0,02	0,02
Ferreira do Alentejo	648,21	0,22	0,03	0,00	0,00
Ferreira do Zêzere	190,38	2,87	1,51	0,04	0,02
Figueira da Foz	379,05	42,05	11,09	1,85	0,49
Figueira de Castelo Rodrigo	508,57	0,00	0,00	0,00	0,00
Figueiró dos Vinhos	173,44	1,92	1,11	19,43	11,20
Fornos de Algodres	131,45	0,15	0,11	0,10	0,08
Freixo de Espada à Cinta	244,14	0,00	0,00	0,00	0,00
Fronteira	248,60	0,19	0,08	0,00	0,00
Fundão	700,20	3,50	0,50	3,13	0,45
Gavião	294,59	3,05	1,04	0,00	0,00
Góis	263,30	0,31	0,12	9,38	3,56
Golegã	84,32	0,02	0,02	0,00	0,00
Gondomar	131,92	0,16	0,12	0,29	0,22
Gouveia	300,61	0,03	0,01	0,10	0,03
Grândola	825,94	23,41	2,83	0,51	0,06
Guarda	712,10	1,15	0,16	0,02	0,00
Guimarães	241,00	3,11	1,29	0,43	0,18
Idanha-a-Nova	1.416,34	0,33	0,02	0,00	0,00
Ílhavo	73,48	1,33	1,81	0,50	0,68
Lagoa	88,25	0,23	0,26	0,00	0,00
Lagos	212,99	1,02	0,48	0,29	0,14
Lamego	165,42	0,02	0,01	0,00	0,00
Leiria	565,09	35,65	6,31	0,92	0,16
Lisboa	100,05	0,00	0,00	0,00	0,00
Loulé	763,67	2,11	0,28	0,08	0,01
Loures	167,24	11,67	6,98	1,73	1,03
Lourinhã	147,17	1,13	0,77	1,41	0,96
Lousã	138,40	4,68	3,38	0,00	0,00
Lousada	96,08	0,05	0,05	0,01	0,01
Mação	399,98	23,02	5,76	4,64	1,16
Macedo de Cavaleiros	699,14	0,30	0,04	0,04	0,01
Mafra	291,65	20,97	7,19	5,39	1,85
Maia	82,95	1,39	1,68	0,00	0,00
Mangualde	219,26	2,91	1,33	1,79	0,82
Manteigas	121,98	0,00	0,00	0,00	0,00

Marco de Canaveses	201,89	0,66	0,33	0,81	0,40
Marinha Grande	187,25	2,53	1,35	0,13	0,07
Marvão	154,90	0,00	0,00	0,00	0,00
Matosinhos	62,42	0,05	0,08	0,00	0,00
Mealhada	110,66	6,14	5,55	0,22	0,20
Mêda	286,05	0,00	0,00	0,02	0,01
Melgaço	238,25	0,00	0,00	0,00	0,00
Mértola	1.292,87	0,01	0,00	0,00	0,00
Mesão Frio	26,65	0,00	0,00	0,00	0,00
Mira	124,03	6,46	5,21	0,00	0,00
Miranda do Corvo	126,38	4,37	3,46	1,68	1,33
Miranda do Douro	487,18	0,00	0,00	0,00	0,00
Mirandela	658,96	0,02	0,00	0,00	0,00
Mogadouro	760,65	0,01	0,00	0,00	0,00
Moimenta da Beira	219,97	0,49	0,22	0,02	0,01
Moita	55,26	0,01	0,02	0,00	0,00
Monchique	395,30	0,00	0,00	0,00	0,00
Mondim de Basto	172,08	0,00	0,00	0,00	0,00
Monforte	420,25	0,00	0,00	0,00	0,00
Monsão	211,31	0,00	0,00	0,02	0,01
Montalegre	805,46	0,00	0,00	0,00	0,00
Montemor-o-Novo	1.232,97	7,14	0,58	0,00	0,00
Montemor-o-Velho	228,96	19,29	8,43	0,00	0,00
Montijo	348,62	38,53	11,05	0,37	0,11
Mora	443,95	0,12	0,03	0,00	0,00
Mortágua	251,18	0,05	0,02	9,34	3,72
Moura	958,46	0,14	0,01	0,00	0,00
Mourão	278,63	0,00	0,00	0,00	0,00
Murça	189,37	0,00	0,00	0,00	0,00
Murtosa	73,09	0,26	0,36	0,00	0,00
Nazaré	82,43	12,09	14,67	1,30	1,58
Nelas	125,71	3,87	3,08	0,22	0,18
Nisa	575,68	5,95	1,03	0,00	0,00
Óbidos	141,55	5,94	4,20	1,77	1,25
Odemira	1.720,60	16,07	0,93	0,00	0,00
Odivelas	26,54	0,13	0,49	0,00	0,00
Oeiras	45,88	0,01	0,02	0,00	0,00
Oleiros	471,09	44,53	9,45	14,84	3,15
Olhão	130,86	0,10	0,08	0,02	0,02
Oliveira de Azeméis	161,10	2,83	1,76	0,21	0,13

