DOCTORAL DISSERTATION

Variability of extreme weather events and influence on the renewable energy sector in the Iberian Peninsula: wind energy

Ana Catarina Redondo Gonçalves

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DECLARE that the present work, entitled ***"Variability of extreme weather events and influence on the renewable energy sector in the Iberian Peninsula: wind energy"***, submitted by Ana Catarina Redondo Gonçalves to obtain the title of Doctor by the Universidade de Vigo, was carried out under our supervision in the PhD Program "Auga, Sustentabilidade e Desenvolvemento", and it is presented under the modality of compendium of research articles.

Ourense, 21st March 2024

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“Para ser grande, sê inteiro: nada
Teu exagera ou exclui.
Sê todo em cada coisa. Põe quanto és
No mínimo que fazes.
Assim em cada lago a lua toda
Brilha, porque alta vive.”

Ricardo Reis, in "Odes"
Heterónimo de Fernando Pessoa

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Contents

Resumen

Los fenómenos meteorológicos extremos (en inglés, *extreme weather events*, EWEs), como son los ciclones extratropicales intensos (en inglés, *extratropical ciclones*, ECs) que se originan en el Atlántico norte y llegan a Europa, pueden generar grandes catástrofes naturales en latitudes medias debido a los amplios impactos socioeconómicos provocados por los fuertes vientos y las intensas precipitaciones que llevan asociados. Además, cuando estos eventos extremos persisten durante varios días causan graves impactos en el sector energético. Estos sucesos se consideran un riesgo grave para los sistemas energéticos (en inglés, *energy systems,* ES) y sus instalaciones, y pueden provocar cortes de suministro y afectar a otras infraestructuras. La generación de electricidad a partir de fuentes de energía renovables (en inglés, *renewable energy sources*, RES), como la energía eólica (terrestre y marina), depende cada vez más de patrones climáticos variables, y estas variaciones intra-anuales aumentan la sensibilidad de los sistemas energéticos a las condiciones climáticas y su variabilidad, lo que presenta un desafío importante para el sector energético. Además, se espera que el cambio climático y los EWEs influyan en gran medida en la disponibilidad y variabilidad de la energía eólica en el futuro. En concreto, la Península Ibérica (en inglés, *Iberian Peninsula*, IP) ubicada en el sur de Europa se identifica como una de las regiones europeas potencialmente más afectadas por el cambio climático y los EWEs.

Por lo tanto, existe una creciente necesidad de comprender el desarrollo de los EWEs, como los ECs, y los mecanismos físicos asociados, que provocan impactos severos debido a eventos de precipitación extrema y tormentas de viento. Es por tanto crucial considerar esta variabilidad en la producción y demanda de energía en el diseño y operación de los sistemas a partir de fuentes de energía renovables para garantizar un suministro de energía continuo y seguro en el futuro. Por lo tanto, la posibilidad de mantener el funcionamiento de los sistemas energéticos durante la ocurrencia de EWEs, a través de medidas de adaptación y control de los sistemas, es importante para el suministro continuo de energía limpia y asequible y la resiliencia de los sistemas energéticos.

Así, los principales objetivos de esta investigación son mejorar el conocimiento de las EWE asociadas a EC en la región del Atlántico Norte europeo, con un enfoque en la IP, y proporcionar avances significativos en la comprensión de estos sistemas

meteorológicos y los mecanismos físicos asociados, e investigar los impactos de las EWE en los sistemas energéticos. Para ello, se pretende evaluar los impactos de los EWEs en la disponibilidad de fuentes de energía renovables y en consecuencia en la producción de electricidad a través de sistemas de energía eólica (en inglés, *wind energy systems*, WES) en la IP. Además, se estudian e identifican medidas y soluciones para adaptar los sistemas energéticos y continuar con el funcionamiento normal durante la ocurrencia de EWEs.

El corpus de esta tesis doctoral está formado por cuatro artículos, tres de ellos publicados en revistas especializadas incluidas en el listado Journal Citation Reports (JCR). Cabe señalar que el orden de los artículos presentados en la tesis doctoral no se corresponde con el orden de su publicación, por lo que pueden aparecer algunas inconsistencias en los periodos analizados en cada artículo.

El primer capítulo presenta una breve reseña general de los EWEs asociados con los ECs basada en una revisión bibliográfica sobre el tema. Además, se presenta el panorama europeo y de IP de las energías renovables, en particular para la energía eólica. Así, para comprender la influencia de los ECs en la producción de energía eólica y los impactos sobre los propios sistemas energéticos y todas las infraestructuras físicas asociadas, se realiza un marco general sobre la temática, a partir de una revisión de la bibliografía y estudios ya publicados. El segundo capítulo proporciona una visión de los objetivos de este estudio y las tareas llevadas a cabo para alcanzarlos. El tercer capítulo incluye una revisión detallada de los métodos y técnicas de investigación utilizados para el estudio de los EWEs asociados con tormentas de alto impacto, recursos eólicos y potencial de energía eólica, así como los impactos de los eventos en los sistemas energéticos. Además, se presentan nuevas tecnologías y soluciones que se están implementando para la resiliencia de la red eléctrica, para reducir impactos en términos de producción y daños físicos a los sistemas e infraestructuras eléctricas. El capítulo cuarto incluye el compendio de los cuatro artículos que forman la parte esencial de este documento de tesis. Por último, el quinto capítulo presenta las principales conclusiones de este trabajo de la investigación realizada. Además, también se presentan recomendaciones para trabajos futuros y limitaciones inherentes del estudio.

Para los tres primeros artículos se utilizaron para los cálculos los datos de reanálisis de ERA5 del Centro Europeo de Pronósticos Meteorológicos a Plazo Medio (en inglés, *European Centre for Medium-Range Weather Forecasts*, ECMWF) para diferentes variables meteorológicas: en primer lugar, para analizar las condiciones sinópticas y dinámicas de los eventos que impactaron el IP, para luego evaluar el potencial de la energía eólica (*wind energy potential*, WEP).

En primer lugar, se identificaron y estudiaron las ECs que afectaron a la Península Ibérica en los cuatro inviernos prolongados de diciembre de 2017 a abril de 2021, y se realizó un análisis de las condiciones dinámicas y sinópticas para comprender los fuertes impactos de estos eventos. Los eventos compuestos (con viento y precipitación asociados) se identificaron comparando los valores del percentil 98%, calculados con base en el análisis climatológico para el período 1991-2020, con los valores obtenidos en los días de mayor impacto tormentoso. También se calcularon anomalías de eventos, considerando el mismo período, para evaluar mejor la intensidad de los impactos socioeconómicos en la región bajo estudio. Los resultados indican que entre las tormentas de alto impacto nombradas por los institutos meteorológicos del Grupo Suroeste de Europa (*Southwest European Group*, SW Group), desde 2017, veintiocho depresiones afectaron a la IP, y diez de estos eventos tuvieron un desarrollo explosivo. En cuanto al análisis de eventos extremos compuestos éste indicó que en los días de tormenta las precipitaciones y los valores de intensidad del viento fueron extremos (valores por encima del percentil 98, con un máximo de 53,80 mm día^{-1} y 20,05 m s^{-1} en la región Noroeste de la IP). Además, la región Noroeste de la IP fue la más afectada por estos eventos, siendo mayor el valor del percentil 98 en el 34,1% de los días de tormenta para la precipitación acumulada diaria, y en el 45,7% de los días de tormenta para los vientos racheados instantáneos a 10 metros, y en el 46,8% de los días de tormenta para una velocidad del viento de 10 metros. Al comparar los valores obtenidos de las variables en estudio con la climatología de referencia para el periodo 1991-2020, se encontraron valores bajos de presión media al nivel del mar (*mean sea level pressure*, MSLP) (inferiores a - 21,6 hPa), valores más altos de IVT (hasta más de 327,6 kg m^{-1}s^{-1}) y valores más altos de intensidad del viento a 250 hPa (mayores a 29,6 m s^{-1}), y valores más altos de temperatura potencial equivalente (θe) a 850 hPa (superior a 19,1 ºC). Los flujos de calor presentaron flujo de calor latente superficial (Q_E) con valores hasta - 150 W m^{-2} y flujo de calor sensible superficial (Q_H) con valores hasta - 40 W m^{-2}. Estos resultados, con valores elevados (en valor absoluto) en las anomalías de los parámetros meteorológicos, revelan que todos estos ellos tuvieron una importancia crucial en el desarrollo e intensificación de las depresiones extratropicales, provocando eventos extremos de precipitaciones, inundaciones y fuertes vientos, que culminaron en varios impactos destructivos. Además, este estudio resalta la importancia de analizar estos eventos y la necesidad de que sean cada vez más predecibles y que se emitan alertas a la población de manera oportuna para minimizar los impactos.

En segundo lugar, para evaluar los impactos de estos eventos en la disponibilidad de RES como energía eólica y en consecuencia en el potencial de energía eólica, se definió un área de estudio y un tiempo de estudio –meses de diciembre de 2017, 2018 y 2019 en el sur de Europa – y la evaluación de la disponibilidad de energía eólica y WEP se realizaron para evaluar la influencia de los EWEs en la producción de electricidad. Además, se utilizaron dos ecuaciones (ley logarítmica de Prandtl (LogL) y ley de potencia (PL)) para la extrapolación vertical del viento a la altura de la turbina, seguidas del cálculo WEP, que destacó su susceptibilidad a la variabilidad de los patrones de viento.

Así, los principales resultados de este trabajo revelaron que con diferencias de hasta el 80%, la ecuación LogL permite valores WEP mayores en regiones marinas (5 a 25 MWh.día^{-1}) mientras que la ecuación PL permite valores WEP mayores en regiones terrestres (15 a 40 MWh.día^{-1}). Sin embargo, a pesar de que todavía no está claro qué ecuación es la mejor opción para extrapolar los perfiles verticales de velocidad del viento tanto en regiones terrestres como marinas, la mayoría de los autores coinciden en que se prefiere la ecuación PL a la LogL debido a su simplicidad y capacidad para proporcionar un mejor ajuste en un rango de altura más amplio y capacidad para hacerlo en condiciones de viento más fuertes.

Además, el cálculo del WEP utilizando los distintos coeficientes de rugosidad y fricción empleados en cada ecuación (LogL (z_0) y PL(α)) mostró que a medida que aumenta el valor del coeficiente, este se devalúa, provocando que el WEP aumente en las regiones terrestres, y una disminución en las regiones marinas, para los tres meses bajo estudio. En cuanto a la producción de electricidad durante los meses de diciembre, los valores teóricos en comparación con los valores reales reportados (estadísticas de los países de la UE-28), fueron consistentes con un aumento de la producción en diciembre de 2017 y 2019, y una disminución en diciembre de 2018. La generación eólica terrestre (casi 90 GW.día) y marina (casi 100 GW.día) en Europa batieron récords el 8 de diciembre de 2018. Además, a pesar de que algunas zonas (la región norte de Europa, incluida la costa de las Islas Británicas, Francia, Alemania, Países Bajos y toda la región del Mar del Norte) se ven afectadas por fuertes rachas de viento (valores entre 10 y 20 m s^{-1}), los aerogeneradores continuaron generando electricidad, como lo demuestran los valores reales reportados. Así, la conclusión general de este análisis demostró que los fuertes vientos de las tormentas de alto impacto que afectaron al suroeste de Europa en los meses de diciembre se han convertido en una contribución positiva e importante a la producción de energía renovable, como lo revelan los altos valores WEP en los días de tormenta.

En tercer lugar, los impactos de los EWEs asociados con ECs en los sistemas energéticos se evalúan mediante un análisis de riesgos para un caso de estudio de líneas eléctricas aéreas (*overhead power lines*, OPL). Se identificaron los eventos que perturbaron la OPL en Portugal y se aplicó y discutió una metodología para implementar un análisis de riesgos basada en varias herramientas y técnicas identificadas en IEC/ISO 31010:2009, NP 31010:2016 y siguiendo la norma NP ISO 31000:2018. Para realizar este estudio, el diagrama causa-efecto y la matriz consecuencia/probabilidad fueron las metodologías aplicadas que permitieron una explicación clara de los efectos, la conexión de varios factores y conclusiones rápidas y precisas. En este sentido, los principales resultados del estudio demostraron que de los 29 eventos identificados con impacto significativo en Portugal continental, el 31% de ellos (9 tormentas) provocaron perturbaciones en la OPL, en las que los fuertes vientos (valores iguales o superiores de 105,1 km h^{-1} (29,22 m s^{-1}), nivel 11 de la escala de fuerza del viento de Beaufort) fueron el factor principal de la perturbación de la OPL. Además, de las nueve tormentas que provocaron la interrupción de la OPL, una se consideró tormenta de nieve y 8 fueron tormentas de viento (6 se caracterizaron por eventos compuestos: viento y lluvia; y 2 tormentas se caracterizaron únicamente por el viento). Las tormentas Elsa y Fabien presentaron el mayor riesgo, calificadas como “Riesgo Medio” con niveles de riesgo entre 10 y 14. La tormenta de Emma también planteó un “Riesgo Medio” con una probabilidad de ocurrencia “Baja”, pero tuvo consecuencias “acentuadas” y significativas que afectaron a millones de personas durante su desarrollo y su paso. Aunque los nueve eventos extremos que perturbaron la OPL presentan un nivel de “Riesgo Medio”, los tipos de consecuencias diferencian los eventos. Así, estos eventos pueden causar diferentes impactos con efectos a largo plazo sobre el medio ambiente y daños socioeconómicos importantes, como la interrupción de algunos servicios públicos y la necesidad de asistencia financiera.

En este contexto, las diversas mejoras y acciones estratégicas consideradas tuvieron como objetivo reforzar la fortaleza física y las capacidades operativas de la red. Su objetivo es reducir la gravedad de los impactos, aumentando así la eficiencia operativa, acelerando la recuperación de la red y mejorando la resiliencia de los sistemas energéticos. El análisis demuestra claramente una relación de causa y efecto entre los

EWEs y la interrupción de la OPL en Portugal. Este hallazgo tiene especial importancia dada la previsión de EWEs más frecuentes y graves que afectarán a regiones densamente pobladas en el futuro. Para minimizar los impactos asociados es necesario considerar las condiciones climáticas, los materiales constitutivos de la OPL, todas las infraestructuras eléctricas y la gestión estratégica implementada en los sistemas. Por lo tanto, este estudio puede considerarse pionero y único en el análisis del riesgo de perturbación de la OPL provocado por los eventos extremos más recientes que han afectado a Portugal, ya que toda la situación en cuestión es diferente de los estudios de otros países analizados en la literatura. Además, el avance y la implementación de estudios tan completos tienen una importancia vital dentro del sector energético. Estos estudios permiten a las empresas energéticas adaptar sus proyectos considerando los escenarios más adversos. Por ejemplo, pueden anticipar y abordar los desafíos que plantean las velocidades del viento excepcionalmente altas que afectan la OPL y comprender las limitaciones máximas que sus infraestructuras físicas pueden soportar. Este enfoque proactivo es esencial para garantizar la resiliencia y adaptabilidad de los sistemas energéticos frente a condiciones extremas.

Finalmente, se realizó una revisión exhaustiva de la literatura de los impactos de los EWEs en los sistemas de energía, ya que estos eventos impactan significativamente en infraestructuras esenciales y se consideran una de las principales causas de perturbaciones eléctricas de gran extensión a nivel mundial. El estudio utilizó 210 artículos de investigación publicados procedentes de las bases de datos *Scopus* y *Google Scholar* para evaluar los efectos de los EWEs (incluidas tormentas severas, vientos, relámpagos, olas de calor, olas de frío y condiciones de heladas) en los ES y las infraestructuras asociadas, que incluyen producción, transmisión y distribución, a escala global. Se puso especial énfasis en el impacto de estos eventos en los sistemas de energía eólica (WES). Luego, se examinaron y registraron las estrategias y medidas para minimizar y mitigar los impactos y mejorar la resiliencia de los sistemas para comprender cómo los ES pueden mantener un funcionamiento normal cuando se ven afectados por eventos extremos.

Al mismo tiempo, la integración de tecnologías emergentes, como los sistemas de almacenamiento de energía (en inglés, *energy storage systems*, ESS), los sistemas de energía distribuida (en inglés, *distributed energy systems*, DES) y las microrredes (en inglés, *microgrids*), desempeña un papel fundamental en el aumento de la resiliencia y confiabilidad de la red eléctrica en general. Este aumento se debe a la mejora de la gestión de la energía en todos los sistemas operativos dentro de la red. Estas tecnologías de vanguardia poseen la capacidad de reaccionar de manera más rápida y hábil a los impactos de condiciones climáticas extremas. De hecho, tienen el potencial no sólo de acelerar la recuperación sino también de facilitar una restauración integral de la red a su capacidad operativa total, reforzando su capacidad general para resistir y recuperarse de circunstancias adversas. Por tanto, este trabajo permite conocer qué medidas se están aplicando para minimizar los impactos de las EWEs en los sistemas energéticos, en los sistemas físicos, en las infraestructuras de transporte y distribución de energía (cortes en la producción/suministro de electricidad a la población), y por otro contribuyendo a aumentar y mejorar la resiliencia de los sistemas, y en particular los sistemas de energía eólica (WES).

En lo que respecta a los WES, la predicción adecuada de los EWEs, en particular los patrones de velocidad del viento, es crucial para mejorar la eficiencia de las turbinas eólicas. Así, se ha demostrado que la implementación de técnicas de aprendizaje automático (*machine learning techniques*), incluidas redes neuronales (*neural networks*) y *random forests*, afina las predicciones de la velocidad del viento durante varios periodos, aumentando así la eficacia operativa del sistema. Así, este análisis buscó aclarar las estrategias e intervenciones necesarias para que los sistemas energéticos mantengan su operación regular ante eventos extremos.

En general, este trabajo tiene considerables implicaciones científicas y socioeconómicas. El estudio de los EWEs asociado con ciclones extratropicales y tormentas de alto impacto que han afectado a la IP durante los últimos inviernos permite comprender los mecanismos que conducen a su desarrollo y así explicar los fuertes impactos asociados. Por otro lado, estudiar los procesos de desarrollo de estos eventos y su influencia en la producción de energía eólica, permite a las empresas energéticas y a las empresas que gestionan parques eólicos poder controlar la energía que se produce durante la ocurrencia de estos eventos. Adicionalmente, el análisis del riesgo de interrupción de la OPL causado por los ECs ayuda a identificar fallos que existen a nivel de la infraestructura eléctrica, fallos en la prevención y mantenimiento, pero también en la resolución de problemas luego de la ocurrencia de eventos, por parte de las entidades responsables (por ejemplo: líneas y postes caídos, o cortes de energía).

Además, este estudio llama la atención sobre cuestiones de infraestructura técnica y física en el proceso de desarrollo e implementación del proyecto. Esto se debe a que es necesario considerar los EWEs y los impactos causados sobre estas infraestructuras y así hacerlas más resilientes ante estos eventos. Alineado a esto, la revisión presentó los impactos de los EWEs en los sistemas energéticos, así como las estrategias, medidas y nuevas soluciones tecnológicas propuestas, que funcionan como una visión presente y futura de estos sistemas. En consecuencia, se hace evidente qué cambios y ajustes se deben realizar para enfrentar estos eventos de manera efectiva, asegurando la producción y distribución ininterrumpida de electricidad para satisfacer las necesidades de la población. Conjuntamente, esta investigación enfatiza la necesidad urgente de que las empresas del sector energético adapten y mejoren sus proyectos y sistemas para resistir la creciente amenaza de los EWEs debido al cambio climático. Los gobiernos deberían apoyar esta necesidad proporcionando datos, fomentando inversiones en resiliencia y mejorando las infraestructuras energéticas. Además, la incorporación de componentes de microrredes y tecnologías inteligentes también puede mejorar la resiliencia de la red y minimizar los impactos de eventos extremos.

La investigación continua sobre los EWEs, particularmente en la región de la IP, es vital para predecir estos eventos y comprender su desarrollo y sus impactos socioeconómicos. Al mismo tiempo, existe una necesidad de fomentar la conciencia pública sobre estos tipos específicos de peligros naturales, con la intención de garantizar que las medidas preventivas y defensivas no sólo se comprendan, sino que también se implementen proactivamente de manera oportuna y eficaz.

Además, es esencial evaluar el impacto potencial de los EWEs en la producción futura de energía eólica y esto es particularmente importante porque la energía eólica es la principal fuente de energía renovable en la región de la IP. El proceso de recopilación de datos de las plantas de energía eólica existentes para ajustar su rendimiento bajo la presión de tormentas de alto impacto es fundamental. Esto implica mejorar la resiliencia estructural de las turbinas eólicas, mejorar los sistemas de mantenimiento predictivo e implementar estrategias de control inteligentes que puedan ajustar la configuración de las turbinas en tiempo real para minimizar los daños y maximizar la producción de energía durante condiciones climáticas adversas. Por lo tanto, el sector energético debe seguir siendo ágil e innovador, aprovechando constantemente los avances tecnológicos y adoptando prácticas de diseño resilientes. Esta adaptabilidad es vital para mitigar los efectos perjudiciales de los EWEs en los sistemas energéticos, asegurando que las fuentes renovables como la energía eólica sigan desempeñando un papel clave en nuestro futuro energético sostenible. Es un esfuerzo multidimensional que exige investigación colaborativa, reformas de políticas y participación pública para asegurar un panorama energético resiliente y sostenible frente a los crecientes desafíos ambientales.

Abstract

Extreme weather events (EWEs) associated with severe extratropical cyclones (ECs) which develop in the North Atlantic and hit Europe are among the most catastrophic natural hazards in mid-latitudes because of the extensive impacts provoked by extreme winds and intense precipitation. Among others, the energy sector is seriously impacted when these extreme events last for a few days. Energy systems (ES) and their components are seriously at risk from these disasters, and they can disrupt supply and affect other structures that rely on the energy supply.

Renewable energy sources (RES) like wind energy (both onshore and offshore), are dependent on the increasing variability of the weather patterns to produce electricity. The intra and inter-annual variations in production also make ES more sensitive to weather conditions and their changes, which represents a significant challenge for the energy sector. Furthermore, climate change and EWEs are expected to significantly influence the availability and variability of wind energy in the future. In particular, the Iberian Peninsula (IP) in Southern Europe is identified as one of the European regions potentially most affected by climate change and EWEs. Therefore, there is a growing need to understand the development and intensification of EWEs, such as extratropical cyclones, and the associated physical mechanisms that cause severe impacts through extreme precipitation events and windstorms. Then, it is crucial to consider this variability in energy production and demand, in the implementation and operation of these energy systems through RES, to guarantee an uninterrupted and reliable energy supply to future generations.

Thus, the key objectives of this research are to improve the scientific knowledge of EWEs associated with ECs in the North Atlantic European region, focusing on the IP, and to provide significant advances in understanding these meteorological systems and associated physical mechanisms. An important focus of this research is the adverse impacts of EWEs on energy systems. For this, the impacts on the availability of RES (wind resources) are evaluated and consequently on the electricity production through wind energy systems (WES) in the IP. Moreover, strategies, measures and solutions are studied and identified to adapt the ES and continue operating normally during extreme events such as high-impact storms.

This doctoral thesis's corpus consists of four articles, three of them published in specialized journals included in the Journal Citation Reports (JCR) list. It should also be noted that the order of the articles presented in the doctoral thesis does not correspond to the order of their publication so some inconsistencies may appear in the periods analysed in each article.

Firstly, the ECs that impacted the IP during the four extended winters (from December 2017 to April 2021) are identified and studied. An analysis of the dynamics and synoptic conditions is completed to understand the strong impacts of these storms. Compound events (CEs) (wind and precipitation associated) are identified when comparing the values of the 98th percentile of these variables over the period 1991-2020 with the values obtained on days of greatest storm impact. The anomalies of the events are also calculated to better assess the intensity of the socioeconomic impacts on the IP. The results indicate that among the high-impact storms named by the meteorological institutes of the Southwest European Group (SW Group), since 2017, 28 storms caused adverse consequences on the IP; of those, 10 storms had an explosive development. Concerning the analysis of concurrent extreme events, this study indicates that during the stormy days, the values of precipitation and wind speed were extremes (values above the 98th percentile, with a maximum of 53.80 mm day^{-1} and 20.05 m s^{-1}, in the Northwest region of IP). In addition, the Northwest region of the IP was the most affected by these storms, with the 98th percentile value being higher in 34.1% of stormy days for daily accumulated precipitation, 45.7% of stormy days for instantaneous gusts of wind at 10 meters, and 46.8% of stormy days for wind speed at 10 meters. When we compared the values obtained for the variables under study with the reference climatology for the period 1991-2020 (anomaly analysis), lower MSLP values (with values lower than - 21.6 hPa), higher values of IVT (up to more than 327.6 kg m^{-1}s^{-1}), higher values of wind speed at 250 hPa (up to more than 29.6 m s^{-1}), and higher values of θe at 850 hPa (up to more than 19.1 ºC) are identified. Concerning heat fluxes anomalies presented surface latent heat flux (Q_E) with values lower than - 150 W m^{-2} and surface sensible heat flux (Q_H) with values lower than - 40 W m^{-2}. These results with high values present by the meteorological parameters reveal that all parameters had a crucial importance in the formation and deepening of ECs, causing large amounts of rain, flooding, and strong winds, which resulted in several destructive impacts. Furthermore, this study highlights the importance of analysing these events and the need for these events to be increasingly predicted and warnings to the population to be issued promptly, to minimize impacts.

Secondly, to evaluate the strong impacts of these events on the availability of RES as wind energy and consequently the wind energy potential (WEP), a study area and study time are defined – the three December months from 2017, 2018, and 2019 in Southwestern Europe – and the assessment of wind energy availability and WEP is performed to estimate the influence of the EWEs on the electricity production. Thus, the general conclusion of this analysis demonstrated that the severe winds from the ECs and affected southwestern Europe during the months under study have become a positive and important contribution to the production of renewable energy, as revealed by the high WEP values on the stormy days.

Thirdly, the adverse impacts of EWEs associated with ECs on ES are assessed through a risk analysis for a study case of overhead powerlines (OPL). The events that caused the disruption of OPL in Portugal are identified, and the methodology to implement a risk analysis is applied and discussed, based on various methods and techniques identified in IEC/ISO 31010:2009, NP 31010:2016 and following the NP ISO 31000:2018. To perform this study, the cause-effect diagram and the consequence/probability matrix are the applied methodologies that facilitated the comprehension of these impacts, the interaction of several aspects, and immediate and precise results. In this sense, the main results of the study demonstrated that of the 29 high-impact storms identified as having a significant impact on mainland Portugal, 31% of them (9 storms) caused disruption on OPL, in which the strong winds (values equal to or higher than 105.1 km h^{-1} (29.22 m s^{-1}) – level 11 of the Beaufort Wind Force Scale) – are the main factor of OPL disruption. Furthermore, of the 9 storms that provoked OPL disruption, one is considered a snowstorm, and 8 are windstorms (6 are compound events involving wind and precipitation, while the remaining 2 storms are wind-only events). Despite the nine extreme events that disrupted the OPL having a "Medium Risk" level, the types of adverse effects differentiate the events. So, these events can cause different negative impacts, including lasting environmental damage and substantial socioeconomic losses, with the disruption of public services, and the need for financial support. In this context, the various enhancements and strategic actions under analysis aim to reinforce the performance and structural strength of the electric grid. Their goal is to minimize the severity of adverse effects, thereby increasing operational efficiency, accelerating network recovery, and enhancing the resilience of energy systems. The analysis demonstrates a cause-and-effect relationship between EWEs and the disruption of the OPL in Portugal. This finding holds particular significance given the anticipation of more frequent and severe EWEs affecting densely populated regions in the future. To minimize the associated impacts, it is necessary to include the weather factors, the components of the OPL and all power facilities, and strategic management implemented in the systems.

Lastly, a comprehensive review of the severe impacts of EWEs on the energy systems (ES) is carried out, as these events significantly impact essential infrastructures and are considered one of the main causes of wide-area electrical disturbances worldwide. The study utilized 210 published research articles sourced from the Scopus and Google Scholar databases to evaluate the effects of EWEs – associated with severe storms, wind, lightning events, heatwaves, cold snaps, and freezing conditions – on ES including the infrastructures of production, transmission, and distribution, on a global scale. Special emphasis is given to the impact of these events on wind energy systems (WES). Then, the strategies and measures to minimize and mitigate the impacts and improve the systems' resilience are examined and registered to understand how the ES can maintain normal operation when affected by extreme events.

Furthermore, the integration of emerging technologies, such as energy storage systems (ESS), distributed energy systems (DES), and microgrids, contributes significantly to increasing the resilience and reliability of the electrical grid. Therefore, this work makes it possible to gain knowledge on what measures are being applied to minimize the impacts of EWEs on the ES, the physical systems, the energy transport, and distribution infrastructures (cuts in the production/supply of electricity to the population). Concerning WES, the accurate forecasting of EWEs, particularly patterns of wind speed, is crucial for improving the efficiency of wind turbines. So, implementing machine learning techniques, including neural networks and random forests, has been shown to refine predictions of wind speed over various periods, thereby increasing operational effectiveness. Thus, this analysis aims to clarify the strategies and interventions necessary for energy systems to maintain their regular operation when facing extreme events.

For the three first articles, the ERA5 reanalysis data (from the European Center for Medium-Range Weather Forecasts (ECMWF)) for different weather variables are used for the calculations: firstly, to analyse the synoptic and dynamic conditions of the storms that impacted the IP, and then to assess the wind energy potential (WEP).

In general, this work has considerable scientific and socio-economic implications. Studying EWEs associated with ECs and high-impact storms that have affected Iberia over the recent winters allows us to understand the mechanisms that lead to their development and thus explain the associated strong adverse impacts. On the other hand, studying the development processes of these events and their influence on the production of wind energy allows energy companies and wind farm management companies to control the energy produced during these events. In addition, the evaluation of the disruption risk of OPL provoked by severe ECs helps to understand the failures that exist at the level of the electrical infrastructure, failures in prevention and maintenance but also the resolution of problems after the occurrence of the events, by the responsible entities (for example: down lines and poles, power cuts).

Furthermore, this work draws attention to technical and physical infrastructure issues in the project development and implementation process. This is because it is necessary to consider the EWEs and the destructive impacts caused on these infrastructures and thus make them more resilient to these events. Allied with this, the comprehensive review presented the impacts of EWEs on energy systems, as well as the proposed strategies and measures, and new technological solutions, that work as a present and future vision for these systems.

Consequently, it becomes evident which changes and adjustments must be made to effectively contend with these events, ensuring the uninterrupted production and distribution of electricity to meet the population's needs.

Resumo

Os eventos meteorológicos extremos (em inglês, *extreme weather events,* EWEs), associados às depressões extratropicais severas (em inglês, *extratropical cyclones*, ECs), que se formam e intensificam sobre o oceano Atlântico Norte e atingem a Europa, são uma das maiores catástrofes naturais nas latitudes médias devido aos extensos impactes adversos provocados por ventos extremos e precipitação intensa.

Quando estes eventos são extremos e persistem por vários dias causam sérios impactes no setor da Energia. Estes eventos são considerados um risco grave para os sistemas de energia (em inglês, *energy systems,* ES) e para as infraestruturas, podendo causar cortes no fornecimento e afetar outras infraestruturas dependentes do fornecimento de energia.

A produção de eletricidade a partir de fontes de energia renováveis (em inglês *renewable energy sources*, RES), como a energia eólica (onshore e offshore), está cada vez mais dependente de padrões climáticos variáveis e estas variações intra e inter-anuais de produção também aumentam a sensibilidade dos ES às condições meteorológicas e à sua variabilidade, apresentando um desafio importante para o sector da Energia. Além disso, espera-se que as alterações climáticas e os EWEs influenciem significativamente a disponibilidade e variabilidade da energia eólica no futuro. Em particular, a Península Ibérica (em inglês, *Iberian Peninsula*, IP), no Sul da Europa, é identificada como uma das regiões europeias potencialmente mais afetadas pelas alterações climáticas e pelos EWEs.

Portanto, há uma necessidade crescente de compreender o desenvolvimento de EWEs, como as depressões extratropicais, e os mecanismos físicos associados, que provocam impactes severos causados por eventos extremos de precipitação e tempestades de vento. Deste modo, é crucial considerar esta variabilidade dos recursos na produção de eletricidade, na implementação e na operação destes sistemas de energia através de RES, de modo a garantir um fornecimento de energia ininterrupto e fiável às gerações futuras.

Assim, os principais objetivos desta investigação são melhorar o conhecimento dos EWEs associados aos ECs na região europeia do Atlântico Norte, com foco na IP, e proporcionar avanços significativos na compreensão destes sistemas meteorológicos e mecanismos físicos associados. Um ponto importante desta pesquisa são os impactos dos

EWEs nos sistemas de energia. Para tal, pretende-se avaliar os impactos dos EWEs na disponibilidade de fontes de energia renováveis e, consequentemente, na produção de eletricidade através de sistemas de energia eólica (em inglês, *wind energy systems*, WES) na IP. Além disso, são estudadas e identificadas medidas e soluções para adaptar os sistemas de energia, de modo a manter o seu normal funcionamento durante a ocorrência de eventos extremos, como as depressões de elevado impacte.

A estrutura desta tese de doutoramento é composta por quatro artigos, três deles publicados em revistas especializadas incluídas na lista *Journal Citation Reports* (JCR). De referir ainda que a ordem dos artigos apresentados nesta tese de doutoramento não corresponde à ordem da sua publicação, pelo que poderão surgir algumas inconsistências nos diferentes períodos analisados em cada artigo.

Em primeiro lugar, foram identificados e estudados os ECs que afetaram a Ibéria nos quatro invernos estendidos (de dezembro 2017 a abril 2021), tendo sido realizada uma análise das condições dinâmicas e sinópticas de modo a compreender os fortes impactes destes eventos. Os eventos compostos (com vento e precipitação associados) foram identificados ao comparar os valores do percentil 98, calculado com base na análise climatológica para o período 1991-2020, com os valores obtidos nos dias de maior impacte das tempestades. As anomalias dos eventos também foram calculadas, considerando o mesmo período, para melhor avaliar a intensidade dos impactes socioeconómicos na região em estudo.

Os resultados indicam que entre as tempestades de alto impacte nomeadas pelos institutos meteorológicos do Grupo Sudoeste Europeu (em inglês, *Southwest European Group*, SW Group), desde 2017, vinte e oito depressões causaram impactos na IP, verificando-se que dez destes eventos tiveram um desenvolvimento explosivo. No que diz respeito à análise de eventos extremos compostos, esta indicou que nos dias de tempestade os valores de precipitação e de intensidade do vento foram extremos (valores superiores ao percentil 98, com o máximo de 53.80 mm day^{-1} e 20.05 m s^{-1}, na região Noroeste da IP). Além disso, a região Noroeste da IP foi a mais afetada por estes eventos, sendo o valor do percentil 98 superior em 34,1% dos dias de tempestade para precipitação acumulada diária, em 45,7% dos dias de tempestade para rajadas de vento instantâneas a 10 metros, e em 46,8% dos dias de tempestade para velocidade do vento a 10 metros. Quando comparamos os valores obtidos para as variáveis em estudo com a climatologia de referência para o período 1991-2020 (análise de anomalias), verificamos valores mais baixos de pressão média ao nível do mar (em inglês, *mean sea level pressure*, MSLP) (inferiores a - 21,6 hPa), valores mais elevados de transporte integrado de vapor (em inglês, *integrated vapour transport*, IVT) (até mais 327,6 kg $m^{-1}s^{-1}$) e valores mais elevados de intensidade do vento a 250 hPa (superiores a 29,6 m s^{-1}), e valores mais elevados de temperatura potencial equivalente (em inglês, *equivalente potential temperature*, *θe*) a 850 hPa (superiores a 19,1 ºC). Os fluxos de calor apresentaram fluxos de calor latente superficial (em inglês, *surface latent heat flux*, Q_E) com valores até menos - 150 W m^{-2} e fluxos de calor sensível superficial (em inglês, *surface sensible heat flux*, Q_H) com valores de até menos - 40 W m^{-2}. Estes resultados, com valores elevados, em valor absoluto, nas anomalias dos parâmetros meteorológicos, revelam que todos estes parâmetros tiveram uma importância crucial no desenvolvimento e intensificação das depressões extratropicais, levando a eventos extremos de precipitação, inundações e ventos fortes, que culminaram em vários impactos destrutivos. Além disso, este estudo destaca a importância da análise destes eventos e a necessidade de que sejam cada vez mais previsíveis e que os alertas à população sejam emitidos atempadamente para, assim, minimizar os impactes.

Em segundo lugar, para avaliar os impactes destes eventos na disponibilidade de RES, como o recurso eólico e consequentemente no potencial de energia eólica (em inglês, *wind energy potential*, WEP), foram definidos uma área de estudo e um período de estudo – para o sudoeste da Europa, os meses de dezembro dos anos de 2017, 2018 e 2019 – e a avaliação da disponibilidade do recurso eólico e do potencial eólico foram feitas para compreender a influência dos EWEs na produção de eletricidade. Assim, como principal conclusão, este estudo demonstrou que os fortes ventos associados às depressões de elevado impacte que afetaram o sudoeste da Europa nos meses em estudo tornaram-se um contributo positivo e importante para a produção de energia renovável, como revelam os elevados valores de WEP nos dias de tempestade.

Em terceiro lugar, os impactes dos EWEs associados aos ECs nos sistemas de energia são avaliados através de uma análise de risco para um estudo de caso de linhas elétricas aéreas (em inglês, *overhead power lines*, OPL). Assim, foram identificados os eventos que causaram disrupção nas OPL em Portugal, e foi aplicada e discutida a metodologia para implementar uma análise de risco, com base em diversas ferramentas e técnicas identificadas nas normas IEC/ISO 31010:2009, NP 31010:2016, e NP ISO 31000:2018.

Para a realização deste estudo, o diagrama de causa-efeito e a matriz de consequência/probabilidade foram as metodologias aplicadas que permitiram uma explicação clara dos efeitos, a interligação de vários fatores e conclusões rápidas e precisas. Neste sentido, os principais resultados do estudo demonstraram que das 29 depressões identificadas como tendo impacte significativo em Portugal continental, 31% delas (9 tempestades) provocaram perturbações nas OPL, em que os ventos fortes (com valores iguais ou superiores a 105,1 km h^{-1} (29,22 m s^{-1}) – nível 11 da escala Beaufort) – foram o principal fator de interrupção da OPL. Além disso, das 9 tempestades que provocaram a interrupção da OPL, uma delas foi considerada tempestade de neve e 8 foram tempestades de vento (6 tempestades caracterizadas por eventos compostos – vento e chuva; e 2 tempestades caracterizadas apenas por vento). Apesar dos nove eventos extremos que perturbaram as OPL apresentarem um nível de "Risco Médio", as várias consequências diferenciam os eventos. Assim, estes eventos podem causar diversos impactes negativos, como danos com efeitos de longo prazo no meio ambiente e danos socioeconómicos significativos, como a interrupção de alguns serviços da comunidade, e a necessidade de assistência financeira. Neste contexto, as diversas melhorias e ações estratégicas consideradas visaram contribuir para reforçar a performance e a robustez física da rede. Estas têm como objetivo reduzir a gravidade dos impactes, aumentando assim a eficiência operacional do sistema, acelerar a recuperação da rede e melhorar a resiliência dos sistemas de energia. A análise demonstrou claramente uma relação de causa e efeito entre os EWEs e a disrupção das OPL em Portugal. Este resultado é particularmente significativo dada a previsão dos EWEs serem mais frequentes e intensos, e afetarem regiões densamente povoadas no futuro. Para minimizar os danos associados, é necessário considerar as condições meteorológicas, os materiais constituintes das OPL e de todas as infraestruturas elétricas, e uma gestão estratégica implementada nos sistemas.

Por último, no quarto artigo, foi realizada uma revisão bibliográfica abrangente dos impactes dos EWEs nos sistemas de energia, uma vez que estes eventos impactam significativamente infraestruturas essenciais e são considerados uma das principais causas de perturbações elétricas em áreas extensas em todo o mundo. O estudo utilizou 210 artigos científicos publicados e provenientes dos bancos de dados *Scopus* e *Google Scholar,* para avaliar os efeitos de EWEs – incluindo tempestades severas, vento, relâmpagos, ondas de calor, ondas de frio e condições de congelamento – nos ES e infraestruturas associadas, que incluem produção, transmissão e distribuição, em escala global. Além disso, foi dada especial ênfase ao impacto destes eventos nos sistemas de energia eólica (WES). Assim, foram analisadas e registadas estratégias e medidas para minimizar e mitigar os impactes, bem como melhorar a resiliência dos sistemas, de modo a compreender como os ES podem manter o funcionamento normal quando afetados pelos eventos extremos.

Além disso, a integração de tecnologias emergentes, como os sistemas de armazenamento de energia (em inglês, *energy storage systems*, ESS), os sistemas de energia distribuída (em inglês, *distributed energy systems*, DES) e as micro-redes (em inglês, *microgrids*), contribui significativamente para o aumento da resiliência e da fiabilidade da rede elétrica. Por outro lado, esta revisão de literatura permite reconhecer quais as soluções que estão a ser implementadas neste campo, com vista à mitigação destes danos nos sistemas de energia, os cortes na produção e/ou fornecimento de eletricidade à população, e por outro lado contribuir para aumentar e melhorar a resiliência dos sistemas. Em relação aos WES, a previsão adequada dos EWEs, particularmente dos padrões de velocidade do vento, é crucial para melhorar a eficiência das turbinas eólicas. Assim, foi demonstrado que a implementação de técnicas de aprendizagem de máquina (em inglês, *machine learning techniques*), incluindo redes neurais (em inglês, *neural networks*) e florestas aleatórias (em inglês, *random forests*), refina as previsões da velocidade do vento para vários períodos, aumentando assim a eficácia operacional do sistema. Portanto, este trabalho procurou esclarecer quais as estratégias e medidas de intervenção necessárias para que os sistemas de energia mantenham o seu normal funcionamento durante os eventos extremos.

Para os três primeiros artigos, foram utilizados os dados de reanálises ERA5 do Centro Europeu de Previsões Meteorológicas de Médio Prazo (em inglês, *European Center for Medium-Range Weather Forecasts*, ECMWF)) para os cálculos e análise de diferentes variáveis meteorológicas: análise das condições sinópticas e dinâmica dos eventos que impactaram a IP e avaliação do potencial da energia eólica (WEP).

No geral, este trabalho apresenta implicações científicas e socioeconómicas consideráveis. Ao estudar os EWEs associados às depressões extratropicais e às tempestades de alto impacte que afetaram a IP nos últimos invernos, permite-nos compreender os mecanismos que levam ao seu desenvolvimento e intensificação e, assim, explicar os fortes impactes associados. Por outro lado, ao estudar os processos de desenvolvimento destes eventos e a sua influência na produção de energia eólica permite às empresas energéticas e gestoras dos parques eólicos controlar a energia que é produzida durante a ocorrência destes eventos. Além disso, a análise do risco de disrupção de OPL causada pelos ECs ajuda a identificar as falhas que existem ao nível da infraestrutura elétrica, as falhas na prevenção e manutenção, mas também na resolução de problemas após a ocorrência dos eventos, por parte das entidades responsáveis (por exemplo: queda de linhas e postes, ou cortes de energia). Este trabalho salienta ainda as questões técnicas e físicas das infraestruturas aquando do processo de desenvolvimento e implementação dos projetos, uma vez que é necessário considerar os impactes causados pelos EWEs nestas infraestruturas e assim torná-las mais resilientes a estes eventos. Além do mais, esta revisão de literatura apresentou os impactos dos EWEs nos sistemas de energia, bem como as estratégias, medidas e novas soluções tecnológicas propostas, que funcionam como uma visão presente e futura para estes sistemas.

Consequentemente, torna-se evidente quais as alterações e adaptações que devem ser feitas para encarar eficazmente estes eventos, garantindo a produção e distribuição ininterrupta de energia elétrica de modo a responder às necessidades da população.

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List of acronyms

AEMet – Agencia Estatal de Meterología

ARs – Atmospheric Rivers

CEs – Compound Events

DER – Distributed Energy Resources

DES – Distributed Energy Systems

ECMWF – European Center for Medium-Range Weather Forecasts

ECs – Extratropical Cyclones

EDP – Energias de Portugal

ES – Energy Systems

ESS – Energy Storage Systems

EU – European Union

EU-27 – European Union 27 countries

EU-27+UK – European Union 27 countries with the United Kingdom

EU-28 – European Union 28 countries

EUMETSAT – European Organization for the Exploitation of Meteorological Satellites

EWEs – Extreme Weather Events

GHGs – Greenhouse gases

i10fg – Instantaneous wind gust at 10 m

IP – Iberian Peninsula

IPMA – Instituto Português do Mar e da Atmosfera

IVT – Integrated Vapor Transport

JCR – Journal Citation Reports

LogL – Prandtl's logarithmic law

MSLP – Mean Sea Level Pressure

ONDJFMA – Months of October to April

OPL – Overhead Power Lines

P – Precipitation

P% – Probability

PL – Power law

q – Specific humidity

Q_E – Surface Latent Heat Flux

Q_H – Surface Sensible Heat Flux

Q_{LW} – Net Surface Thermal Radiation

Q_N – Sum of Q_{SW}, Q_{LW}, Q_H, and Q_E

Q_{SW} – Surface Solar Radiation

RES – Renewable Energy Sources

RH – Relative humidity

SDG – Sustainable Development Goals

SLP – Sea Level Pressure

SST – Sea Surface Temperature

SW Group – Southwest European Group

T – Temperature

TCWV – Total Column Water Vapor

v10 – Wind speed at 10 m

W – Windstorms

W+P – Wind and Precipitation

WED – Wind Energy Density

WEP – Wind Energy Potential

WES – Wind Energy Systems

WP – Wind Potential

θe – Equivalent Potential Temperature

1 Introduction

1.1 State-art

One of the greatest natural hazards in the mid-latitudes are the severe extratropical cyclones (ECs) that develop in the North Atlantic and move towards Europe where the weather is largely determined by them and their associated fronts (Catto *et al.*, 2019; Dacre and Pinto, 2020). The Global Risk Report (2020) points to the increase in the frequency of occurrence and severity of extreme weather events (EWEs) associated with ECs, because of climate change. This change is causing alterations in weather patterns, precipitation, and wind, which can lead to the occurrence of extreme rainfall, strong winds, and snowstorms. Furthermore, EWEs result in widespread negative effects on ecosystems, populations, and infrastructures, resulting in losses that exceed those caused by natural climate variability. In particular, the Iberian Peninsula (IP) is one of the southern European regions most vulnerable to these consequences (Global Risk Report, 2020; IPCC, 2022).