Oliveira de Frades	145,35	0,00	0,00	0,10	`0,07
Oliveira do Bairro	87,32	16,96	19,42	0,00	0,00
Oliveira do Hospital	234,52	0,89	0,38	0,10	0,04
Ourém	416,68	9,30	2,23	0,72	0,17
Ourique	663,31	1,53	0,23	0,15	0,02
Ovar	147,70	2,32	1,57	0,04	0,03
Paços de Ferreira	70,99	0,13	0,18	0,02	0,03
Palmela	465,12	8,24	1,77	0,10	0,02
Pampilhosa da Serra	396,46	0,48	0,12	28,53	7,20
Paredes	156,76	4,67	2,98	0,53	0,34
Paredes de Coura	138,19	0,00	0,00	0,00	0,00
Pedrógão Grande	128,75	16,49	12,81	7,37	5,72
Penacova	216,73	0,28	0,13	2,39	1,10
Penafiel	212,24	12,86	6,06	2,83	1,33
Penalva do Castelo	134,34	0,00	0,00	0,00	0,00
Penamacor	563,71	0,52	0,09	0,00	0,00
Penedono	133,71	0,07	0,05	0,00	0,00
Penela	134,80	8,95	6,64	6,51	4,83
Peniche	77,55	0,05	0,06	0,00	0,00
Peso da Régua	94,86	0,00	0,00	0,00	0,00
Pinhel	484,52	0,01	0,00	0,00	0,00
Pombal	626,00	15,63	2,50	2,54	0,41
Ponte da Barca	182,11	0,00	0,00	0,00	0,00
Ponte de Lima	320,25	0,11	0,03	0,24	0,07
Ponte de Sor	839,71	14,30	1,70	0,00	0,00
Portalegre	447,14	0,90	0,20	0,02	0,00
Portel	601,01	0,17	0,03	0,00	0,00
Portimão	182,06	1,05	0,58	0,00	0,00
Porto	41,42	0,00	0,00	0,00	0,00
Porto de Mós	261,83	1,98	0,76	0,00	0,00
Póvoa de Lanhoso	134,65	0,30	0,22	0,00	0,00
Póvoa de Varzim	82,21	0,67	0,81	0,00	0,00
Proença-a-Nova	395,40	73,58	18,61	9,23	2,33
Redondo	369,51	0,01	0,00	0,00	0,00
Reguengos de Monsaraz	464,00	0,05	0,01	0,00	0,00
Resende	123,35	0,00	0,00	0,36	0,29
Ribeira de Pena	217,46	0,00	0,00	0,00	0,00
Rio Maior	272,76	7,53	2,76	2,45	0,90
Sabrosa	156,92	0,00	0,00	0,00	0,00
Sabugal	822,70	0,00	0,00	0,00	0,00