In this context, the energy sector faces significant consequences with the increases of ECs which can directly influence the energy demand in crucial sectors of consumption (IPCC, 2021; IEA, 2022), and simultaneously, it can affect the energy supply in the most vulnerable regions (Panteli and Macarella, 2015; Mikellidou *et al.*, 2018; Otto *et al.*, 2020). Therefore, these effects extend within the energy sector, affecting production, transmission, and distribution infrastructures (Waseem and Manshadi, 2020; Añel *et al.*, 2024), leading to severe impacts on the reliability, performance, and resilience of energy supply systems as well as other economic sectors reliant on a stable energy supply (Panteli and Macarella, 2015; Perera *et al.*, 2020; Ashrafi and Parhizkar, 2023; Brás *et al.*, 2023). EWEs are recognized as a leading cause of extensive power disruptions around the world (Dumas *et al.*, 2019), and these weather-related power disruptions have a significant and long-lasting impact, ranging from hours to weeks, causing extensive damage to transmission and distribution facilities (Tomaszewski *et al*., 2013; Panteli *et al*., 2017; Forzieri *et al*., 2018; McMahan *et al*., 2020).

Furthermore, EWEs have significant consequences for the reliability and effectiveness of both renewable energy systems, such as wind energy systems (WES), and non-renewable energy systems (Schaeffer *et al*., 2012; Perera *et al*., 2020; Russo *et al*., 2022; Brás *et al*., 2023).

Wind energy is currently experiencing the most significant growth among renewable energy sources (RES), and it is anticipated to surpass all other forms of renewable energy in terms of installed capacity by the year 2030 (IEA, 2022; WindEurope, 2023). In this sense, wind energy contributes to energy security and diversification, moving away from fossil fuels, benefiting from public support and economic benefits, including job creation. The EU's 2030 Climate and Energy Framework sets ambitious targets, including a 40% reduction in greenhouse gas emissions from 1990 levels and a significant increase in renewable energy consumption and energy savings. Moreover, in the Net Zero Emissions by 2050 scenario, renewables, particularly wind, play a dominant role in decarbonizing electricity production (IEA, 2021). Thus, the rapid expansion of wind energy's installed capacity is driven by technological advances that lead to larger, more efficient turbines and significant cost reductions, enhancing its competitiveness (IEA, 2023; European Commission, 2024). Historically, onshore wind farms have dominated the wind power sector, but offshore wind power is gaining more and more traction owing to its reliable wind resources, minimizing environmental footprint, and less restrictive turbine size requirements (Tizpar *et al*., 2014; El Khchine *et al*., 2019; Nogueira *et al*., 2019; Li *et al*., 2020).

However, to align with the Net Zero Scenario goals of approximately 7,400 TWh of wind electricity generation by 2030, a significant increase in annual capacity additions is required, needing enhanced policy support and private-sector investment (IEA, 2023; European Commission, 2024).

At the end of 2022, Europe had 225 GW of onshore and 30 GW of offshore wind capacity installed. The European Union 27 countries (EU-27[1]) has 204 GW installed,

[1] **EU-27**: Abbreviation of European Union (EU) which consists of 27 countries (Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden), as of 1 February 2020. (UK left the EU on 31/1/2020)

including 188 GW onshore and 16 GW offshore. Wind energy accounted for a record-breaking 17% of the EU-27+UK's total demand, marking a 2% increase since 2021. Concerning the electricity mix, the countries with the highest percentage of wind share were Denmark and Ireland, with 55% and 34% respectively. Other countries, such as the UK (28%), Germany (26%), Portugal (26%), Spain, and Sweden (both 25%), have more than 20% of the electrical demand being provided by wind energy (WindEurope, 2023). Favourable wind conditions, particularly in northern Europe, along with substantial installations in Sweden and Finland, contributed to a more than 9% growth in generation for the EU-27+UK compared to 2021 (WindEurope, 2023). Nevertheless, the current wind power capacity falls significantly short of what the EU needs to achieve its 2030 Climate and Energy objectives. However, it is projected that Europe will install 129 GW of new wind farms between 2023 and 2027, with the EU-27 accounting for 98 GW of that total. Hence, the EU must aim to build an average of over 30 GW of new wind capacity annually to meet its 2030 targets. Despite the challenging economic environment and supply chain obstacles, the year 2022 witnessed a record-breaking year for wind turbine installations in Europe, with a 4% increase over 2021. Furthermore, wind energy production has grown steadily, from 370 TWh in 2018 to 487 TWh in 2022. Concurrently, the demand for electrical power has decreased from 2,960 TWh in 2018 to 2,830 TWh in 2022, in part because of the COVID-19 pandemic lockdowns in 2020 and the conflict in Ukraine in 2022. Considering the significant contribution of wind energy to the overall European energy mix (WindEurope, 2023), the availability of wind resources is highly sensitive to weather conditions, as wind energy production depends on the cube of wind speed, and so, minimal changes in wind speed can have a significant influence on the generation of wind energy (Davy *et al*., 2018; Ravestein *et al*., 2018). In addition, the extreme wind events associated with intense ECs pose significant challenges to the safe and reliable operation of wind turbines (Zhang *et al*., 2019). Therefore, changes in the occurrence of ECs in Europe (Catto *et al*., 2019) can lead to variations in calm or strong wind periods, resulting in fluctuations in electric energy generation (Moemken *et al*., 2018; Ravestein *et al*., 2018; Nogueira *et al*., 2019; Costoya *et al*., 2022). Thus, due to its influence on resource availability and electrical energy production, the wind has become one of the most extensively studied meteorological variables in the issue of global warming (Santos *et al*., 2015; Tobin *et al*., 2018; Carvalho *et al*., 2021; Martinez *et al*., 2023; Fernández-Alvarez *et al*., 2023).

In this context, it is increasingly crucial to improve the energy systems (ES) resilience against these events (Panteli *et al*., 2017; Perera *et al*., 2020), as well as check the possibility of ES operation during the occurrence of EWEs, through the adaptation and control of the systems (Zhang *et al*., 2019; Najafi *et al*., 2021). ES are vulnerable to these events which make them susceptible to disruptions. In this way, the concept of vulnerability assesses the difficulties a system encounters in sustaining its functionality during and after an undesirable event (Doorman *et al*., 2006; Sperstad *et al*., 2020). That is the susceptibility to threats and the system's ability to deal with such events that include technical, human, and organizational factors of the power system operator (Sperstad *et al*., 2020). On the other hand, resilience is the network's ability to quickly recover from disruptions, as defined by Holling (1973). Concerning ES, resilience is influenced by EWEs and involves the system's ability to predict, tolerate, restore, and respond to challenges (Panteli and Mancarella, 2015; Mahzarnia *et al*., 2020 and references therein; Gosh and De, 2022). In addition, the concept of grid resilience covers the ability to anticipate, absorb, restore, and adapt to the negative impacts caused by EWEs, to swiftly return the grid to its normal operating state (Jufri *et al*., 2019; Hossain *et al*., 2021). So, it is imperative to account for the resource variability due to atmospheric conditions and possible impacts of EWEs, in the phases of energy systems design and operation for both energy production and consumption (Ravestein *et al*., 2018; Staffell and Pfenninger, 2018). Furthermore, developing strategies and measures to improve ES and grid resilience is also decisive for the planning and operation of ES. This is particularly important given the substantial effect of EWEs on the reliability of power supply and its socioeconomic factors (Panteli and Macarella, 2015; Panteli *et al*., 2017; Jufri *et al*., 2019; Bhusal *et al*., 2020).

Therefore, the increase of the integration of renewable energy, particularly wind energy, is a key strategy in this area, contributing to the achievement of multiple Sustainable Development Goals (SDGs) and ensuring sustainability and resilience of the energy sector (UNPD, 2023; United Nations, 2023).

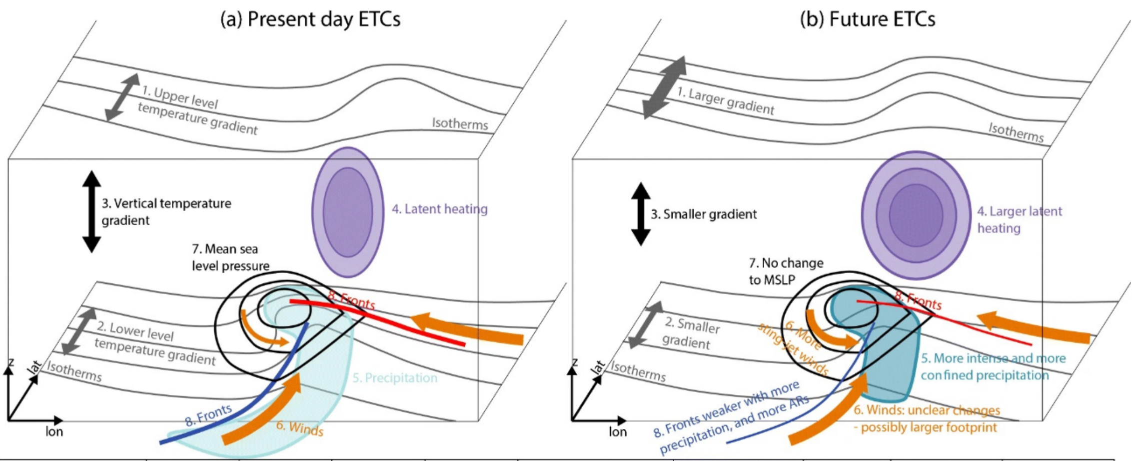
Being a relevant pattern in the mid-latitudes, extratropical cyclones (ECs), also known as mid-latitude cyclones, are large-scale weather systems that occur predominantly in the Earth's temperate zones, between 30° and 60° latitude. Unlike tropical cyclones, which draw their energy primarily from warm ocean waters, ECs are powered mainly by baroclinic processes, which occur due to the interaction of horizontal temperature differences between the equator and poles or between land and sea, and vertical shear in the Earth's atmosphere. Therefore, the formation and strengthening of ECs primarily depend on two processes: baroclinicity and the release of latent heat within the cyclones (Dacre, 2020; Raible *et al*., 2020). These cyclones form in areas with strong baroclinicity, such as over the Gulf Stream or Kuroshio Current in the Northern Hemisphere. Their complex structure includes a cold front and a warm front, forming a wave-like pattern, with the cyclone's centre often near the apex of the wave. Therefore, the life cycle of an extratropical cyclone involves several stages, including cyclogenesis (the development or strengthening of the cyclone), maturity, and occlusion (where the cold front catches up with the warm front). The development and intensification of ECs are often described by baroclinic instability (Liberato, 2014), a physical process where the energy from the temperature gradient is converted into kinetic energy, leading to the formation, and strengthening of cyclonic circulation. This process is governed by the laws of thermodynamics and fluid dynamics, particularly the conservation of angular momentum and the principle of potential vorticity, which is a key concept in understanding the movement and evolution of these systems. Their evolution and structure are closely tied to the conservation of potential vorticity and the dynamics of atmospheric fronts. So, ECs are characterized by a low-pressure centre, fronts, and strong winds, generally moving from west to east, steered by the prevailing westerly winds in the mid-latitudes, often leading to diverse and severe weather patterns, ranging from rain and snow to thunderstorms and intense winds (Catto et al. 2010; Catto *et al*., 2019; Dacre, 2020; Raible *et al*., 2020).

Furthermore, during the repeated occurrence of ECs, strong frontal systems often coincide with simultaneous high-intensity winds and rainfall which can result in cumulative effects such as flooding and wind damage (Catto and Pfahl, 2013; Raveh-Rubin and Wernli, 2015; Schemm *et al*., 2017; Raveh-Rubin and Catto, 2019; Dacre and Pinto, 2020), impacting numerous areas worldwide, including the IP, where the western coasts of the IP are the most vulnerable to ECs and where 85% of the observed precipitation and wind-extremes are linked to ECs (Liberato and Trigo, 2014; Eiras-Barca et al., 2018; Pereira *et al*., 2018; Hénin *et al*., 2021). According to Hawcroft *et al*. (2012) and Catto *et al*. (2012), ECs account for over two-thirds of the climatological precipitation in storm-track regions, such as much of North America and parts of Europe. This proportion may get as high as 90% in the main principal storm path areas (e.g., around Japan). Daily weather is directly influenced by the presence of ECs in these areas (Pfahl and Wernli, 2012; Sinclair *et al*., 2020). Moreover, the passage of ECs is strongly associated with most large-scale extreme rainfall episodes in the extratropics (Pfahl and Wernli, 2012; Catto and Pfahl, 2013, Hawcroft *et al*., 2015). Most flood events in these regions are caused by these extreme events (Nieto *et al*., 2019; Gimeno *et al*., 2022), which can generate very strong surface wind speeds that extend across a wide geographical area (Roberts *et al*., 2014; Hewson and Neu, 2015; Karremann *et al*., 2016; Befort *et al*., 2019).

Severe ECs are storms involving strong winds and heavy precipitation with extensive damage, commonly denoted as compound events (CEs) (Zscheischler *et al*., 2020). By definition, CEs can be classified as (i) the simultaneous or successive occurrence of two or more extreme events, (ii) the merging of extreme events with underlying conditions that enhance their effects, or (iii) the convergence of events that, while not individually extreme, culminate in an extreme event or its consequences when they occur together (Leonard *et al*., 2014; McPhillips *et al*., 2018). CEs, such as the concurrence or sequential occurrences of multiple extremes, result in greater damage to both populations and the environment than the effects of individual extremes alone (Dacre and Pinto, 2020; Zscheischler *et al*., 2020;). It is noteworthy that the individual factors contributing to CEs do not necessarily have to reach extreme values individually to have a substantial impact when they occur together (Liberato *et al*., 2012; Bevacqua *et al*., 2017). Numerous studies have examined extratropical cyclones as CEs, which include heavy precipitation and extreme wind events, in different geographical areas, as over the European and Mediterranean areas (e.g., Fink *et al*., 2009; Liberato *et al*., 2013; Liberato, 2014; Raveh-Rubin and Wernli, 2015; Waliser and Guan, 2017; De Luca *et al*., 2020; Poschlod *et al*., 2020; Owen *et al*., 2021; Patlakas *et al*., 2021; Flaounas *et al*., 2023; Bloomfield *et al*., 2023), western North America, or China (e.g., Zhang *et al*., 2021). Furthermore, research on CEs has also been conducted at a global scale (e.g., Martius *et al*., 2016; Zscheischler *et al*., 2020; Messmer and Simmonds, 2021; Catto and Dowdy, 2021; Ridder *et al*., 2022).

Over the past few decades, the frequency and intensity of ECs have increased significantly (Kron *et al*., 2019), with destructive consequences such as strong winds, heavy rainfall leading to flash floods and landslides, travel disruption, extensive property damage, and even loss of life (Liberato, 2014; Eiras-Barca *et al*., 2018; Sinclair *et al*., 2020; Stojanovic *et al*., 2021) Moreover, some severe ECs originated in the North Atlantic and exhibited an exceptional intensification at atypical lower latitudes as they moved towards Europe, finally reaching the IP with an unusual intensity (Fink *et al*., 2009; Liberato *et al*., 2011; 2013; Liberato, 2014; Pradhan *et al*., 2018; Stojanovic *et al*., 2021). These strong cyclones are characterized by extremely low core pressure and are often accompanied by extreme winds and heavy rain (Pfahl, 2014; Catto *et al*., 2015; Pfahl and Sprenger, 2016; Sinclair and Catto, 2023). Several impactful events affected the IP, such as the windstorms Klaus (January 23-24, 2009), Xynthia (February 27-28, 2010), and Gong (January 18-19, 2013) (Liberato *et al*., 2011; 2013; Liberato, 2014), and which often resulted in considerable precipitation and flooding are also related to atmospheric rivers (ARs) (Liberato *et al*., 2012; Ramos *et al*., 2015; Ferreira *et al*., 2016; Sousa *et al*., 2019). Additionally, recent research demonstrates that the winters of 2018–2021 were exposed to ECs with variable development and wide-ranging effects that impacted the IP (Stojanovic *et al*., 2021; Coll-Hidalgo *et al*., 2021; Zschenderlein and Wernli, 2022; Ribeiro *et al*., 2022) and other European countries (Vautard *et al*., 2019; Zhuozhuo *et al*., 2019; Doiteau *et al*., 2021; Flaounas *et al*., 2022).

In the future, ECs are expected to change in frequency, location, characteristics, and impacts which lead to different weather conditions. Figure 1 presents the structure of the ECs (ETCs, in Figure 1) in the Northern Hemisphere and the main differences associated with future changes are summarized according to the study by Catto *et al*. (2019).



Feature	1	2	3	4	5 (intensity)	5 (extent)	6	7	8
Confidence	High	High	High	High	High	Low	Low	Medium	Low

Figure 1. Schematic diagram of the structure of ECs and the future changes in the Northern Hemisphere. The table presents the confidence in changing each of the characteristics indicated in the diagram, based on the assessment of Catto *et al*. (2019).

Hence, the development of storms will be influenced by a combination of factors. These include an increased temperature gradient in the upper troposphere (feature 1), a decreased temperature gradient in the lower troposphere (feature 2), greater static stability (feature 3), and increased latent heat release (feature 4). The intensity of precipitation within ECs is anticipated to rise (feature 5), and therefore increased flooding is expected, due to the rise in precipitation and moisture transport (feature 8). However, the effects of this increased precipitation on wind intensity (feature 6) and the central pressure (feature 7) of the storms show inconclusive results. Moreover, and although there is uncertainty regarding the projections of wind strength (feature 6), the expected increase in storm-related costs is a significant concern (Catto *et al*., 2019).

Therefore, future climate change is expected to reduce the temperature gradient near the Earth's surface due to greater warming at the poles, while in the upper troposphere, this gradient is likely to increase. Additionally, the latent heat release, under climate change conditions, is intensified or reduced and thus has implications on the strength of ECs (Catto *et al*., 2019; Raible *et al*., 2020).

In this sense, Ulbrich *et al*. (2009; 2013) and Catto *et al*. (2019) agree that while the overall number of ECs remains constant, the frequency of extreme cyclones affecting western Europe and the eastern North Atlantic could slightly rise in the future due to a stronger polar jet that is reaching out towards Europe. Higher temperatures in the extratropics are also expected to increase precipitation intensity during the most intense ECs (Pfahl and Wernli, 2012; Catto and Pfahl, 2013; Hawcroft *et al*., 2015). Furthermore, ECs are projected to intensify along with increased precipitation due to forcing from latent heat release (Sinclair *et al*., 2020; Binder *et al*., 2023). On the other hand, in the study by Priestley and Catto (2022), the number of ECs of a given magnitude (i.e., the frequency distribution of EC intensity) is not expected to change significantly under high emissions scenarios. Nevertheless, there is a distinct projection that ECs will intensify in terms of vorticity, maximum wind speeds, and high wind speed footprints (Pfahl *et al*., 2015; Sinclair *et al*., 2020; Dolores-Tesillos *et al*., 2022; Priestley and Catto, 2022). This suggests that different ECs respond differently to climate change scenarios (Sinclair and Catto, 2023).

Thus, these results highlight how climate change is expected to influence ECs, affecting atmospheric conditions, with hydrological and socio-economic impacts, and so the importance of studying these events.

In this context, the present study focuses on a better understanding of ECs that affected the Iberian Peninsula in the extended winters (2017/2018 to 2020/2021), their serious societal impacts, and the influence on the energy sector, specifically on wind energy resources, systems, and grid resilience. Moreover, strategies, measures, and new technological engineering solutions are assessed to adapt systems to maintain normal operations during the occurrence of EWEs. This knowledge aims to contribute to minimizing their impact on ES and ensuring a reliable and stable electricity supply to the population.

1.2. Identification and naming of high-impact storms in Southwest Europe

The meteorological services of Portugal, Spain, and France (*Instituto Português do Mar e da Atmosfera, IPMA, Spanish Agencia Estatal de Meteorología*, AEMet, and *Météo-France*) have coordinated common strategies for naming high-impact storms and followed this standard since December 2017 (IPMA, 2023a; AEMet, 2023a; Météo-France, 2023). A high-impact storm can affect one or several of these countries and the naming is attributed to the country that is first affected. A high-impact storm is a low-pressure system or cyclone (a generic term that includes hurricanes, typhoons, polar lows, extratropical and subtropical low-pressure systems) and that has negative societal effects. These are low-pressure systems where the wind rotates counterclockwise in the northern hemisphere and associated with these storms are usually strong or very strong winds, which will be more intense the lower the minimum pressure in the centre of the low. Therefore, the storms that will be named will be those that deepen in such a way that they can greatly impact property and people. However, it will not be necessary for them to experience a process of explosive cyclogenesis (fall equal to or greater than 24 hPa in 24 hours in the centre of the low at latitudes of 60 degrees) (AEMet, 2023a). Thus, a storm is generally named when conditions are expected to give rise to the issuance of orange or red-level wind speed/gust warnings in the international meteorological warning system associated with the low-pressure system in any of the countries of the Southwest European Group (SW Group) and which should have a major impact in several areas. So, the first meteorological institute that plans to issue orange or red level alerts will name the storm. On the other hand, as the intensity of the wind is the criterion chosen to give the name to a cyclone, storms can occur that have not been given any name, but may be associated with precipitation, thunderstorms, snowfall, or sea disturbances which have a significant impact on our country and also result in the issuing of meteorological warnings (AEMet, 2023a; IPMA, 2023b). The SW Group increased its membership by joining the meteorological institutes of Belgium (RMI, 2023) and Luxembourg (MeteoLux, 2023) in 2019 and 2021, respectively. The adoption of practices for naming storms with significant impact in Europe has proven to be effective in terms of transparent communication by meteorological services, and in raising public awareness. The SW Group works with other regional meteorological institutes such as the Western Europe Group (comprising the United Kingdom, Ireland, and the Netherlands), the Northern Group (Norway, Sweden, and Denmark), the Central Group (Germany, Austria, Switzerland, Poland, Czech Republic, Slovakia, and Hungary), the Central Mediterranean Group (Italy, Slovenia, Croatia, North Macedonia, Montenegro, and Malta), and the Eastern Mediterranean Group (Greece, Cyprus, and Israel). All these meteorological institutions work closely together to ensure coordinated responses to EWEs (AEMet, 2023a, Met Office, 2023a; Met Éireann; KNMI; 2023).

On the other hand, as early as 1954, the Institute of Meteorology at Freie Universität Berlin has given names to every low-level pressure system in Central Europe. To assign names, male and female names are given interleaved starting with the male in odd years, and the opposite in even years (Met.fu-berlin, 2023). However, there is a difference between the nowadays named storms: the University of Berlin names all the storms, whereas the European National Meteorological and Hydrological Services system names only those storms that can potentially produce a substantial impact on properties and people (AeMet, 2023a).

Therefore, the initial task of this work is to identify the high-impact storms that provoked serious impacts in the IP during the 2017-2018 to 2020-2021 extended winters (months from October to April, ONDJFMA).

1.3. General characterisation of the 2018-2021 extended winters

A general analysis of the four winters is presented at this point, considering the available data from the IPMA (2023c) and AEMet (2023b) and the recently published scientific literature.

In general, winter 2017-2018, in mainland Portugal, was characterized by values below the normal for the mean air temperature and the total precipitation, classifying it as a cold and dry winter (IPMA, 2018a); in mainland Spain, the winter was characterized by lower temperatures, and an average precipitation of 2% above the average value for the quarter (a normal December and a wet January and February), according to the reference period 1981-2010 (AEMet, 2018); winter 2018-2019 in Iberia was classified as being hot, with high air temperatures, and being extremely dry when considering precipitation (AEMet, 2019; IPMA, 2019a); winter 2019-2020, in mainland Portugal, was classified as extremely hot and dry (IPMA, 2020a); in mainland Spain, the winter was, in general, wet with values close to normal, with a wet December and January but ended with an extremely dry February (AEMet, 2020); winter 2020-2021, in mainland Portugal, was very cold weather between December 24, 2020, and January 19, 2021, and a very hot February 2021 but with heavy and persistent precipitation during some days of the month (IPMA, 2021a); in mainland Spain, the winter was in general wet, with a mean precipitation value of 11% above the mean value of the quarter for the reference period (1981-2010) (AEMet, 2021a).

Additionally, a more detailed review of each winter season is presented in the following paragraphs.

Unlike in most parts of Europe, the winter season of 2017-2018 was longer and more active with some heavy snow events in IP, particularly compared to the mild winters of the previous 6 years (MeteoGroup, 2018). In mainland Portugal, this winter was characterized by values below the normal for the mean air temperature and the total precipitation (reference period of 1971-2000, considering the years 1931 to 2018), classifying it as a cold and dry winter. In addition, the total amount of precipitation that occurred from December to February was 240 mm, about 68% of the average for mainland Portugal, and in February 2018, 83% of the area was experiencing a severe drought, and 1% was experiencing an extreme drought (IPMA, 2018a). In mainland Spain, the 2017-2018 winter was characterized by a mean temperature of 0.3 ◦C below the normal value (reference period of 1981-2010), and wet, with an average precipitation of 2% above the average value for the quarter (a normal December and a wet January and February), according to the reference period 1981-2010 (AEMet, 2018).

The winter of 2018-2019 was characterized by above-normal surface pressure over Europe’s western and northern half, the North Atlantic (Greenland and Iceland), and Russia. On the other hand, the Mediterranean and the Balkan Peninsula were often under the influence of lows, resulting in a strongly negative surface pressure anomaly (Severe Weather Europe, 2019). According to IPMA (2019a), this winter in mainland Portugal was classified as hot, with high air temperatures, and extremely dry when precipitation is considered. The total amount of precipitation, 145.7 mm, corresponds to about 41% of the mean value, being the 4th driest winter since 2000 (the driest being in 2012, 2005, and 2000). This rainfall deficit in winter led to a situation of meteorological drought throughout the territory but with greater intensity in the southern region. Moreover, in mainland Spain, this winter was considered generally very dry, with an average rainfall of 98 mm, a value 51% lower than the average for the 1981-2010 reference period (the 5th driest winter since 1965 and the second driest in the 21st century, after 2011-2012) (AEMet, 2019).

The winter of 2019-2020 in mainland Portugal was classified as extremely hot and dry. The total amount of precipitation, 275.1 mm, corresponds to about 78% of the average value. During this winter some relevant episodes stood out: December 2019 recorded the 3rd highest maximum air temperature since 1931; some meteorological stations in the South area have surpassed the previous highest values of maximum air temperature for December; the passage of storms Daniel (15–17), Elsa (18–20), and Fabien (21–22) had associated persistent and intense precipitation and strong winds during these. December days; the 24-hour precipitation value which occurred on the 16th with 141.9 mm (00–24h), corresponds to the absolute daily extreme (at the Guarda meteorological station); on December 19, the Pampilhosa da Serra meteorological station recorded a gust of 41.66 m s^{-1} (150 km h^{-1}); the maximum air temperature for February 2020 was the highest since 1931 and the month was the warmest on record (IPMA, 2020a). In Spain, the 2019-2020 winter was, in general, wet with values close to normal. The average rainfall was 192 mm (4% lower than the average value for the same quarter of the reference period 1981-2010). The quarter started with a wet December and January but ended with an extremely dry February, which also turned out to be the driest of the series since 1965 (AEMet, 2020b). However, the storm Gloria, on 18th-25th January 2020, stood out with abundant rains on the Mediterranean coast and the Balearic Islands, where the accumulated values exceeded 100 mm in an extensive coastal strip (AEMet, 2021b).

Lastly, the winter of 2020-2021, in mainland Portugal, was characterized by the passage of several named high-impact storms, and the following situations should be highlighted: very cold weather between December 24, 2020, and January 19, 2021 - a situation of prolonged and widespread cold throughout the territory with values of maximum and minimum air temperature much lower than the value of 1971-2000 climatological normal (IPMA, 2021a); storm Barbara, in October 2020, was highlighted with low pressure and very significant precipitation occurred, with a particular incidence on the 19th and 20th in the Center and South regions. The wind gusts had values around 16.66 - 22.22 m s^{-1} (60-80 km h^{-1}), with a maximum of 35.56 m s^{-1} (128 km h^{-1}) observed in Fóia (IPMA, 2020b); in the period of 5 to 9 January 2021, a complex system occurred, the Filomena storm, which affected the Azores to the IP, with very cold weather and snow in the North and Center above 700/900 m and there was snowfall in the interior at very low levels, around 250/300 m, especially in the Alentejo (IPMA, 2021b); February 2021 was the 5th hottest since 1931 (with an average temperature of 11.66 °C, with more 1.68 °C than the normal value), but it had heavy and persistent precipitation during the month due to the passage of a cold frontal surface associated with storm Karim, with wind gusts of around 27.78 m s^{-1} (100 km h^{-1}) on the coast and 30.56 m s^{-1} (110 km h^{-1}) in the highlands. In general, the total winter precipitation, 373.3 mm, corresponds to about 106% of the average value, interrupting the persistence of winters with below-normal precipitation that occurred in the previous 4 years (IPMA, 2021a).

In mainland Spain, in the winter of 2020-2021, some events were highlighted such as: storm Barbara from October 19 to 22, 2020, which caused abundant precipitation in the west of the Iberia, and was very intense in the Central System, with strong winds; the episode from November 4 to 5, 2020, which left abundant rains in areas of Extremadura, western Andalusia, Castile-La Mancha and especially in the provinces of Valencia, Castellón, and Tarragona, where they were very intense (AEMet, 2021b); the fronts linked to the storms Dora and Ernest, in December 2020, brought persistent rainfall for four to ten consecutive days, resulting in abundant precipitation in most of the Spanish territory, being very intense in areas of Galicia and the Cantabrian Sea (AEMet, 2021b); storm Filomena (January 2021) affected the IP with very lower temperatures and a snowfall that left parts of Spain blocked, with a red warning in half of the country, more precisely the Madrid region, where the snow reached more than 20 cm in height (BBC, 2021). So, in general, the winter was wet, with a mean precipitation value of 11% above the mean value of the quarter for the reference period (1981-2010) (AEMet, 2021a).

The winters under study were characterized by several hazards associated with high-impact storms which affected the IP with strong winds, extreme precipitation, and snowstorms. Consequently, these events caused damage to the population, the environment, the energy sector, and associated infrastructures in different ways.

1.4. Scope of this thesis

The energy sector is central in reducing GHGs, with a shift from fossil fuels to renewable energy sources (RES) like solar, wind and hydroelectric power being crucial for lowering global carbon emissions. Investing in RES not only cuts down GHG emissions but is also a major step towards the Net Zero 2050 emissions target, as well as reducing the impact of EWEs (IPCC, 2023). In addition, this effort is vital for sustainable development and aligns with the Sustainable Development Goals (SDGs). Therefore, transitioning to renewable energy, especially wind energy which is a clean, sustainable, and cost-effective option for generating electricity, is a key strategy in achieving multiple SDGs and ensuring a sustainable, resilient, and equitable energetic future for everyone (UNPD, 2023; United Nations, 2023).

In this context, the study is motivated by the significant number of impactful extratropical cyclones (ECs) that have affected the Iberian Peninsula (IP) over the considered four extended winters (2018-2021), leading to several socioeconomic consequences on the population and the energy sector, particularly in the wind energy systems.

Moreover, and unexpectedly, there is a lack of comprehensive research that examines all these events collectively in the IP region, together with a study of the synoptic and dynamic conditions that characterize these consecutive winters. Therefore, this research aims to improve our understanding of the variability of the recent ECs in the IP, and their influence on the energy sector, in terms of wind energy production and the physical impacts on associated systems. Furthermore, investigating the effects of ECs is crucial for developing strategies to adapt the energy systems, particularly those relying on wind energy. So, it is fundamental to implement new technological engineering solutions that minimize the negative impacts of ECs, enhance system resilience, and ensure uninterrupted energy production and distribution, even during these extreme events.

These points summarize the importance of this study and the real impact of these events on our daily lives.

2 Objectives

In this chapter, the objectives of this study are outlined. The main purpose of the current study is to improve the knowledge about the variability of recent extreme weather events (EWEs) associated with extratropical cyclones (ECs) and their influence on renewable energy sources (RES), with a focus on wind energy, in the Iberian Peninsula (IP).

2.1. Specific objectives

The study is guided by a set of specific objectives described in the following points and summarised in Figure 2.

1. **To understand the weather systems as well as the physical mechanisms associated with the ECs that affected the IP.**

Firstly, and as the basis of the work, it is important to start by studying and understanding the behaviour of the weather systems that affected the IP. Therefore, the work involves analysing the dynamics of ECs by studying the physical mechanisms and the associated synoptic conditions that occurred during these phenomena. At this point, the severe impacts of these events in the IP are assessed. Subsequently, the variability of the events is analysed, considering their magnitude and frequency. This objective is addressed in the article titled "*Synoptic and Dynamical Characteristics of High-Impact Storms Affecting the Iberian Peninsula during the 2018–2021 Extended Winters*" (Gonçalves *et al*., 2023b) published in *Atmosphere*.

2. **To assess how the ECs affect the availability of RES and the production of renewable electricity (wind energy) in the IP.**

Once assessed the ECs and their variability, it is crucial to analyse how these events may interfere with the availability of RES, wind energy potential, and consequently the renewable electricity production in the IP. The goal is to evaluate the available wind resources and wind energy potential, focusing on the December months of 2017, 2018, and 2019, which were particularly stormy months in Southwestern Europe and the IP. Additionally, the study seeks to investigate how severe storms affect electricity generation using wind energy technology in this region. This objective was attended in the paper titled "*Wind Energy Assessment during High-Impact Winter Storms in Southwestern Europe*" (Gonçalves *et al*., 2021) published in *Atmosphere.*

3. **To assess the need to adapt renewable energy capture systems to keep their physical integrity and operation, maintaining electricity production and grid stability.**

When completing the previous objectives, it is fundamental to assess the need to adapt and control the energy conversion systems to keep their physical integrity and operation, moreover, maintaining electricity production, and grid stability while minimizing the strong impacts during the occurrence of the EWEs. To attain this objective, the study goes through identifying the impacts of ECs on energy systems, with a particular analysis of the Portuguese overhead power lines. This objective is addressed in the paper titled "*Disruption risk analysis of the overhead power lines in Portugal*" (Gonçalves *et al*., 2023a) in *Energy*.

The identification of existing innovative engineering solutions that are currently being implemented is conducted. Furthermore, strategies, measures, and solutions to minimize the effects of extreme events are identified, aiming to enhance the resilience of energy systems and to adapt and control electricity production during these events, especially for wind energy systems. This objective is achieved in the paper titled "Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures" (Gonçalves *et al*., 2024) in *Sustainable Energy Research.*

Figure 2 illustrates how the multiple objectives of this project are interrelated as well as the sequence of steps that were adopted in the development of this work.

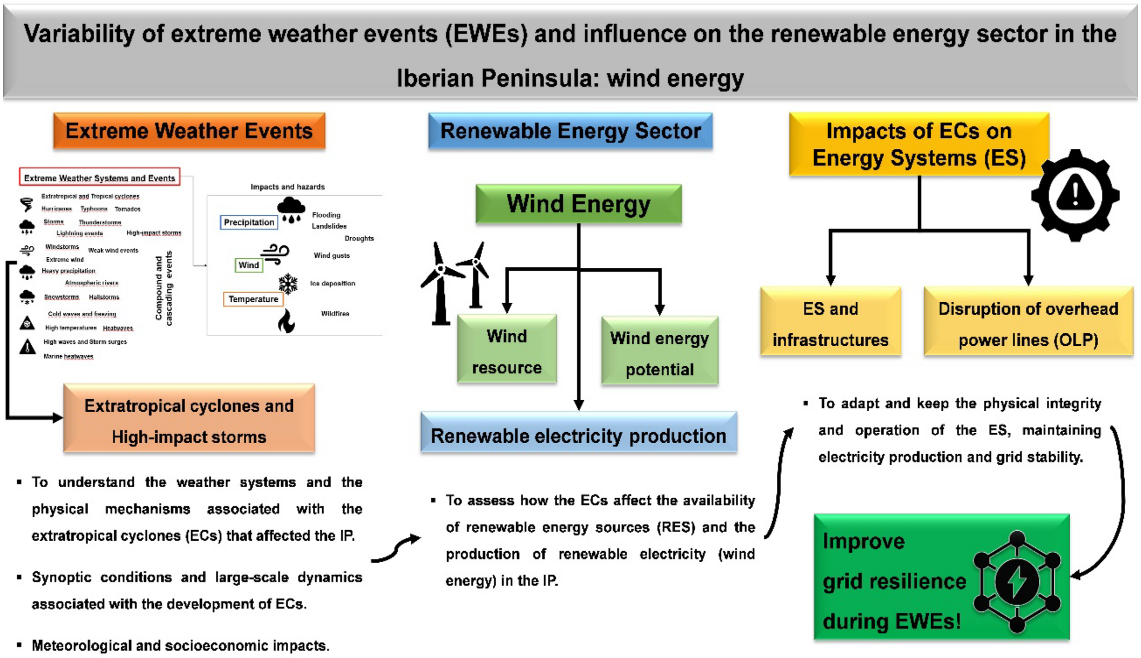


Figure 2. Outline of the main objectives of the study and their interconnection.

Chapter 3 presents the data and methodology applied throughout the study to achieve the objectives outlined above.

3 Data and Methodology

Chapter three presents the data and the methodology used to study extreme weather events (EWEs) associated with extratropical cyclones (ECs) and their influence on the energy sector (electricity production and infrastructures), more precisely in the wind energy production and the physical impacts on energy systems, (such as wind energy systems, WES), and to identify the strategies, measures, and solutions to minimize the effects of EWEs.

The following sections present the different data and methodologies used to identify and analyse the events that affected Iberia and their influence on the energy sector.

3.1. Datasets

To identify and analyse the high-impact storms in the four extended winters from December 2017 to April 2021, several datasets are used to complete the research, which is described in the following sections.

3.1.1. Observational meteorological data

The published reports of the meteorological institutes of Portugal (IPMA, 2023a) and Spain (AEMeT, 2023a) were consulted for data and the meteorological effects (wind, precipitation, and/or snow) of each event from December 2017 to April 2021. The climatological bulletins (AEMet, 2023b; IPMA, 2023c) present a national summary of the weather conditions and the changes in the major meteorological variables over time, particularly in terms of temperature and precipitation on a monthly, seasonal, and annual scales.

With data derived from the US GFS model (Global Forecast System), the DWD models (German Weather Service), and several additional models, *Weather3.com* provides a large selection of up-to-date weather charts. Several parameters serving as quasigeostrophic theory forcings for weather dynamics are presented in addition to all the standard meteorological variables that are crucial for producing specific weather forecasts (Weather3.com, 2023a). So, for the surface study of the synoptic evolution of the storms, weather charts from the *Archive UKMET analysis charts* (Weather3.com, 2023b) were used. These charts are available every six hours, where the positions (latitude and longitude) were collected for these instants, and their trajectories were tracked. In addition, the pressure values were gathered for each position every 6 hours, and each storm's greatest intensity — that is, the moment at which its core pressure is minimal — was identified.

The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is the operational satellite organization for Europe, responsible for tracking weather, climate, and the environment from space (Eumetsat, 2023a). It runs a network of weather satellites that monitor the atmosphere, the oceans, and the surface of the land 365 days a year. The National Meteorological Services of the organization's Member and Cooperating States in Europe and users worldwide receive the predictive data. These data allow meteorologists to identify and monitor the development of potentially disastrous weather conditions, as well as issue early projections and warnings to local authorities and emergency services, helping to minimize the effects of severe weather and safeguarding property and lives. This information also plays a crucial role in ensuring the safety of air travel, shipping, and road traffic, as well as in the everyday operations of agriculture, construction, and numerous other sectors (Eumetsat, 2023b; 2023c). Thus, the satellite images available from EUMETSAT (Eumetsat, 2023d) were used to follow the synoptic development of the surface storm in which, using the air mass RGB composite image, it is possible to analyse differences in temperature, humidity, and cloud height. These images are available every 15 minutes.

3.1.2. ECMWF ERA5 reanalysis data

The synoptic conditions and the large-scale dynamics related to the formation of the high-impact storms in the IP and the wind energy potential assessment were analysed through the meteorological variables from the European Centre for Medium-Range

Weather Forecasts (ECMWF) ERA5 Reanalysis (Hersbach *et al*., 2020; Bell *et al*., 2021), as summarized on Table 1.

In this work four different domains were analysed: two different domains of the Euro-Atlantic region (90ºW-25ºE; 15ºN-65ºN and 40ºW-5ºE; 30ºN-50ºN), the Northeast Atlantic and southwestern Europe region (40ºW-25ºE; 30ºN-65ºN), and the Iberian Peninsula (10ºW-4ºE; 35ºN-45ºN), for different periods (1981-2010; 1991-2020; 2017-2019; 2017-2021) and meteorological variables.

The eight historical decades of global climate and weather are covered by the ECMWF fifth-generation reanalysis or ERA5. Data are accessible starting in 1940 when ERA5 replaced the ERA-Interim reanalysis. Reanalysis is a process that integrates model data and global observations, creating a comprehensive and consistent dataset through the application of physical laws. This approach, known as data assimilation, draws inspiration from the techniques employed by numerical weather prediction centres. These centres periodically combine a prior forecast with newly acquired observations to generate an updated and more accurate assessment of atmospheric conditions, referred to as "analysis", which serves as the foundation for improved forecasts. Thus, in the case of reanalysis, this methodology is employed with some modifications to accommodate a reduced resolution, enabling the creation of datasets that span multiple decades. Unlike real-time forecasting, reanalysis is not bound by the need to produce immediate predictions, affording more time to gather observations. Moreover, when analysing historical data, there is a capacity to incorporate enhanced versions of original observations, contributing to the overall quality of the reanalysis product.

From “ERA5 hourly data on pressure levels from 1940 to present” (Hersbach *et al*., 2023a), the data of temperature (T), relative (RH) and specific (q) humidity, and wind (u and v components) at 37 pressure levels (from 100 to 1000 hPa) have been extracted from years 1991 to 2021 and for two different domains of the Euro-Atlantic region (90ºW-25ºE; 15ºN-65ºN and 40ºW-5ºE; 30ºN-50ºN) with a horizontal spatial resolution of 0.25º (31km). From “ERA5 hourly data on single levels from 1940 to present” (Hersbach *et al.,* 2023b), mean sea level pressure (MSLP), integrated vapour transport (IVT), total column water vapour (TCWV), sea surface temperature (SST), 10 m wind components (10 m u and v wind components), total precipitation, instantaneous 10 m wind gust (i10fg), and the fields of heat fluxes have been extracted from 1981 to 2021 and for different domains (see Table 1) with a horizontal spatial resolution of 0.25º (31km).

Concerning heat fluxes, in the study, were used the variables of net surface thermal radiation (Q_{LW}), surface solar radiation (Q_{SW}), surface sensible heat flux (Q_H), and surface latent heat flux (Q_E). Therefore, the thermal radiation that the atmosphere and clouds release that reaches the surface of the Earth, minus the thermal radiation that is reflected from the surface, is referred to as the net surface thermal radiation (Q_{LW}). Surface solar radiation (Q_{SW}) is the total amount of solar radiation, including direct and diffuse radiation, that reaches the Earth's surface after subtracting the amount that is reflected by it. Q_H includes the sensible heat transfer with the surface, whereas Q_E is the flux of latent heat across the surface by turbulent diffusion. The values of Q_E and Q_H are affected by several variables, including wind speed, moisture content, and temperature changes involving the surface and lower atmosphere. So, Q_N is given through equation: $Q_N = Q_{SW} + Q_{LW} + Q_H + Q_E$ (1), where the vertical flux standard used by the ECMWF takes positive values in the downward direction (Hersbach *et al.,* 2023b).

Table 1 summarizes the meteorological variables used, the periods, and the geographical domains analysed according to the initially defined objective for each of the different articles.

Table 1. Variables, periods, domains, and spatial resolution of ERA5 reanalysis datasets.

Variables	Periods	Domains	Horizontal spatial resolution (lon × lat)
On pressure levels			
T at 850 hPa	1991-2020; 2017-2021; 6 hourly time steps (00, 06,12,18 UTC); ONDJFMA.	90°W – 25°E; 15°N – 65°N	0.25° (31 km)
RH at 850 hPa			
Q at 850 hPa			
Wind (u and v) at 250 hPa			
Wind (u and v) at 900 hPa		40°W – 5°E; 30°N – 50°N	
On single-pressure levels			
MSLP	1991-2020; 2017-2021; 6 hourly time steps (00, 06,12,18 UTC); ONDJFMA.	90°W – 25°E; 15°N – 65°N	
IVT			
SST			
TCWV		40°W – 5°E; 30°N – 50°N	
Q_{SW}		90°W – 25°E; 15°N – 65°N	
Q_{LW}			
Q_{H}			
Q_{E}			
Total precipitation	1991-2020; 2017-2021; hourly dataset; ONDJFMA.	10°W– 4°E; 35°N– 45°N	
i10fg			
10 m wind (u and v)	1991-2020; 2017-2021; hourly dataset; ONDJFMA.	10°W– 4°E; 35°N– 45°N	
	1981-2010; 2017-2019; 6 hourly time steps (00, 06,12,18 UTC) only December months.	40°W– 25°E; 30°N– 65°N	

However, when comparing model parameters with observations care must be taken because observations are frequently local and specific to a point in space and time, instead of expressing averages throughout a model grid box and model time step. This is particularly important in the wind components and instantaneous wind gusts since they change on small spatial and temporal scales and are influenced by the local topography, vegetation, and structures. The ECMWF Integrated Forecasting System only shows average wind data. In this study, we utilize data from the ERA5 reanalysis, which comes with inherent uncertainties. It is worth noting that the ERA5 reanalysis data used in this study are up-to-date and incorporate new information, reflecting ongoing improvements in reanalysis techniques. These enhancements involve integrating more accurate versions of the initial observations, ultimately enhancing the overall quality of the reanalysis product. Nevertheless, it is essential to consider the potential associated errors.