Salvaterra de Magos	243,93	33,90	13,90	0,76	0,31
Santa Comba Dão	111,95	0,21	0,19	0,00	0,00
Santa Maria da Feira	215,88	0,29	0,13	0,48	0,22
Santa Marta de Penaguião	69,28	0,00	0,00	0,00	0,00
Santarém	552,54	46,40	8,40	8,38	1,52
Santiago do Cacém	1.059,69	35,37	3,34	0,83	0,08
Santo Tirso	136,56	0,33	0,24	0,08	0,06
São Brás de Alportel	153,37	5,27	3,44	0,81	0,53
São João da Madeira	7,94	0,00	0,00	0,00	0,00
São João da Pesqueira	266,11	0,08	0,03	0,33	0,12
São Pedro do Sul	348,95	0,62	0,18	0,11	0,03
Sardoal	92,15	0,64	0,69	0,00	0,00
Sátão	201,94	0,47	0,23	0,16	0,08
Seia	435,69	24,68	5,66	1,88	0,43
Seixal	95,45	0,00	0,00	0,00	0,00
Sernancelhe	228,61	0,30	0,13	0,29	0,13
Serpa	1.105,63	0,79	0,07	0,00	0,00
Sertã	446,73	13,35	2,99	4,77	1,07
Sesimbra	195,72	3,19	1,63	0,17	0,09
Setúbal	230,33	0,29	0,13	0,03	0,01
Sever do Vouga	129,88	0,09	0,07	3,69	2,84
Silves	680,06	19,35	2,85	1,15	0,17
Sines	203,30	0,93	0,46	0,76	0,37
Sintra	319,23	14,98	4,69	2,22	0,70
Sobral de Monte Agraço	52,10	10,33	19,83	2,04	3,92
Soure	265,06	22,01	8,30	0,42	0,16
Sousel	279,32	3,01	1,08	0,00	0,00
Tábua	199,79	11,82	5,92	0,00	0,00
Tabuaço	133,86	1,91	1,43	1,29	0,96
Tarouca	100,08	0,01	0,01	0,02	0,02
Tavira	606,97	9,72	1,60	3,15	0,52
Terras de Bouro	277,46	0,00	0,00	0,00	0,00
Tomar	351,20	17,23	4,91	1,90	0,54
Tondela	371,22	0,89	0,24	1,81	0,49
Torre de Moncorvo	531,56	0,00	0,00	0,00	0,00
Torres Novas	270,00	14,39	5,33	0,85	0,31
Torres Vedras	407,15	70,81	17,39	15,76	3,87
Trancoso	361,52	0,27	0,07	0,02	0,01
Trofa	72,00	11,38	15,81	0,38	0,53
Vagos	164,92	11,79	7,15	0,33	0,20

Vale de Cambra	147,33	0,04	0,03	4,48	3,04
Valença	117,13	0,00	0,00	0,00	0,00
Valongo	75,12	0,52	0,69	0,15	0,20
Valpaços	548,74	0,33	0,06	0,00	0,00
Vendas Novas	222,39	9,02	4,06	0,56	0,25
Viana do Alentejo	393,67	0,02	0,01	0,00	0,00
Viana do Castelo	319,02	3,89	1,22	1,37	0,43
Vidigueira	316,61	0,33	0,10	0,00	0,00
Vieira do Minho	216,44	0,00	0,00	0,04	0,02
Vila de Rei	191,55	1,65	0,86	0,27	0,14
Vila do Bispo	179,06	0,00	0,00	0,00	0,00
Vila do Conde	149,03	3,79	2,54	0,00	0,00
Vila Flor	265,81	0,01	0,00	0,00	0,00
Vila Franca de Xira	318,19	0,55	0,17	0,00	0,00
Vila Nova da Barquinha	49,53	1,36	2,75	0,06	0,12
Vila Nova de Cerveira	108,47	0,00	0,00	0,00	0,00
Vila Nova de Famalicão	201,59	3,30	1,64	0,00	0,00
Vila Nova de Foz Côa	398,15	0,00	0,00	0,00	0,00
Vila Nova de Gaia	168,46	0,19	0,11	0,00	0,00
Vila Nova de Paiva	175,53	0,05	0,03	0,14	0,08
Vila Nova de Poiares	84,45	3,74	4,43	0,78	0,92
Vila Pouca de Aguiar	437,07	0,00	0,00	0,00	0,00
Vila Real	378,80	0,00	0,00	0,00	0,00
Vila Real de Santo António	61,25	0,00	0,00	0,00	0,00
Vila Velha de Ródão	329,91	11,23	3,40	0,00	0,00
Vila Verde	228,67	0,21	0,09	0,10	0,04
Vila Viçosa	194,86	1,29	0,66	0,00	0,00
Vimioso	481,59	0,00	0,00	0,00	0,00
Vinhais	694,75	0,00	0,00	0,00	0,00
Viseu	507,10	10,61	2,09	0,37	0,07
Vizela	24,70	0,00	0,00	0,00	0,00
Vouzela	193,69	0,19	0,10	0,27	0,14
TOTAL	**89.102,14**	**1514,86**	**1,70**	**267,30**	**0,30**

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