3.1.3. Energy sector and socioeconomic impact data

The adverse impacts of the storms, mainly on the energy sector (electricity production and infrastructures) and the socioeconomic impacts, were identified and obtained from official reports and the news published by the media.

Information on the destructive impacts of high-impact storms on infrastructures of electricity, the interruption of the electricity supply, as well as the number of incidences that occurred, specifically noted as disruption of overhead power lines (OPL) in mainland Portugal, was acquired from Energias de Portugal (EDP) reports (EDP – Distribuição, 2017; 2018; 2019; E-Redes, 2020), and mentioned in IPMA reports (IPMA, 2017; IPMA, 2018b; 2018c; IPMA, 2019b; 2019c; 2019d; IPMA, 2020c; 2020d; 2020e).

The real data on wind energy produced in Europe and in the IP for the period 2017-2021 were obtained in the following reports and official websites (Wind Europe, 2020; European Commission, 2020; APREN, 2017; 2018; 2019; REE, 2017, 2018, 2019). From the energy reports, data was obtained on wind energy production (TWh) – onshore and offshore; daily peak production (GW.day); percentage of wind energy (%) in the EU electricity mix, and EU electricity consumption (TWh).

3.2. Methodology

3.2.1. Synoptic and dynamical characteristics of high-impact storms

In this section, methods used to identify and study high-impact storms that affected the IP throughout the extended winters of 2018–2021 and the associated synoptic and dynamical aspects as well as their impacts are described.

Events with explosive development

Several studies in the literature (Lim and Simmonds, 2002; Allen *et al.,* 2010; Liberato *et al*., 2013) have shown that ECs are particularly impactful when they undergo explosive development at the time or near to landfall.

To detect events with explosive development, Sanders and Gyakum (1980) developed a method that is used to identify when the central pressure, geostrophically adjusted to 60 ºN, decays by at least 24 hPa in 24 hours,

$$\frac{dp}{dt\text{adj}} = \frac{dp}{dt}\frac{\sin\varphi\text{Ref}}{\sin\varphi} \leq -24\ \text{hPa}/24\ \text{h}, \quad (2)$$

where φ is the storm latitude, and φ_{Ref} is 60° N. So, the events are described to undergo explosive cyclogenesis when the surface pressure in the core (MSLP) decreases by at least (24 sin φ /sin 60°) hPa in a 24-hour period.

High-impact storms are assessed based on Bergeron's deepening rate (referred to as "DR in Bergeron") by Sanders and Gyakum (1980) and then are subsequently categorized following Sanders (1986). An explosive extratropical cyclone is defined as a cyclone whose central sea level pressure (SLP) drops at a rate of at least 1 Bergeron on average:

$$1\ \text{Bergeron} = (24\ \text{hPa}/24\ \text{h}) \times \sin 60°/\sin\varphi, \quad (3)$$

where φ is the latitude of the cyclone centre and 60º is the adjusted latitude in geostrophically equivalent rate. So, explosive ECs can be classified as weak (1.0-1.2 Bergeron), moderate (1.3-1.8 Bergeron), or strong (>1.8 Bergeron).

The description of explosive ECs originally stated by Sanders and Gyakum (1980) has been adjusted by Zhang *et al*. (2017) to include cyclones where the core SLP reduction standardized at 45º N, exceeds 12 hPa in 12 hours. To identify the most rapid deepening in a cyclone's lifecycle, the 12 h SLP change is used. The revised definition of explosive ECs by Zhang *et al.* (2017) was applied in this work and the deepening rate of a cyclone's SLP (hPa h^{-1}) can be determined by equation (4):

$$\left(\frac{P_{t-6}-P_{t+6}}{12}\right) \times \left(\frac{\sin 45°}{\sin\frac{\varphi_{t-6}+\varphi_{t+6}}{2}}\right), \quad (4)$$

where P is the core SLP, φ is the cyclone center's latitude, and t denotes the period studied in hours. The timesteps 6 hours before and after the time *t* are indicated by the subscripts "*t-6*" and "*t + 6*," respectively. This, an extratropical cyclone is characterized as an explosive cyclone if its rate of deepening is greater than or equal to 1 Bergeron. These ECs are further classified into different intensity levels, including weak (1.00–1.29), moderate (1.30–1.69), strong (1.70–2.29), and super (≥2.30).

Classification of events into groups

The characteristics, trajectories, and intensity of the high-impact storms are evaluated.

In addition to intensity, the events are categorized into groups according to their trajectories following the Karremann *et al.* (2016) criteria developed for windstorms occurring in the Iberian Peninsula. The large-scale atmospheric conditions and cyclone trajectories linked to the 100 most significant potential losses in the IP region caused by severe wind events (windstorms) are described.

Thus, to classify the events into groups, the trajectory of each event and a MSLP composite (MSLP average at the instant of maximum intensification of the events) was calculated, so the magnitude of the events under study was compared with the results of Karremann *et al.* (2016), about trajectories and magnitude.

The events are then classified into four distinct groups:

- *"Iberia" Group*: this group comprises cyclones with tracks that directly intersected Iberia on the event day.
- *"North" Group:* cyclone tracks in this category traversed north of the IP, following a predominantly west-to-east path, primarily affecting the southwest of the British Isles. They mostly influenced the IP through the extension of their frontal systems.
- *"West" Group:* cyclone tracks within this group crossed from the southwest to the northeast but remained west of the IP.
- *"Hybrid" Group:* this group represents a synoptic pattern characterized by the juxtaposition of a cyclone and an anticyclone, resulting in a notable MSLP gradient across the IP, subsequently leading to severe winds.

Extreme precipitation events, wind events, and concurrent events

To perform a more detailed study of the meteorological impacts, the events are divided into different categories: precipitation (P) storms, windstorms (W), and storms with both wind and precipitation (W + P). This distinction relies on values for each variable (daily accumulated precipitation, wind speed at 10 m, and instantaneous wind gust at 10 m) that, on the days of the storms, exceeded the 98th percentile in at least one ERA5 grid point in the IP domain (10°W, -4°E; 35°N, -45°N) for the reference period of 1991–2020 and the extended winter (ONDJFMA) months.

The day of maximum intensity (i.e., minimum central pressure) is used as an indicator to determine, for each storm, the days that had the most impact. Each storm was compared to the others, and then the complete set of occurrences was examined. For stormy days, the percentage of days in which the values of each variable surpassed the 98th percentile at least once within the defined domain is evaluated.

Identification and characterization of high-impact storms

During the four considered extended winters (December 2017 to April 2021), forty-nine high-impact storms were identified and named by the meteorological services of SW Group; however, not all of them had a major impact on the IP. Therefore, thirty high-impact storms caused damage in Iberia due to strong winds and/or heavy rainfall (IPMA, 2023a; AEMET, 2023a).

As a result of the mentioned methodology, it was necessary to create a new database that brings together information on all storms that impacted the IP from December 2017 to April 2021. Therefore, Table 2 is a new database of high-impact storms that allows us to carry out the entire investigation, and depending on the objective of each study, different groups of events were analysed each event, it is registered the instant of minimum pressure and the instant of highest impact in Portugal, marked with an asterisk (*) and in bold, which in some cases is the same instant.

Table 2. Characteristics of the named storms by SW European Group in the extended winters of 2018-2021 that impacted the IP: name (including the designation by the Institute of Meteorology of the Freie Universität Berlin, Germany), date, position (latitude and longitude), for the minimum pressure, and the instant of highest impact in Portugal (with an * and bottom line in bold) of each storm.

Name of the storm		**Date, position, minimum pressure, and the instant of highest impact in Portugal (*, bottom line in bold) of each storm**			
SW European Group	**Met Fu Berlin**	**Date (dd/mm/yyyy UTC)**	**Latitude (°N)**	**Longitude (°E)**	**Pressure (hPa)**
2017-2018					
Ana	Yves	11/12/2017 06	48	-2	958
		11/12/2017 00	*47*	*-7*	*964**
Carmen	Ingmar	01/01/2018 06	49	-6	989
Emma	Ulrike	26/02/2018 06	42	-35	963
		28/02/2018 06	**38**	**-25**	**977***
Félix	Yuliya	11/03/2018 00	45	-11	967

Gisele	Zsuzsa	14/03/2018 12	51	-18	965
Hugo	Carola	23/03/2018 18	49	-10	969
2018-2019					
Beatriz	Yaprak	07/11/2018 06	55	-28	958
		11/11/2018 00	**56**	**-26**	**967***
Carlos	Cornelia	15/11/2018 06	51	-48	947
		18/11/2018 00	**62**	**-40**	**977***
Diana	Halka	29/11/2018 12	58	-16	949
Gabriel	Oskar	29/01/2019 18	47	0	985
		29/01/2019 06	**48**	**-9**	**996***
Helena	Quirin	31/01/2019 12	52	-15	971
		01/02/2019 12	**47**	**-7**	**981***
Laura	Cornelius	06/03/2019 18	56	-8	974
		06/03/2019 00	**52**	**-10**	**980***
2019-2020					
Cecilia	Luis	22/11/2019 12	46	-9	976
Daniel	Xander	16/12/2019 18	45	-3	994
		16/12/2019 12	**39**	**-8**	**995***
Elsa	Yadid	19/12/2019 00	55	-15	965
		19/12/2019 18	**59**	**-18**	**968***
Fabien	Ailton	21/12/2019 12	49	-11	962
Gloria	Ilka	17/01/2020 12	48	-29	988
		18/01/2020 12	**45**	**-8**	**1015***
Jorge	Charlotte	29/02/2020 12	56	-11	953
Karine	Diana I	02/03/2020 00	51	-5	984
Leon	Diana II	01/03/2020 12	48	0	991
		01/03/2020 06	**46**	**-5**	**993***
2020-2021					
Alex	Brigitte	02/10/2020 06	49	-2	968
Barbara	Imika I	21/10/2020 06	49	-2	989
		20/10/2020 12	**38**	**-11**	**996***
Dora	Wenke I and II	04/12/2020 06	52	2	968
Ernest	Yvonne	07/12/2020 12	47	-7	988
Filomena	Bartosz	08/01/2021 18	36	-6	996
Gaetan	-	21/01/2021 18	58	3	950
		20/01/2021 06	**45**	**-12**	**984***
Hortense	Irek	21/01/2021 18	50	1	983
		21/01/2021 06	**48**	**-12**	**986***
Ignacio	Lars	23/01/2021 12	45	-9	999
Karim	Christopher	19/02/2021 00	55	-27	955
		20/02/2021 12	**55**	**-21**	**960***
Lola	-	22/04/2021 18	43	-24	982
		23/04/2021 18	**43**	**-21**	**986***

Six of the nine named storms that occurred during the extended winter of 2017–2018 had serious negative effects in the IP. Six storms from a total of thirteen are selected in 2018–2019, eight from fifteen are considered in 2019–2020, and ten out of twelve storms in 2020–2021 are chosen.

Synoptic analysis

The synoptic conditions and the large-scale dynamics associated with the development of high-impact storms are studied through the analysis of the meteorological fields of wind speed at 250 hPa and 900 hPa, T, RH and *q* at 850 hPa, MSLP, IVT, Q_E, Q_H, Q_N, TCWV, SST, precipitation, wind speed at 10m and i10fg at 10m.

The approximate location of the surface fronts is often determined using equivalent potential temperature (θe) at 850 hPa (Catto *et al*., 2010; Schemm *et al*., 2015) and here θe is calculated applying Bolton's equation (Bolton, 1980) and ERA5 reanalysis data (T and RH at 850 hPa).

To evaluate the heat transfer involving the ocean and the atmosphere in the ECs, heat fluxes are used. According to Dacre *et al*. (2020), heat and moisture fluxes through the ocean and atmosphere can result in ocean cooling during the most powerful storms in the cold sector behind the cold front of the ECs. Zhang *et al*. (2021) also demonstrated the significant role of latent and sensible heat fluxes in the first stages of the formation of super explosive cyclones.

The precipitation between 00 UTC (timestep 01 UTC of day *n*) and 00 UTC on the following day (timestep 01 UTC of day $n + 1$) is used to compute the daily accumulated precipitation dataset. The i10fg is the greatest wind gust at the indicated time, measured ten meters above the surface of the Earth.

Case studies and composite analysis

To analyse the case studies, different meteorological parameters (MSLP, θe at 850 hPa, IVT, wind speed at 250 hPa, Q_E, Q_H, Q_N, and SST) are used in different instants of their development – the instant of maximum intensity (minimum pressure), as well as 12 h before and 24 h before the instant of maximum intensity.

The composite analysis – which consists of calculating the average of the meteorological parameters under study – in the instant of maximum intensification of the events is applied in different articles to analyse the synoptic conditions and the large-scale dynamics of the high-impact storms:

- For the IP: MSLP, *θe* at 850 hPa, IVT, wind speed at 250 hPa, Q_E, Q_H, Q_N, SST, was applied to study 28 high-impact storms.
- For mainland Portugal: MSLP, TCWV, IVT, and wind speed at 900hPa, were applied to study the 9 high-impact storms that disrupted overhead power lines.

Climatological and anomaly analysis

A climatological study is conducted for the extended winter months (October to April), covering the 30 years from 1991 to 2020. This analysis focused on studying the above-mentioned meteorological fields.

For the 1991-2020 period (months ONDJFMA), the anomalies of the storm composites – which are the deviations of the arithmetic mean of the composites of the respective climatology – are calculated for the same meteorological parameters.

3.2.2. Disruption risk analysis

The methodology to assess the risk of disruption to electrical transmission and distribution systems in Portugal due to EWEs – such as high-impact storms – is exposed, and mitigation strategies and measures are suggested. This work is a follow-up of a preliminary study performed for 12 high-impact storms of 2017 and 2018 by Loureiro (2019).

Characterization and socioeconomic impacts of EWEs

For this study, high-impact storms that provoked serious impacts on the IP during 2018-2021 extended winters are analysed (Table 2), and among these are selected only those that caused disruptions in overhead power lines (OPL) in mainland Portugal, due to severe winds, intense precipitation, and snow or ice rain, were considered.

In this sense, twenty-nine events that caused significant damage across mainland Portugal during the considered four extended winters (2018–2021) are identified (see Table 1 by Gonçalves *et al.* 2023a, page 97). Therefore, to identify which of these events, – in addition to being considered explosive and extreme – had socioeconomic impacts in

Portugal, a review of the most relevant impacts is carried out through the news on media and is presented in Table 3. Associated impacts include fatalities, injured and homeless people, the downfall of hundreds of trees, and disrupted infrastructures including power lines and floods.

Table 3. Collection of impacts associated with storms on the news.

Storm associated	Title	References
Ana (December 2017)	Tempestade Ana: um morto, dois feridos e centenas de árvores derrubadas	Público, 2017
Emma (February 2018)	Tempestade Emma passa por Portugal e dirige-se para o Reino Unido	Weather, 2018
Gisele (March 2018)	Proteção Civil registou 445 ocorrências até às 14:00	SicNoticias, 2018
	Gisele já faz estragos: Caiu telhado da Porto Editora	Jornal da Maia, 2018
Helena (January 2019)	Depressão "Helena" deixa Portugal em alerta vermelho na sexta-feira	Jornal de Notícias, 2019
Elsa and Fabien (December 2019)	Tempestade Elsa e Fabien cortaram a luz a 17 milhões de clientes em 2019	Observador, 2020
	Seguradoras estimam danos das tempestades Elsa e Fabien em Portugal em 34 milhões	Diário de Notícias, 2020
	Tempestade "Daniel" está prestes a terminar, mas vem aí a "Depressão Elsa"	CMJornal, 2019
	Depressão Elsa e Fabien deixam rasto de destruição de norte a sul do país	SicNoticias, 2019
	Tempestades Elsa e Fabien causaram danos de 34 milhões de euros	ZAP.aeiou, 2020
	Dois mortos, um desaparecido e 70 desalojados	Renascença, 2019a
	Postes elétricos destruídos, árvores arrancadas. O caos provocado pela depressão Elsa em imagens	Renascença, 2019b
	Análisis de la evolución atmosférica, ciclón Fabien 21-12-19	Meteovigo, 2019
	A dimensão das cheias no Mondego vista por satélite	Diário de Notícias, 2019
Glória (January 2020)	Tempestade 'Glória' semeia destruição no Centro do País	CMJornal, 2020
Karine and Leon (March 2020)	Mau tempo provoca dezenas de quedas de árvores em oito distritos	Público, 2020

In the following points, the methodology used in the risk analysis is presented, and Table 3 was used to confirm the impacts of these events in mainland Portugal and thus validate the results presented in the risk matrix.

Risk assessment

The entire process of risk identification, analysis, and assessment is known as risk assessment. This must be performed in an orderly, cooperative, iterative manner based on the knowledge and data acquired for the purpose. This process is carried out using a wide range of tools and techniques presented in the international standard "Risk Management Techniques for Risk Assessment (IEC/ISO 31010:2009)" (IEC/ISO 31010:2009, 2009) and in accordance with NP 31010:2016 (NP 31010:2016, 2016) and NP ISO 31000:2018 (NP ISO 31000:2018, 2018).

The multiple steps involved in assessing the risk of OPL disruption in Portugal are outlined below.

✓ **Identification of the reference situation**

In this research, when assessing the impact on electrical infrastructure, it is crucial to recognize that mainland Portugal often experiences EWEs, particularly ECs, followed by intense rainfall and severe winds. These events have significant implications for buildings, and power infrastructures (distribution and transmission, such as power lines), as well as for falling trees and injuries to people, even fatalities. In addition, these occurrences can impact a large geographic region, as well as extremely small parts of the domain with concentrated effects (ANEPC, 2019).

The ECs which influenced mainland Portugal during the extended winters of 2018–2021 and impacted the electricity network, disrupting the OPL, is the reference situation considered in this study.

✓ **Risk identification and characterization**

The objective of risk identification is to locate, determine, and characterize risks that have the potential to assist or restrict an organization in accomplishing its goals. So, to identify hazards, it is crucial to have information that is appropriate, relevant, and current. Different methodologies are used to uncover uncertainties that could impact goals, culminating in various potential outcomes with tangible or intangible consequences.

Risk characterization aims to enhance understanding of risk factors, their location, potential damage severity, and the likelihood of occurrence, particularly for people, materials, or the environment. Ideally, risk categorization should be qualitative, quantitative, and descriptive, considering available data and a range of possibilities

(ANPC, 2009; IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016; NP ISO 31000:2018, 2018).

✓ **Risk analysis**

The analysis of the risk intends to comprehend the origin, attributes, and, when relevant, the level of risks. This process entails a thorough evaluation of elements like uncertainties, sources of risk, potential outcomes, probabilities, events, scenarios, controls, and their efficacy. Events may impact multiple objectives and have various causes and consequences. The depth and intricacy of the risk analysis can differ based on the study's objectives, data accessibility, reliability, and available resources, as well as the techniques' limits, and how they are applied. Additionally, risk analysis supports risk assessment, guides decisions on risk mitigation, and aids in selecting appropriate risk management strategies. Ultimately, its results provide valuable guidance for decision-making in situations involving diverse types and levels of risk (ANPC, 2009; IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016; NP ISO 31000:2018, 2018).

Considering the nature of the data and the specific study, the most appropriate approach is the cause-and-effect diagram in conjunction with the risk matrix (or consequence/probability matrix), as outlined in the standard "Risk Management Techniques for Risk Assessment" (IEC/ISO 31010:2009), (IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016).

- **Cause-effect diagram (Ishikawa diagram):** is a method used to show the relationships between an effect and its numerous causes to determine the root causes of quality issues. This diagram offers a structured approach to examining the causes and the effects that either generate or contribute to those effects. It guides team members in thinking systematically and facilitates the identification of the source of the problem. It is particularly useful for identifying possible root causes, selecting, and listing interactions between factors, and analysing existing problems for corrective action. Developing a cause-and-effect diagram aids in systematically uncovering the root causes of a problem, presenting cause-and-effect relationships in a clear and accessible format, and identifying areas where additional data collection is needed (Ishikawa, 1990; IEC/ISO 31010:2009, 2009; Ilie and Ciocoiu, 2010; NP EN 31010:2016, 2016; Coccia, 2017; Botezatu *et al.*, 2019; Loureiro, 2019). Therefore, this qualitative scenario analysis tool serves to identify contributing factors, which are organized into various categories and represented in a tree structure or fishbone diagram (see Fig. 1. Gonçalves *et al.*, 2023a, page 99). It offers a simple interpretation, illustrating the interconnection of different causes and their effects. The diagram is useful for determining possible mechanisms of failure, risks, decision-making criteria, and/or available resolutions. This analysis requires relatively low resource allocation and capacity while exhibiting moderate complexity, resulting in a qualitative outcome (IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016; NP ISO 31000:2018, 2018).

- **A risk matrix (consequence/probability matrix):** is a risk assessment technique that evaluates the severity and probability of a given risk. It is a qualitative or semi-quantitative method that estimates the severity of different scenarios and identifies the frequency of adverse consequences for the population, environment, and socioeconomic factors. This method is simple to use and provides a rapid classification of risks according to significance levels. It is also useful when there is not enough information for extensive analysis or when the circumstances do not justify a more quantitative analysis (ANPC, 2009; IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016; NP ISO 31000:2018, 2018) Severity is measured by the magnitude of adverse consequences for people, property, and the environment, while vulnerability refers to the potential for generating casualties or economic losses due to an event (Markowski and Mannan, 2008; Lin and Xu, 2016; Peace, 2017; Luo *et al.*, 2018; Loureiro, 2019; Luejai *et al.*, 2021; Qazi and Dikmen, 2021; Ibrahim *et al.*, 2022).

In simple terms, risk can be defined as the product of the probability that some event (or sequence of events) will occur, and the adverse consequences of that event ($Risk = Probability \times Consequence$). However, there is a variety of expressions for this concept, and the disaster risk management community often applies $Risk = Hazard \times Vulnerability \times Exposure$ (Seneviratne *et al.*, 2012; Leonard *et al.,* 2014). Therefore, the hazard comprises the probability of an extreme event with a potentially large impact, and thus, a change in the probability of the hazard directly affects the risk (Zscheischler and Seneviratne, 2017).

The various degrees of probability and severity (consequence) are determined through the criteria in the norms IEC/ISO 31010:2009, (2009), NP EN 31010:2016 (2016) and NP ISO 31000:2018 (2018) (adapted in Tables A1 and A2, supplementary material of Gonçalves *et al*., 2023a, Appendix A, page 160), and positioned on a risk matrix.

Probability computation

Probability (*P%*) values (0 to 100%) are calculated respecting 5 risk levels (see Table A1, supplementary material of Gonçalves *et al*., 2023a, Appendix A, page 160):

- level 1, $P \leq 20\%$
- level 2, $20\% < P \leq 40\%$
- level 3, $40\% < P \leq 60\%$
- level 4, $60\% < P \leq 80\%$
- level 5, $80\% < P \leq 100$ %.

Three distinct scenarios were used to categorize the events, such as snowstorms, windstorms, and compound events (wind and precipitation events), and were considered separately when determining the number of occurrences that disturbed the OPL.

These three situations were considered while calculating the probability values of the risk of OPL disruption for the first four extended winters of the study period (2018–2021, for 29 events) and then only three extended winters, excluding the last one (2018–2020) because there was no data available on OPL disruption, so 20 events were considered.

The following formula can be used to determine the probability (P%) of OPL disruption:

$$P = \frac{number\ of\ events\ that\ disrupted\ OPL}{total\ number\ of\ events\ considered\ in\ the\ study} x\ 100\% \qquad (5)$$

Following the computation of probability values (Table 3 of Gonçalves et al., 2023a, page 104), the severity (consequence) levels were determined according to the impacts generated by the events (Table 4 of Gonçalves et al., 2023a, page 104, and Table A2 of supplementary material, Appendix A, page 160).

The risk matrix was developed using the probability and severity data and validated with the socioeconomic data from Table 3. The matrix has a 5-level scale for both probability and consequence (Table 4), where the scale definitions of the risks are arranged according to their degree of risk, which is usually represented by distinct colours (red usually indicates an unacceptable risk degree, yellow or orange indicates a reduced risk, and green usually indicates an acceptable risk).

Table 4. Risk matrix (Adapted: Cox, 2008; Markowski and Mannan, 2008; IEC/ISO 31010:2009, 2009; NP EN 31010:2016, 2016; NP ISO 31000:2018, 2018).

Probability \ Severity	Residual (1)	Reduced (2)	Moderate (3)	Accentuated (4)	Critical (5)
High (5)	Medium	High	High	Extreme	Extreme
Medium-high (4)	Medium	Medium	High	Extreme	Extreme
Medium (3)	Medium Low	Medium	Medium	High	High
Medium-low (2)	Low	Medium	Medium	Medium	High
Low (1)	Low	Low	Medium Low	Medium	Medium

Then, the risk levels for each event were analysed, and these can be used to establish if further assessment or appropriate risk management actions are required (Cox, 2008; Markowski and Mannan, 2008; Peace, 2017; Luo *et al.*, 2018).

✓ **Risk mitigation measures and strategies**

Risk treatment involves selecting and implementing strategies to address identified risks, which requires careful planning and should consider the impact on internal and external stakeholders. Despite careful actions, risk management can have unintended consequences, necessitating ongoing monitoring and periodic reviews

(IEC/ISO 31010:2009; NP EN 31010:2016; NP ISO 31000:2018). Thus, the final step in risk assessment is to identify and apply strategies to mitigate long-term risks (ANPC, 2009; Loureiro, 2019).

3.2.3. Wind energy assessment

The methods applied to assess the wind energy potential (WEP) during the high-impact storms that hit southwest Europe in December months of 2017–2019 are presented in this point.

The WEP is determined by correcting and extrapolating wind speeds at 10 m (V10) from ERA5 to 135 m, that is the height of the onshore wind turbine taken into consideration in this thesis (Hoogwijk *et al*., 2004; ENERCON, 2015). Then, Prandtl's logarithmic law (LogL) and the Power-law (PL) (Frank *et al*., 2020) were used to define the vertical wind profiles in the surface layer, which enable dependable vertical interpolations and extrapolations on plan and uniform terrain (Emis, 2014; Hadi, 2015).

The LogL is a suitable representation of the impact of soil roughness and terrain topography on the profile of wind speeds (Henderson-Sellers, 1987; Strataridakis *et al*., 1999; Nogueira *et al*., 2019) and expressed by equation (6):

$$\bar{v}(z) = \frac{v_r}{k}\ln\left(\frac{z}{z_0}\right) \tag{6}$$

where $\bar{v}(z)$ is the mean wind speed at height H, v_r is the friction speed, k is the Von Karman constant (k = 0.4), and z_0 (m) is the length of the soil roughness (Hoogwijk *et al*., 2004; Masters, 2004). Equation (6) is frequently applied to extrapolate wind speeds to different altitudes (Strataridakis *et al*., 1999; Ritter *et al*., 2015). Wind extrapolation involves the application of a logarithmic wind profile, assuming the atmosphere to be neutrally stratified Hoogwijk *et al*. (2004). The PL method has no physical basis but appears to provide a better fit for most of the data across a larger range of heights and stronger wind scenarios (Frank *et al*., 2020).

Equations that accurately forecast wind speeds at one height based on measurements made at a different height should be used to determine the wind energy collected at wind speeds of higher heights. PL describes how the earth's surface roughness affects wind speed (Pryor *et al*., 2005; Hueging *et al*., 2013; Tobin *et al*., 2015; Nogueira *et al*., 2019), and normally, a height (H_0) of 10 m above the ground is used as a reference height, along with a corresponding reference wind speed (v_r), as it is expressed by Equation (7):

$$v_h = v_r(\frac{H}{H_0})^{\alpha} \quad (7)$$

where the power-law exponent (α) varies according to factors such as the terrain nature (surface roughness) (Peterson *et al.*, 1978; Masters, 2004; Bañuelos-Ruedas *et al.*, 2010; Santos *et al.*, 2015).

The values of the coefficient of soil roughness, z_0, and the power-law exponent, α, used in this study were obtained from Masters (2004) (see Table S1 and Table S2 supplementary material of Gonçalves *et al.*, 2021, Appendix A, page 156).

Wind energy density, wind potential (WP), or the power generated by a wind turbine quantifies the energy carried by the wind, that is the flow of kinetic energy carried by the wind and is proportional to the wind speed cubed (Holton, 2004; Pryor and Barthelmie, 2011; Tobin *et al.*, 2016; Carvalho *et al.*, 2017; Nogueira *et al.*, 2019).

WP is determined by several factors including air density (typically 1.225 $kg{\cdot}m^{-3}$ near the surface), the radius of the turbine (R, in m), wind speed (V, in $m{\cdot}s^{-1}$), and the rotor power coefficient, *Cp*. This coefficient, also known as the Betz limit (*Cp* = 16/27), defines the theoretical maximum energy that a turbine can extract from the wind. Furthermore, it represents the relationship between wind power density and rotor power density (mechanical power at the turbine shaft per unit of swept area) (IEC, 2005; Ritter *et al.*, 2015). Nevertheless, real values of *Cp* often range from 0.35 to 0.50, which is substantially below the limit of Betz (Libii *et al.*, 2013; Devis *et al.*, 2018; Martin *et al.*, 2020). Within the wind speed range between the specific cut-in wind speed at which a turbine begins to generate power and its nominal wind speed, the WP increases in direct proportion to the cube of the wind speed:

$$\mathrm{WP} = \frac{1}{2} \times C_p \rho \pi R^2 V^3, \quad (8)$$

WP is extremely sensitive to wind speed and is dependent on the power coefficients of a particular turbine model (Santos *et al.*, 2015).

The following equation is used to calculate the WEP for a given period (t):

$$\mathrm{WEP} = WP \times t \quad (9).$$

To assess the differences in wind speed at 10 m and wind energy potential between each December month under study and the respective climatology, anomalies were calculated for every month (individually) of the meteorological variables under study and the corresponding climatological average of the December months of 1981-2010.

3.2.4. Comprehensive review of extreme weather events' impacts on energy systems

In this section are presented the data and methods applied to perform the comprehensive literature review about the impacts of extreme weather events (EWEs) on energy systems (ES) and their associated infrastructures worldwide, particularly on the wind energy systems (WES), as well as propose the strategies, measures, and solutions aimed at mitigating the effects on ES.

Scientific data for literature review

The information and literature consulted include publications sourced from online scientific databases, specifically Scopus (Scopus, 2022) and Google Scholar (Google Scholar, 2022). Table 5 provides an overview of the research topics and their corresponding keywords, considered representative of the study theme.

Table 5. Topics and keywords of the research.

Topics	Research keywords
Extreme weather events (EWEs)	Weather variables EWEs Impact of EWEs on ES
Energy systems (ES)	Vulnerabilities of ES The resilience of ES Renewable and non-renewable ES Energy production and distribution systems Impacts of EWEs on electricity production technologies Impacts of EWEs on energy transmission and distribution infrastructures
Wind energy systems (WES)	Impacts of EWEs on WES Solutions to minimize the impacts of EWEs on WES
Measures and solutions	Mitigation of EWEs impacts on ES Energy storage systems (ESS) Distributed energy systems (DES) Smart grids and microgrids

Thus, data for this review was collected from a variety of credible sources, including scientific articles, reports, books, and doctoral theses, all in English and published globally. In short, 210 documents published between 1973 and 2023 were collected.

A comprehensive and objective assessment of the existing data on the research question - *"The impacts of extreme weather events on energy systems"* - using an interdisciplinary methodology was carried out. Therefore, this type of review emphasises contextual understanding and interpretative analysis, offering a comprehensive and critical overview of the literature in this field. It represents a qualitative synthesis of information, as described in various works (Green *et al.*, 2006; Grant and Booth, 2009; Onwuegbuzie and Frels, 2016; Machi and McEvoy, 2016).

The processes exposed in Figure 3 were adopted to perform the comprehensive literature review, ensuring a thorough presentation and critical evaluation of the existing information on the specified topic (Green *et al.*, 2006; Pautasso, 2019).

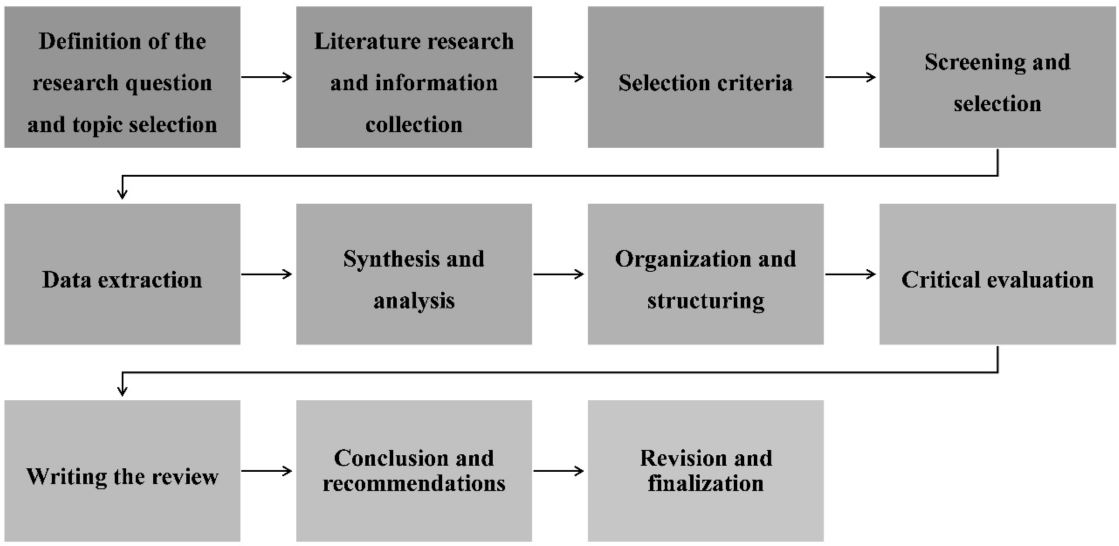


Figure 3. Processes of the comprehensive literature review applied in the study.

The data selection process was employed based on relevance and research quality, involving a detailed screening of literature to align with the focus of the study. This led to the exclusion of irrelevant materials and the selection of 210 key scientific documents, published between 1973 and 2023. From the selected documents, key objectives, methods, and conclusions were extracted, synthesised, and analysed to outline patterns in the gathered information. This data was organised around the themes of the study, forming a coherent narrative. The review categorises the impacts of EWEs on electricity production systems by event type, including extreme winds, lightning, storms, hurricanes, heatwaves, droughts, weak winds, cold waves, high temperatures resulting from climate change, floods, and general extreme events. In addition, the research covers a wide range of harmful impacts on energy production systems, including thermoelectric, nuclear, hydroelectric, photovoltaic, and wind energy production technologies. This work also examines energy transmission and distribution systems. Moreover, strategies and measures to minimise and mitigate the impact of EWEs, protect, and adapt the systems to maintain normal operation during these events, and enhance the network resilience of the systems are critically revised and summarized. Physical changes to systems and the integration of new technological solutions such as energy storage systems (ESS), distributed energy systems (DES), and developments in smart grids and microgrids. are also analysed.

Thus, this review was methodically structured to present information, results, and conclusions logically. To conclude, the narrative was revised for clarity and precision, supported by evidence from the literature, and supplemented with figures to synthesise the most significant findings.

4 Set of publications

A total of four published papers forms the PhD document. The order of the articles does not correspond to the order of the publication dates. Table 6 presents the basic information of each paper (title, authors, year of publication, and journal where the papers have been published). Table 7 indicates a brief description of each journal (the quartile, the scientific impact factor, and the ISSN of the publication). The supplementary material of each paper is presented in Appendix A: Supplementary Material.

The first article is “Synoptic and dynamical characteristics of high-impact storms affecting the Iberian Peninsula during the 2018-2021 extended winters” by **Ana C. R. Gonçalves**, Raquel Nieto, Margarida L. R. Liberato; published in *Atmosphere* in 2023 (Gonçalves *et al*., 2023b). This study performed an analysis of the synoptic and dynamic conditions of the formation of high-impact storms that mostly affected the IP during the four extended winters of 2018-2021. The novelty of the paper is the study and characterization of the set of storms named by the SW Group that had serious impacts on IP, caused by strong winds and associated intense precipitation, to warn the population and promote the prevention of these natural disasters.

The second article of this thesis is “Wind Energy Assessment during High-Impact Winter Storms in Southwestern Europe” by **Ana Gonçalves**, Margarida L. R. Liberato, Raquel Nieto; published in *Atmosphere* in 2021 (Gonçalves *et al*., 2021). This article aims to evaluate the wind resources and the WEP in the December months of 2017, 2018, and 2019 in southwestern Europe, a period marked by several significant storms in the region. It is shown that the highest values of wind energy production were obtained on stormy days. Furthermore, the study compares Prandtl's logarithmic law (LogL) and Power-law (PL) equations for extrapolating the vertical wind profile in onshore environments, to assess the changes in the power production when applying the different equations. The results show the highest WEP values for offshore regions when using the LogL equation, and the highest WEP values for onshore regions when using the PL equation.

The third article of this thesis is "Disruption Risk Analysis of the Overhead Power Lines in Portugal", by **Ana Gonçalves**, Margarida Correia Marques, Sílvia Loureiro, Raquel Nieto, and Margarida L. R. Liberato; published in *Energy* in 2023 (Gonçalves *et al*., 2023a). The approach for risk analysis of the EWEs on the OPL in Portugal is presented in this article. As these events become more frequent and intense, they have a greater impact on energy systems, customers, and the infrastructure that supports power transmission. According to the cause-effect analysis and the probability of occurrence and potential consequences in a risk matrix, the level of risk linked to each of the identified events is categorised. This paper corresponds to the first published risk matrix for EC impacts in Portugal, and it highlights the need to adapt power infrastructures to EWEs.

Table 6. List of articles within this thesis.

Title	Authors	Year	Journal
"Synoptic and dynamical characteristics of high-impact storms affecting the Iberian Peninsula during the 2018-2021 extended winters"	Ana C. R. Gonçalves, Raquel Nieto, Margarida L. R. Liberato	2023	Atmosphere
"Wind Energy Assessment during High-Impact Winter Storms in Southwestern Europe"	Ana Gonçalves, Margarida L. R. Liberato, Raquel Nieto	2021	Atmosphere
"Disruption Risk Analysis of the Overhead Power Lines in Portugal"	Ana Gonçalves, Margarida Correia Marques, Sílvia Loureiro, Raquel Nieto, and Margarida L. R. Liberato	2023	Energy
"Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures"	Ana C. R. Gonçalves, Xurxo Costoya, Raquel Nieto, Margarida L. R. Liberato	2024	Sustainable Energy Research

Finally, the fourth article of this thesis is "Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures", by

Ana C. R. Gonçalves, Xurxo Costoya, Raquel Nieto, and Margarida L. R. Liberato; published in *Sustainable Energy Research* in 2024 (Gonçalves *et al*., 2024). This work presents a systematization of the assessment of the impacts of EWEs on the ES and their associated infrastructures, as well as an analysis of the real impact of these events on the ES, particularly the WES. This assessment considers previous studies carried out and published on the subject. It also includes a review and proposal of strategic recommendations and measures aimed at mitigating the adverse effects on ES and ensuring their adaptability to maintain electricity production and the stability of the electrical network, even during the occurrence of EWEs.

Table 7. A brief description of the journals listed in Table 6 and a summary of their quality indices for the year 2022 (data available on the date of writing this thesis). SJR: SCImago Journal Rank; JCR: Journal Citation Reports; IF: Impact Factor.

Journal	Description	Quality Indices (2022)
Atmosphere	It is an international journal of atmospheric scientific research that is open-access, peer-reviewed, and published by MDPI.	SJR: 0.66 JCR: 0.55 Current IF: 2.9 5-year IF: 3.0 CiteScore (Scopus): 4.1 Q2 in Atmospheric Sciences and Environmental Sciences
Energy	It is an international and multi-disciplinary journal, published by Elsevier, and is dedicated to research in energy engineering, energy systems, renewable energy, energy in buildings, and economic and policy issues, among others.	SJR: 1.99 JCR: 1.55 Current IF: 9 CiteScore (Scopus): 14.9 Q1 in Energy Engineering and Power Technology; Energy (miscellaneous); Management, Monitoring, Policy, and Law; Renewable Energy, Sustainability, and the Environment.
Sustainable Energy Research	It is published by Springer Nature (Springer Open) and includes research that includes all energy sources that support a sustainable approach to energy transformation such as renewable energy, energy-efficient systems, and advanced, sustainable systems that help reduce energy poverty and the use of polluted, inefficient energy sources.	As of the 1st of January 2023, *Renewables: Wind, Water, and Solar* is published under the new title *Sustainable Energy Research*. Journal ISSN: 2731-9237 (online) Current IF: 2.4

The articles are presented in a logical sequence rather than in the order in which they were published. The supplementary material associated with each article is also included in Appendix A.

atmosphere

Article

Synoptic and Dynamical Characteristics of High-Impact Storms Affecting the Iberian Peninsula during the 2018–2021 Extended Winters

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Abstract: In the extended winters from December 2017 to April 2021, numerous high-impact storms affected the Iberian Peninsula (IP) with heavy precipitation and/or strong winds. Here, we provide a comprehensive assessment of these events, synoptic conditions, large-scale dynamics associated with storms, and a climatological analysis to improve public awareness and natural disaster prevention. Variability analysis presents that their maximum intensity ranges from 955 hPa to 985 hPa, a two-to-four-day lifetime, and the highest frequency (eight events) occurred in January. At the instant of maximum intensity, anomalies presented low MSLP values (−21.6 hPa), high values of water vapor (327.6 kg $m^{-1}s^{-1}$) and wind speed at 250 hPa (29.6 m s^{-1}), high values of θe at 850 hPa (19.1 °C), SST (−1 °C), and Q_E (−150 W m^{-2}), near Iberia. The values obtained during the storm impact days exceeded the 98th percentile values in a high percentage of days for daily accumulated precipitation (34%), instantaneous wind gusts (46%), wind speed at 10 m (47%), and concurrent events of wind/instantaneous wind gusts and precipitation (26% and 29%, respectively). These results allow us to characterize their meteorological impacts on the IP, namely those caused by heavy precipitation and wind.

Keywords: extreme events; extratropical cyclones; explosive development cyclones; winter storms; Iberian Peninsula

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1. Introduction

Extratropical cyclones (ECs) are a major cause of damaging winds and heavy precipitation in mid-latitudes. Moreover, the highest-impact weather within them is associated with mesoscale structures such as fronts [1,2]. ECs are a fundamental part of atmospheric circulation in the mid-latitudes due to their ability to transport large amounts of heat and moisture [3–5].

More than two-thirds of the climatological precipitation in much of Europe and North America is caused by ECs, and in the main storm track regions, this percentage can reach 90% [6,7], affecting the daily weather conditions in these regions [5,8]. In addition, most large-scale extreme precipitation events in the extratropics are linked to the passage of ECs [8–10], and these events, which originate in the North Atlantic and reach Europe, are the main cause of flood events in these regions [11].

Some previously studied high-impact events affecting the Iberian Peninsula (IP) crossed the North Atlantic in the direction of Europe and underwent an explosive development at unusual lower latitudes, reaching the IP with an uncommon intensity [12–17]. ECs with explosive development that affect Europe form when baroclinic disturbances over the North Atlantic undergo rapid intensification, which leads to a fall in surface pressure and steep pressure gradients, producing extremely high surface wind speeds over a large footprint region [18–20]. Intense cyclones, with very low pressure at the core center, are frequently accompanied by strong winds and heavy precipitation [21,22]. Events that affect the IP often lead to high amounts of precipitation and flooding associated with atmospheric rivers (ARs) [23–26]. Furthermore, such events have also been observed in France and Western Europe [27].

Studies by Ulbrich et al. [28] and Catto et al. [1] suggest that even if the total number of ECs remains stable, the number of extreme cyclones affecting Western Europe and the eastern North Atlantic in the future may slightly increase in association with an intensified polar jet extended towards Europe. Besides that, the precipitation intensity of the most severe ECs is expected to increase in a warmer climate in the extratropics [8–10].

In recent decades, the number and intensity of ECs have increased significantly [29]. These events cause substantial economic damage, including property damage, flash floods, landslides, travel disruptions, and fatalities due to strong winds and extreme precipitation [5,16,18,30]. The frequent occurrence of ECs in quick succession over the same location can also lead to accumulated impacts such as flooding and wind damage [2]. These events often involve simultaneous strong wind and precipitation events along with frontal structures [9,31–33], affecting several worldwide regions, such as the IP [34–36]. ECs are classified as wind and precipitation storms with widespread impacts and are referred to as compound events (CEs) [37–39]. CEs result from the combination of multiple causes and hazards, contributing to societal and environmental risks [40], and their combined occurrence can have significant impacts, even without the individual factors reaching extreme values [41,42]. Many studies have analyzed CEs involving heavy precipitation and extreme wind episodes, e.g., Refs. [13,15,16], in various regions, including the Mediterranean region [31]; Europe, e.g., Refs. [43–46]; western North America and northern Europe, e.g., Ref. [47]; China, e.g., Ref. [48]; and at a global scale, e.g., Refs. [39,49–52]. The importance and impact of the ECs in Europe are such that since 1954, the Institute of Meteorology of the Freie Universität Berlin has named all pressure systems in Central Europe [53]. Recent impactful storms demonstrated the need to communicate severe weather clearly and naming storms is proven to help to raise public awareness. Therefore, the need to increase public awareness of extreme ECs and their impacts has meant that since 2017, the names of high-impact storms that may affect Portugal, Spain, and France, which are part of the so-called meteorological Southwest European Group (SW Group), have been assigned by their national meteorological services [54–56]. The meteorological services of Belgium [57] and Luxembourg [58] joined the initiative in 2019 and 2021, respectively. The named storms can affect all five SW Group countries, simultaneously or just only one of them. These meteorological services are also in coordination with the Western European Group formed by the United Kingdom, Ireland, and the Netherlands [59–61].

Recent works mentioned have proven that the four winters of 2018–2021 have been prone to high-impact storms with different behaviors and development, leading to extensive socioeconomic impacts caused by heavy rainfall, snow, and strong winds in the IP region [17,62–64] and other European countries [65,66]. In the IP, the results of Hénin et al. [36] show that 85% of recorded precipitation and wind-extreme events are associated with ECs, and western IP coasts are the areas most exposed to ECs [30]. In addition, the three consecutive ECs named Daniel, Elsa, and Fabien that occurred in the extended winter of 2019–2020 affected the IP, with extreme rainfall that led to flash floods, extensive landslides, and strong winds, which caused numerous socioeconomic impacts, especially in the north and center of Portugal and Spain [17]. Moreover, the study by Ribeiro et al. [67] highlights the heavy damage to the Portuguese forest—in terms of woody material—caused by the winter 2017–2018 events resulting from the strong winds associated with the high-impact storms. EC Filomena was studied by Zschenderlein and Wernli [63], which was responsible for a heavy snowfall event, developed from a precursor low-pressure system over the central North Atlantic, that affected Spain in early January 2021.

In this sense, an important motivation for this study is the high number of high-impact ECs that affected Iberia and caused numerous socioeconomic impacts in the four extended winters (2018–2021), and the fact that there are no studies that systematically analyzed all the events that affected the IP with heavy precipitation and/or strong winds.

The occurrence of a high number of named events (frequency) with societal impact in the IP makes these winters anomalous in terms of climatology. According to the cyclone climatology presented by Sousa et al. [68] (see Figure 7 of Sousa et al. [68]), the IP is affected on average by up to two cyclones per year. Ulbrich et al. [69] (see Figure 1 of Ulbrich et al. [69]) show that according to historical data, Iberia is affected on average by less than five cyclones per winter, and when referring to strong cyclones, it is affected on average by less than one cyclone per winter. Results from Neu et al. [70] (see Figure 1 of Neu et al. [70]), based on fifteen cyclone detection and tracking methods, show that the IP is affected by less than fifteen cyclones per winter lasting twenty-four hours or more. Pinto et al. [71] (see Figures 3 and 4 of Pinto et al. [71]) analyzed the characteristics of cyclones over the North Atlantic and Europe and found that Iberia may be affected by between five to ten cyclone days/winter and by less than one extreme cyclone day/winter. Furthermore, Karremann et al. [72] showed that there is a decal variability of cyclones with extreme winds' impact on the IP and characterized these events. These and additional studies carried out within the scope of the Stormex and WEx-Atlantic projects demonstrated that there is a need to systematize the extreme events that have occurred in recent winters. So far, only case studies have been published.

Thus, the present study aims to understand, from a synoptic and dynamic point of view, the different conditions of development of the high-impact storms that mainly hit the IP in the four extended winters, 2017–2018 to 2020–2021.

Thus, the goals of this study are:

(i). To assess the named events that affected the IP with heavy precipitation and/or strong winds and the impacts caused by the studied events;
(ii). To characterize the variability of the events under study considering the maximum intensity (minimum central pressure), the lifetime of each event, and the number of events per month;
(iii). To characterize the synoptic and dynamical conditions driving the events through critical meteorological variables;
(iv). To evaluate the intensity of the selected events considering the precipitation and wind speed values reached for these;
(v). Finally, to analyze the meteorological variable anomalies for the high-impact storms studied relative to the climatology of the 1991–2020 reference period.

The paper is structured in the following sections: Section 2 presents the data and method used in this study. Section 3 assesses the characteristics and variability of high-impact storms. Section 4 discusses the results of the case study analysis; the intensity of the selected events concerning the precipitation, wind speed, and instantaneous wind gust; the identification of extreme concurrent events of these variables; and the climatology and the respective anomaly analysis of the variables under study. Finally, Section 5 shows the discussion of the results, and the last section presents the conclusions and significance of this work.

2. Materials and Methods

2.1. Identification and Characterization of the High-Impact Events Affecting the IP

ECs that caused high impacts in the IP during the four extended winters (October 2017 to April 2021) are selected from the forty-nine high-impact storms designated by the so-called meteorological Southwest European Group (SW Group) dataset, and each event is analyzed individually.

First, the official reports of the meteorological institutes of the two countries IPMA [54] and AEMET [55] collected the information and meteorological impacts—wind and/or precipitation and/or snow—of each event. These climatological bulletins can be consulted in the respective links [73,74].

Then, weather charts (UK Met Office, available from www.wetter3.de/ (accessed on 7 June 2021) were used for the surface analysis of synoptic development, collecting the position (latitude and longitude) every six hours, and tracing their trajectories. Likewise, the pressure values in each position (six hours) were collected, and the instant of maximum intensity of each event was identified, that is, the instant when the storm reached the minimum core pressure. That said, having identified the high-impact storms that affected the IP, the events and their lifecycle characteristics were characterized.

Moreover, to identify the events with explosive development (explosive cyclogenesis or meteorological "bombs"), the criterion and definition used by Sanders and Gyakum [75] is followed, that is, when the central pressure, geostrophically adjusted to 60° N, decays at least 24 hPa in 24 h, i.e.,

$$\frac{dp}{dt\text{adj}} = \frac{dp}{dt}\frac{\sin\varphi\text{Ref}}{\sin\varphi} \leq -24\ \text{hPa}/24\ \text{h} \tag{1}$$

where φ is the storm latitude, and φ_{Ref} is 60° N. Thus, when the surface pressure falls in the central MSLP of at least (24 sin φ/sin 60°) hPa in 24 h, the events are characterized as events with explosive cyclogenesis [75,76].

In addition, the events were analyzed according to Bergeron's rate of deepening (DR) (DR in Bergeron) by Sanders and Gyakum [75] and classified according to Sanders [77]. Thus, an EC is characterized as a cyclone with a central sea level pressure (SLP) that decreases at an average rate of at least 1 Bergeron:

$$1\ \text{Bergeron} = (24\ \text{hPa}/24\ \text{h}) \times \sin 60°/\sin\varphi, \tag{2}$$

where φ is the latitude of the cyclone center and 60° is the adjusted latitude in geostrophically equivalent rate. Furthermore, Sanders [77] categorized ECs into three intensity levels: weak (1.0–1.2 Bergerons), moderate (1.3–1.8 Bergerons), and strong (>1.8 Bergerons).

Zhang et al. [78] revised the definition of EC given by Sanders and Gyakum [75] to be a cyclone where central SLP decrease normalized at 45° N is greater than 12 hPa within 12 h. The 12 h SLP change is used to find an instance of the most rapid deepening in a cyclone's life.

In this study, the modified EC definition introduced by Zhang et al. [78] was used. The deepening rate (DR in Bergeron) of a cyclone's SLP (hPa h^{-1}) can be computed using the following equation:

$$\left(\frac{P_{t-6} - P_{t+6}}{12}\right) \times \left(\frac{\sin 45°}{\sin\frac{\varphi_{t-6}+\varphi_{t+6}}{2}}\right), \tag{3}$$

where t represents the analyzed time in hours, P is the central SLP, and φ is the latitude of the cyclone center defined as the position of minimum SLP. The subscripts "$t - 6$" and "$t + 6$" denote the time 6 h before and after the time t, respectively. EC is defined as a cyclone with a deepening rate greater than or equal to 1 Bergeron and classified as weak (1.00–1.29), moderate (1.30–1.69), strong (1.70–2.29), and super (≥2.30).

Cyclones were also classified according to their trajectories following the Karremann et al. [72] criteria developed for windstorms. They characterized the large-scale atmospheric conditions and cyclone trajectories associated with the 100 largest potential losses in the IP due to strong wind events (windstorms). The events could be classified as (1) group "Iberia", those cyclones with tracks crossing over Iberia on the event day; (2) group "North", cyclone tracks that cross north of Iberia on a zonal track, mainly to the southwest of the British Isles, and influence Iberia mainly due to their extended fronts; (3) group "West", cyclone tracks that cross from southwest to northeast, but west of Iberia; (4) group "Hybrid", the synoptic pattern with the juxtaposition of a cyclone and an anticyclone leading to a pronounced mean sea level pressure (MSLP) gradient over Iberia, and thus strong winds. They also found differences between these groups concerning the mean values of the minimum core pressure. The lowest minimum mean value for the ±1 day of the event was found for the West group (966 hPa), followed by the North group (976 hPa), and the Iberia and Hybrid groups (both with 983 hPa).

In the present study, an MSLP composite of the minimum pressure value reached for each event was calculated, and the trajectory of each event was analyzed, to then classify the events into the groups defined for windstorms by Karremann et al. [72]. Thus, it is possible to analyze the behavior and magnitude of the events under study and compare them with the results of Karremann et al. [72], in terms of their trajectories and magnitude.

2.2. Meteorological Data and Synoptic Analysis

To analyze the synoptic conditions and the large-scale dynamics associated with the development of the high-impact storms that affect the IP, meteorological parameters from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 Reanalysis [79] were used. Fields of wind; temperature (T); relative (RH) and specific humidity (q) at 27 pressure levels (from 100 to 1000 hPa); mean sea level pressure (MSLP); integrated vapor transport (IVT); and sea surface temperature (SST) have been used for the Euro-Atlantic region (90° W–25° E; 15° N–65° N). These fields were extracted for the 1991–2021 extended winter months (October to April, ONDJFMA), for the 6-hourly timesteps (00, 06, 12, and 18 UTC), with a horizontal spatial resolution of 0.25° (31 km) on a latitude/longitude grid.

To assess heat exchange between the ocean and atmosphere associated with high-impact storms, heat fluxes were used. The study of Dacre et al. [80] demonstrates that heat and moisture exchanges between the ocean and atmosphere in the cold sector behind the cold front of the ECs can lead to ocean cooling for the strongest cyclones, and Zhang et al. [81] showed the high contribution of latent and sensible heat fluxes in the initial development of super explosive cyclones. The net surface thermal radiation (Q_{LW}) refers to the thermal radiation emitted by the atmosphere and clouds reaching the Earth's surface, minus the amount radiated back from the surface. Surface solar radiation (Q_{SW}) is the amount of solar radiation that reaches the surface, considering both direct and diffuse radiation, minus the portion reflected by the surface. Surface latent heat flux (Q_E) involves the exchange of latent heat with the surface through turbulent diffusion, while surface sensible heat flux (Q_H) involves the exchange of sensible heat with the surface. The magnitudes of Q_E and Q_H are influenced by factors such as wind speed, moisture, and temperature differences between the surface and the lower atmosphere. Q_N is given by the sum of Q_{SW}, Q_{LW}, Q_H, and Q_E. The ECMWF convention for vertical fluxes considers positive values in the downward direction.

Equivalent potential temperature (θe) signifies the temperature an air parcel would reach if all the contained water vapor condensed, releasing latent heat, and the parcel was compressed adiabatically to a standard reference pressure. So, achieving the equivalent potential value for an air parcel involves lifting it from its initial level until all water vapor condenses and then adiabatically compressing it to 1000 hPa pressure. Since the condensed water is assumed to fall out, the parcel's temperature increase during compression follows the dry adiabatic rate, leading to a temperature higher than the initial level upon descent. This process is termed pseudoadiabatic ascent, and while not fully adiabatic due to heat carried by falling liquid water, it is a significant concept in atmospheric science [15,82,83]. θe at the 850 hPa was computed using ERA5 reanalysis data (T and RH) following Bolton's formula [82]. The equivalent potential temperature at 850 hPa is commonly used to identify the approximate position of the surface fronts [84,85].

To analyze the synoptic conditions and the underlying dynamics of the events under study, a case study was chosen (Storm Ana, see Table 1 and Table S1) and the analysis was made for different meteorological variables (MSLP, θe at 850 hPa, IVT, wind speed at 250 hPa, Q_E, Q_H, Q_N, and SST) in different states of their development—the instant of maximum intensity (minimum pressure), as well as 12 h before and 24 before the instant of maximum intensity.

Table 1. Characteristics of the studied SW European Group named storms in the extended winters of 2018–2021 affecting IP: name (including the name attributed by the Institute of Meteorology of the Freie Universität Berlin, Germany); date; position (in latitude and longitude); minimum pressure; and impacts of the storms in terms of wind (W), precipitation (P), wind and precipitation (W + P). Explosive cyclones are highlighted with an asterisk (*).

Name of the Storm		Date, Position, and the Minimum Pressure of the Storm				Impacts of Storm (W, P, W + P)
SW European Group	Met Fu Berlin	Date (dd/mm/yyyy UTC)	Latitude (°N)	Longitude (°E)	Minimum Pressure (hPa)	
			2017–2018			
Ana *	Yves	11/12/2017 06	48	−2	958	W + P
Carmen	Ingmar	01/01/2018 06	49	−6	989	W
Emma *	Ulrike	26/02/2018 06	42	−35	963	W + P
Félix	Yuliya	11/03/2018 00	45	−11	967	W + P
Gisele	Zsuzsa	14/03/2018 12	51	−18	965	W + P
Hugo *	Carola	23/03/2018 18	49	−10	969	W + P
			2018–2019			
Beatriz	Yaprak	07/11/2018 06	55	−28	958	W + P
Diana	Halka	29/11/2018 12	58	−16	949	P
Gabriel *	Oskar	29/01/2019 18	47	0	985	W + P
Helena	Quirin	31/01/2019 12	52	−15	971	W + P
Laura	Cornelius	06/03/2019 18	56	−8	974	W + P
			2019–2020			
Ceciclia	Luis	22/11/2019 12	46	−9	976	W + P
Daniel	Xander	16/12/2019 18	45	−3	994	W + P
Elsa *	Yadid	19/12/2019 00	55	−15	965	W + P
Fabien *	Ailton	21/12/2019 12	49	−11	962	W + P
Gloria	Ilka	17/01/2020 12	48	−29	988	W + P
Jorge *	Charlotte	29/02/2020 12	56	−11	953	W + P
Karine	Diana I	02/03/2020 00	51	−5	984	W + P
Leon	Diana II	01/03/2020 12	48	0	991	W + P
			2020–2021			
Alex *	Brigitte	02/10/2020 06	49	−2	968	W + P
Barbara	Imika I	21/10/2020 06	49	−2	989	W + P
Dora *	Wenke I and II	04/12/2020 06	52	2	968	W
Ernest	Yvonne	07/12/2020 12	47	−7	988	W + P
Filomena	Bartosz	08/01/2021 18	36	−6	996	P
Gaetan *	-	21/01/2021 18	58	3	950	W + P
Hortense	Irek	21/01/2021 18	50	1	983	W + P
Ignacio	Lars	23/01/2021 12	45	−9	999	W + P
Lola	-	22/04/2021 18	43	−24	982	W + P

The climatological analysis was carried out for the extended winter months (ONDJFMA) of the 1991–2020 period and the meteorological fields studied. The anomalies of the storm composites—the average of the composites minus the long-term average—were calculated for the variables mentioned above. The composite was calculated for the average of meteorological variables considered at the instant maximum intensity (minimum central pressure) of each event. The analysis is also presented in Supplementary Material (See Table S1 and Figures S1 and S2).

The total precipitation, 10 m wind components (u and v components), and instantaneous 10 m wind gust (i10fg) fields are also obtained from ERA5 reanalysis on an hourly basis for a smaller region shown in Section 4.2 (10° W–4° E; 35° N–45° N). The hourly dataset covers the extended winter period of ONDJFMA for 1991–2020, and the same parameters are extracted for the days of greatest impact of the studied storms in the IP.

Moreover, the daily accumulated precipitation dataset was calculated from the hourly data adding the precipitation between 00 UTC (timestep 01 UTC of day n) and 00 UTC on the next day (timestep 01 UTC of day $n + 1$). The instantaneous 10 m wind gust used in this study corresponds to the maximum wind gust at the specified time, at a height of ten meters above the surface of the Earth.

2.3. Extreme Precipitation and Wind Associated with the Storms, and Concurrent Events

For a more specific analysis of the IP, high-impact storms are classified here into three types: windstorms (W), storms involving both wind and precipitation (W + P), and precipitation storms (P). These classifications are based on the values exceeding the 98th percentile for each respective variable in at least one ERA5 grid point in the IP domain (10° W–4° E; 35° N–45° N), during the storm days, as outlined in Table 1 and Sections 2.3 and 4.2.

The days with the greatest impact of each storm are counted considering as a reference the day of maximum intensity (minimum central pressure). Comparative analysis was performed for each storm and then for the set of events. Each variable is analyzed individually to assess the percentage of days in which their values exceed the 98th percentile in at least one grid point in the domain considered during the storm days. In addition, to check if there are concurrent extreme events in terms of precipitation and wind, these shall be considered to reach values higher than the 98th percentile for both wind and precipitation variables at the same time.

3. Results

3.1. Characterization of the High-Impact Storms during Extended Winters 2018–2021

Of the forty-nine high-impact storms named and identified by the meteorological institutes of the Southwest European Group (SW Group), twenty-eight of them caused severe impacts on the IP, due to heavy precipitation and/or strong winds. Table 1 records the names of the storms that caused severe impacts on the IP during the four extended winters of 2018–2021, showing the date, position, and the instant of maximum intensity (defined as the instant when the EC reaches the minimum central pressure). In addition, it is worth noting that ten out of the twenty-eight high-impact storms have explosive cyclogenesis (marked with an asterisk in Table 1).

Concerning meteorological impacts (for details, see Sections 2 and 4.2), high-impact storms are characterized by windstorms (W), wind and precipitation (W + P) storms, and precipitation storms (P), according to the values being higher than the 98th percentile of each variable (Table 1), in at least one grid point in the domain considered during the storm days. Most of the events (25 storms out of 28) that hit the IP are found to be accompanied by high precipitation values and strong winds (W + P), that is, extreme compound events. Only two of them are W storms, and two events are classified as P storms.

To identify the events with explosive development, the deepening rates of the core pressure for 24 h were analyzed for each storm and then geostrophically adjusted to the reference latitude of 60° N (see Equation (1)) and classified according to Sanders [77] (Equation (2)), and to Zhang et al. [78] (Equation (3)). The results are presented in Table S1 (see Supplementary Material). According to the classification of Sanders and Gyakum [75] and Sanders [77], all events with explosive development are considered "weak". However, differences were found in the classification according to Zhang et al. [78], which are explained in each extended winter analyzed.

In the extended winter of 2017–2018, out of three events with explosive development, two are considered "strong" (Ana, DR = 1.74; and Hugo, DR = 2.28). In the extended 2018–2019 winter, the only event with explosive development is classified as "moderate" (Gabriel, DR = 1.43). In the extended winter of 2019–2020 in the IP, three storms presented explosive development and two of them are classified "moderate" with a DR of 1.59 (Fabien) and 1.38 (Jorge). During the last extended winter considered, 2020–2021, three storms had explosive development, with one being classified as "strong" (Alex, DR = 2.16) and another as "moderate" (Dora, DR = 1.46).

The definition of EC given by Sanders and Gyakum [75] was revised to be a cyclone whose central SLP decrease normalized at 45° N is greater than 12 hPa within 12 h, and thus, the 12 h SLP change was used to find an instance of the most rapid deepening in a cyclone's life. Thus, the results suggest that the modified definition is suitable to describe more detailed processes of the rapid deepening of ECs because the longer period for pressure dropping in Sanders and Gyakum [75] potentially smooths out the rapid development of ECs [78]. This is confirmed by the number of events classified as "moderate" and "strong", instead of the 10 events classified as "weak" according to Sanders and Gyakum [75] and Sanders [77]. In addition, this analysis was made for the 28 events; however, the 10 events considered with explosive development according to Sanders and Gyakum [75] remain the same according to the classification of Zhang et al. [78].

Figure 1 shows the tracks and evolution of central pressure over the lifetime of the twenty-eight high-impact storms.

In the left panel (tracks), it can be observed that the storms started their development over the North Atlantic Ocean, moving towards Europe, where they mostly affected the north of the IP and the British Islands. The instants of maximum intensity of each storm are marked with an "X", which allows us to verify the intensity of storms over the IP, British Islands, and northern France. The right panel shows the evolution of central pressure over the lifetime of the storms, where it is possible to easily observe events with explosive development (Table 1 and Table S1—Supplementary Material) through the more accentuated lines, for example, the storm Ana, Emma, Gabriel, Jorge and Gaetan, where the slope is very visible.

In addition, these events were classified according to their trajectories following the Karremann et al. [72] criteria for windstorms (see Section 2.1) as presented in Figure 2. In this way, of the twenty-eight storms, nine were classified as Iberia, thirteen as North, three storms as West, and another three as Hybrid.

Figure 2A presents the position of each storm in the instant of maximum intensity for the different groups, where it is possible to observe that most of the events reach this instant in the region of the IP (over the IP and south of the British Islands). Therefore, the events of the Iberia (Figure 2B) and North (Figure 2C) groups were the most impactful in the IP. Hybrid events (Figure 2E) present a different variety of tracks, and they are not clear as the other groups, because this group is primarily characterized by a strong large-scale pressure gradient over Iberia due to the juxtaposition of a low and a high-pressure center [72]. Some of these events reached the minimum pressure still far from the Iberian coast, over the ocean, as is the case of storm Emma (West group), Beatriz, Gloria, and Lola (Hybrid group), as shown in Figure 2D,E. Moreover, the mean values of minimum core pressure for the groups are as follows: Iberia = 986.56 hPa; North = 967.31 hPa; West = 967.33 hPa; Hybrid = 976 hPa. For the North group, the results show that the considered events are more intense (967.31 hPa) than those (976 ± 13.1 hPa) analyzed by Karreman et al. [72], in which of the thirteen considered in this group, seven presented explosive development. In the same way, the mean minimum pressure value for the Hybrid group (976 hPa) of under-study events is lower than those considered in the mentioned work (983 ± 15.8 hPa). On the other hand, the values obtained for the Iberia (986.56 hPa) and West (967.33 hPa) groups were higher than those obtained by Karreman et al. [72] (Iberia = 983 ± 9.31 hPa and West = 966 ± 13.3 hPa). Although there were few events, it is possible to verify that these presented very low minimum pressure values.

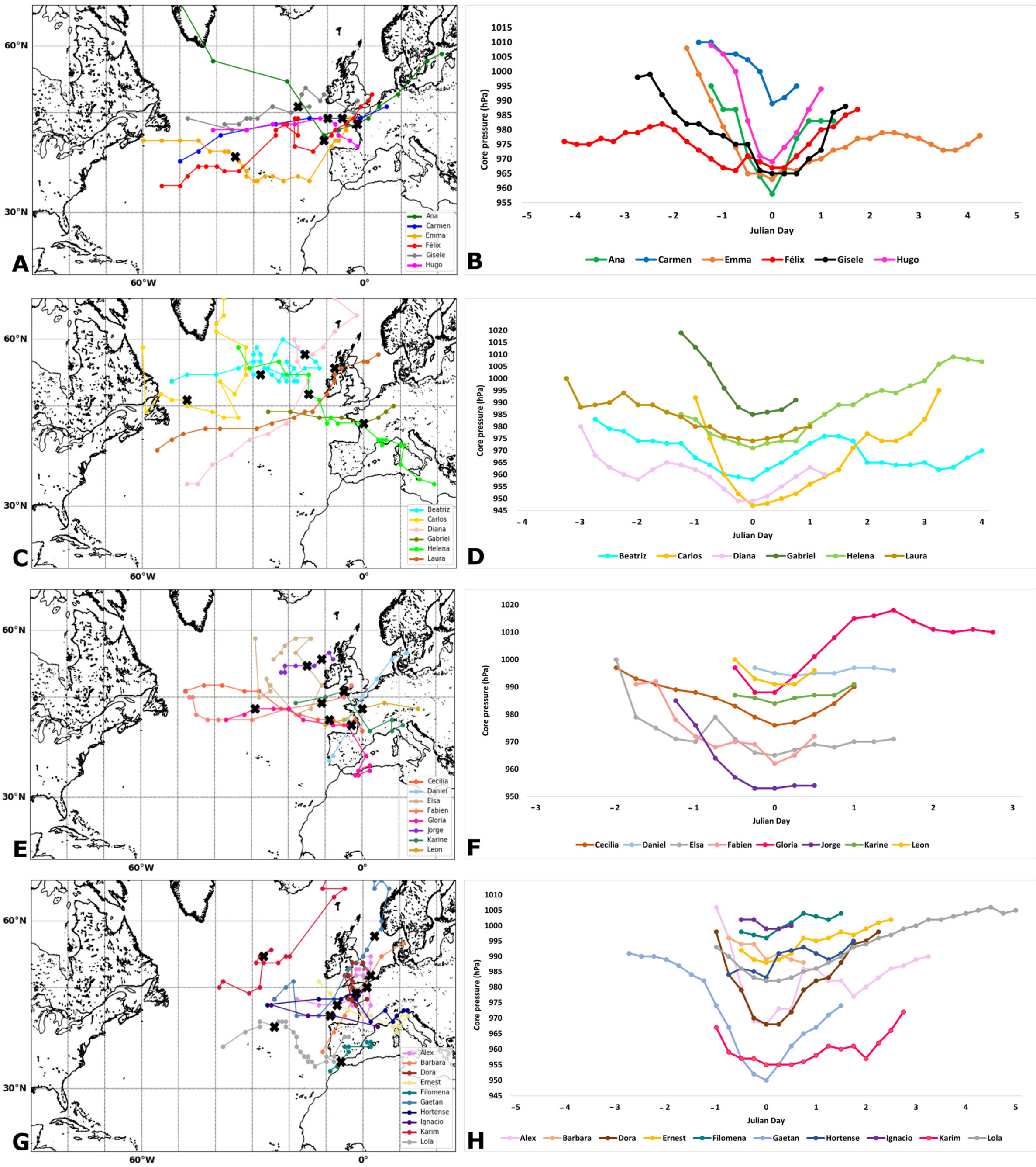

Figure 1. Tracks of high-impact storms with dots indicating storms' location at six-hour intervals. Maximum intensity instants of each storm are marked with an 'X', for winters: (**A**) 2017–2018; (**C**) 2018–2019; (**E**) 2019–2020; (**G**) 2020–2021. Central MSLP evolution over the lifetime of each storm (core pressure in hPa). Dates are relative to the minimum core pressure time (zero Julian day) for winters: (**B**) 2017–2018; (**D**) 2018–2019; (**F**) 2019–2020; (**H**) 2020–2021.

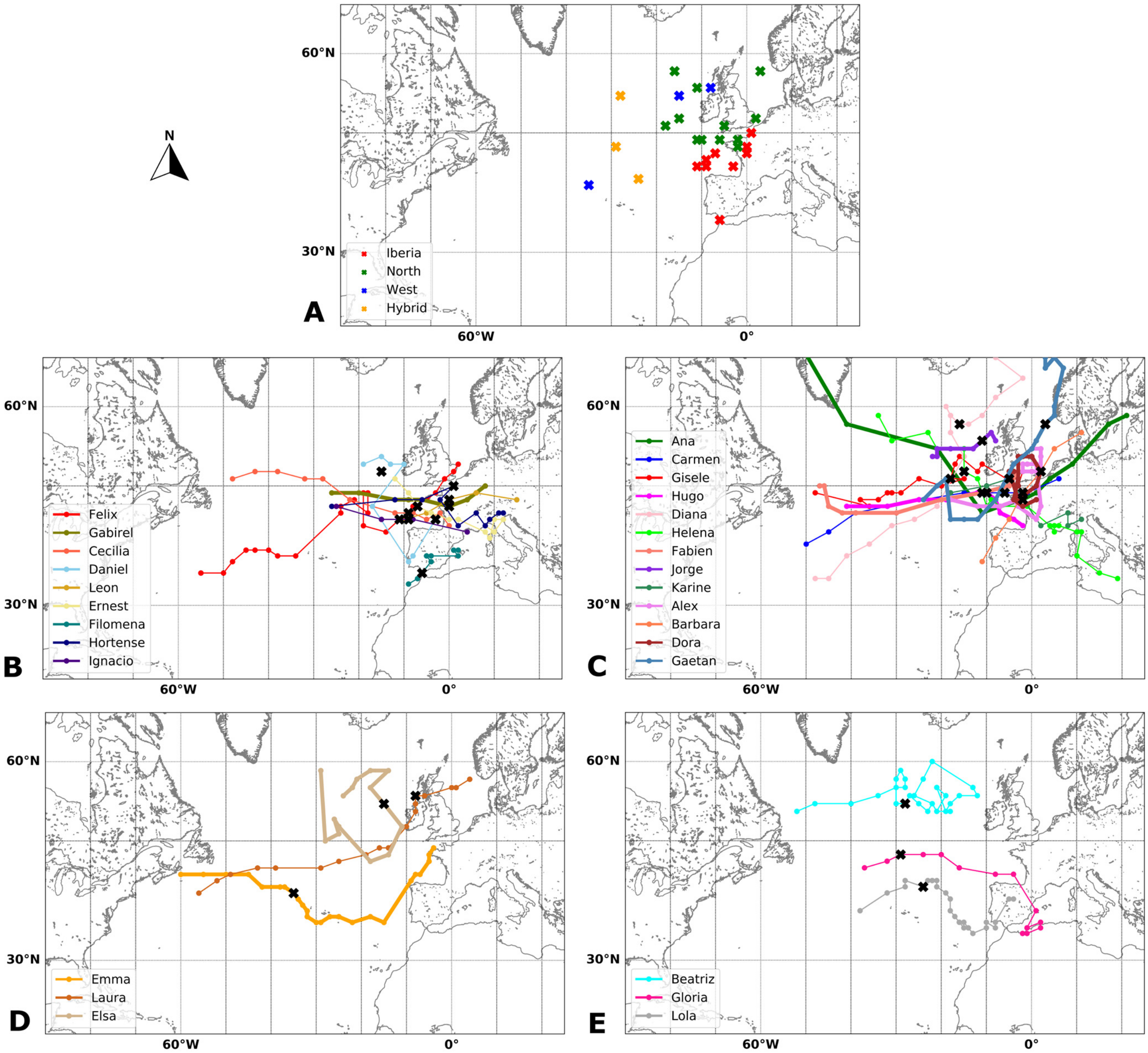

Figure 2. (**A**) Position of each storm in the instant of maximum intensity (marked with an "X"), for the different groups; Tracks of each storm and the position in the instant of maximum intensity marked with an "X" for the groups: (**B**) Iberia (9 events); (**C**) North (13 events); (**D**) West (3 events); (**E**) Hybrid (3 events). The thick lines present the event with explosive development.

Hence, further study is essential due to the significant number, intensity, and severe impacts of all twenty-eight storms observed during the four consecutive extended winters.

3.2. Lifecycle Characteristics of the High-Impact Storms

Figure 3 presents the statistics of the lifecycle characteristics of high-impact storms: the distributions by intensity (minimum central pressure), lifetime, monthly distribution, and deepening rate classification by Zhang et al. [78] (see Section 2.1).

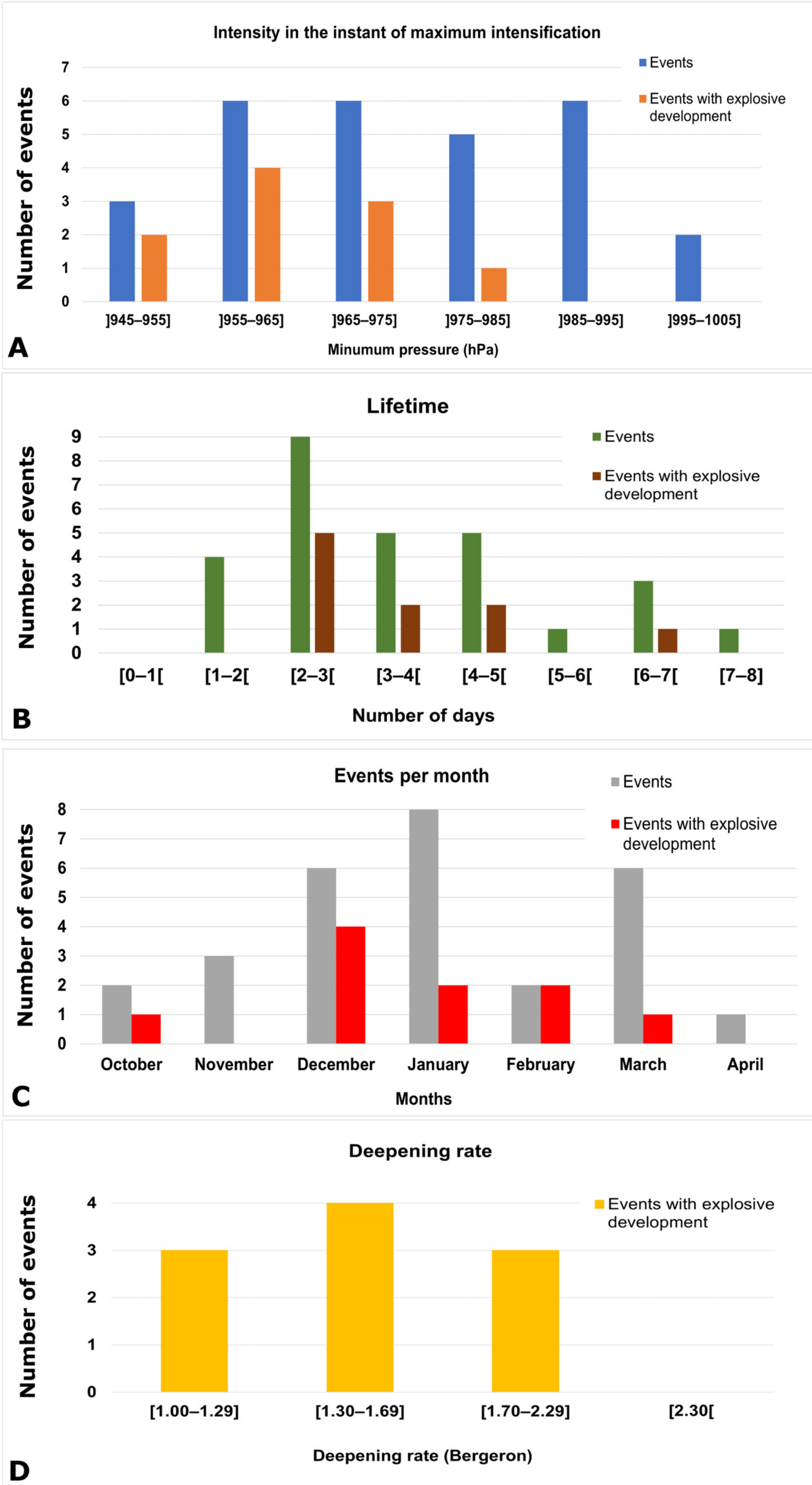

Figure 3. (**A**) Distribution of high-impact storm intensity (the instant of maximum intensity, hPa) for all events (in blue) and the events with explosive development (in orange); (**B**) distribution of lifetime (in days) for all events (in green) and the events with explosive development (in maroon); (**C**) distribution per month for all events (in gray) and the events with explosive development (in red); (**D**) deepening rate (in Bergeron) of the events with explosive development (in gold).

In general, all identified events (28 high-impact storms) present a wide range of values of minimum pressure reached in the instant of maximum intensity, between 955 hPa and 985 hPa (Figure 3A); in the lowest value ranges (the most intense storms) are those events with explosive development (10 events). Concerning the duration of high-impact storms, 70% of the events had a lifetime of between two to four days (Figure 3B); the same pattern occurred for the events with explosive development. However, four events with a minimum lifetime of one day and four events with a maximum duration of six to eight days were also identified, and one of them underwent explosive development.

Regarding the temporal variability of the events (Figure 3C), the monthly distribution of occurrence shows that January is the month in which the most storms occurred (8 events), followed by December and March (each month with 6 events). For the events with explosive development, the maximum occurred in December (4 events), followed by January and February (2 events, each month).

Figure 3D presents the deepening rate (in Bergeron) classification of the events with explosive development, and three of them are considered weak events (1.00–1.29 Bergeron), four are considered moderate events (1.30–1.69 Bergeron), and the other three are classified as strong events (1.70–2.29 Bergeron). This classification further reinforces the fact that these events were impactful.

4. Synoptic Analysis

4.1. Case Study Analysis

To investigate the synoptic conditions, a case study was chosen (storm Ana, see Table 1 and Table S1) and the analysis was made for different meteorological variables (MSLP, θe at 850 hPa, IVT, wind speed at 250 hPa, Q_E, Q_H, Q_N, and SST) in different states of their development—the instant of maximum intensity (minimum pressure), as well as minus 12 h before and minus 24 h before of the instant of maximum intensity. Storm Ana was the first named high-impact storm in December 2017. This storm formed in the center of the North Atlantic on 10 December 2017, and on 12 December 2017, it moved quickly toward northern Europe until it disappeared [86,87]. It showed explosive development and is classified as "strong" by Zhang et al. [78] (See Table 1 and Table S1, Supplementary Material).

This analysis is shown in Figure 4 (first column (Figure 4A,D,G,J,M,P)—24 h; second column—12 h (Figure 4B,E,H,K,N,Q); third column (Figure 4C,F,I,L,O,R), 0 h—the instant of maximum intensity).

Storm Ana appears as a very intense extratropical and complex system centered on the Bay of Biscay and affecting the northeast Atlantic, British Islands, IP, France, and the Mediterranean Sea. This system reached its maximum intensity at 06 UTC on 11 December 2017, with a minimum pressure of 958 hPa and with its pressure center located on the Bay of Biscay (48° N, −2° E), as shown in Figure 4C by the MSLP field, and the storm track in Figure 1.

The θe at 850 hPa is presented in Figure 4A–C, where the marked latitudinal gradient from 5 °C at northern latitudes is observed, and reaches the highest values over tropical regions (Gulf of Mexico) up to 70 °C. Around the IP, the values range between 25 °C and up to 50 °C at the instants of 24 and 12 h before the instant of maximum intensity. So, this event is accompanied by high values of θe at 850 hPa at unusually high latitudes up to 60° N, corresponding to a warm, moist air mass that travels north and acts as a source of energy, intensifying the storm's development. These values confirmed the influence of moisture content and latent heat on the development and intensification of the studied storms.

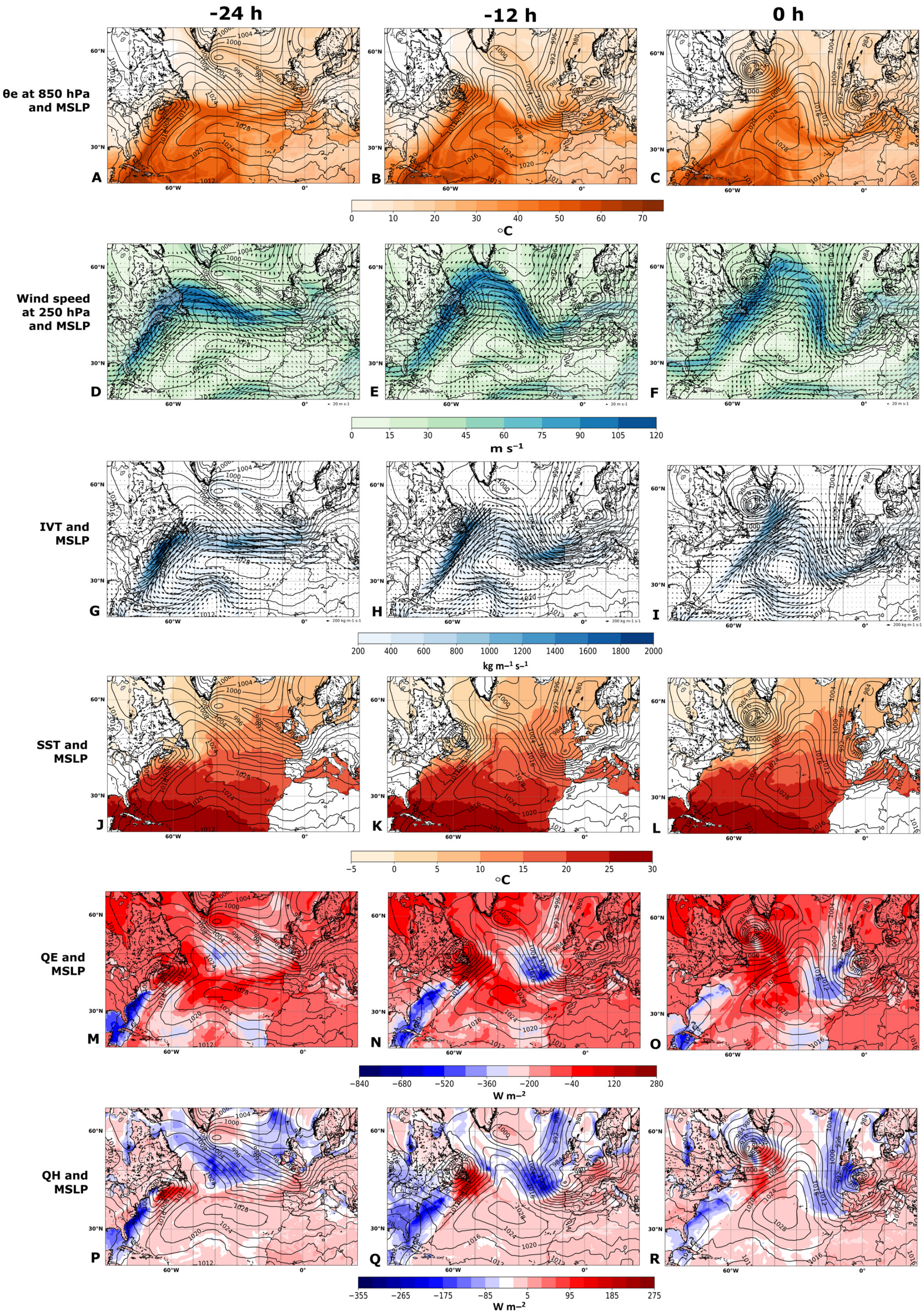

Figure 4. Analysis of storm Ana at 24 h (first column) and 12 h (second column) before the instant of maximum intensity (third column). MSLP (black contours at intervals of 4 hPa) is plotted in all figures. (**A**–**C**) Equivalent potential temperature field at 850 hPa (θe; in °C); (**D**–**F**) wind speed (m s $^{-1}$) intensity and direction (vectors) at 250 hPa; (**G**–**I**) integrated vapor transport (IVT; kg m^{-1} s^{-1}) intensity and direction (vectors); (**J**–**L**) sea surface temperature (SST; °C); (**M**–**O**) surface latent heat flux (Q_E) (W m^{-2}); (**P**–**R**) surface sensible heat flux (Q_H) (W m^{-2}).

Figure 4D–F show the field of the wind speed at 250 hPa for the three analyzed instants, where the jet stream position is observed, meandering over the North Atlantic and heading towards the IP, with strong winds up to 90 ms^{-1} at 12 h before the instant of maximum intensity (Figure 4E). IVT values (Figure 4G–I) allow us to identify the water vapor/moisture associated with this high-impact storm. The highest values are centered on the Atlantic Ocean, the Azores region, and the IP coast, where the values reached more than 1200 kg $m^{-1}s^{-1}$ (Figure 4H), 12 h before the instant of maximum intensity. The high IVT values associated with this event can explain the episodes of heavy precipitation and consequent flooding on the days of the storm passage.

The SST values are presented in Figure 4J–L, where the North Atlantic shows the highest values over tropical regions (Gulf of Mexico and Caribbean Sea) with a maximum of 29.2 °C, and near the IP, the values ranged from 10 °C in northern regions to 20 °C in southern regions.

Heat fluxes (Q_E, $Q_{H,}$ Q_N) were used to evaluate the heat exchange between the ocean and atmosphere associated with the impactful storms. The Q_E analysis (Figure 4M–O) strongly presents negative values of up to—680 W m^{-2} (-12 h; Figure 4N) in the region where the pressure system is located. At the instant of maximum intensity (Figure 4O), the Q_E values around the system center (the IP and the southwest of the British Islands) are strongly negative (more than -520 W m^{-2}), showing the latent heat exchange between the ocean and the atmosphere (energy supplied by the ocean to the storm).

Also noteworthy are the high Q_E values over the Atlantic Ocean, particularly in the Caribbean region and the Gulf of Mexico, with maximums reaching -838 W m^{-2} and 278 W m^{-2} (-24 h; Figure 4M).

At the same time, the Q_H field was also analyzed, and we obtained the same pattern with values that reached more than -175 W m^{-2} in the region of the system pressure (Figure 4Q,R). The maximum values concern the east coast of the United States of America, with -351 W m^{-2} and 265 W m^{-2} (Figure 4P). As the Q_H is related to sensible heat exchanges with the surface, the region of Europe affected by high-impact storms has positive values up to 35 W m^{-2} (Figure 4Q,R).

Moreover, the Q_N analysis of the event (shown in Supplementary Material Figure S1) presents the same pattern of Q_E and Q_H with negative values of up to -810 W m^{-2} in the region of the low-pressure system (Figure S1B,C). These results represent the heat fluxes between the ocean and atmosphere at those times when the ocean provided energy to the atmosphere, thus fueling storm development. So, it is verified that in the region where the center of pressure was located, the values of the fluxes ($Q_{E,}$ $Q_{H,}$ and Q_N) between the ocean and the atmosphere are higher (more negative), showing heat exchanges and the influence of the ocean on storm development. In addition, these fluxes are also influenced by factors such as wind speed, moisture, and temperature differences between the surface and the lower atmosphere, as was observed in the remaining parameters analyzed.

By analyzing the meteorological fields in these three different instants, it is possible to verify that despite the minimum pressure (instant of maximum intensity) having occurred on 11 December at 06 UTC, the storm presented higher values of wind and humidity to reach the region of Iberia in the 12 h before (12 December 2017 at 18 UTC).

The combination of all the above parameters over the IP region contributed to and allow for the justification of the heavy precipitation and strong winds that caused extensive damage during the passage of these extratropical storms over Iberia.

4.2. Concurrent Extreme Events Analysis

To assess and understand whether the values of moisture/water vapor and wind speed were extreme, the value of the 98th percentiles, at each grid point, of daily accumulated precipitation, wind speed at 10 m, and instantaneous wind gust (i10fg) at 10 m were calculated for the reference period 1991–2020 and the months in analysis (Figure 5), and they were compared with the values obtained from the same variables on the days of greatest impact of storms (Figure 6).

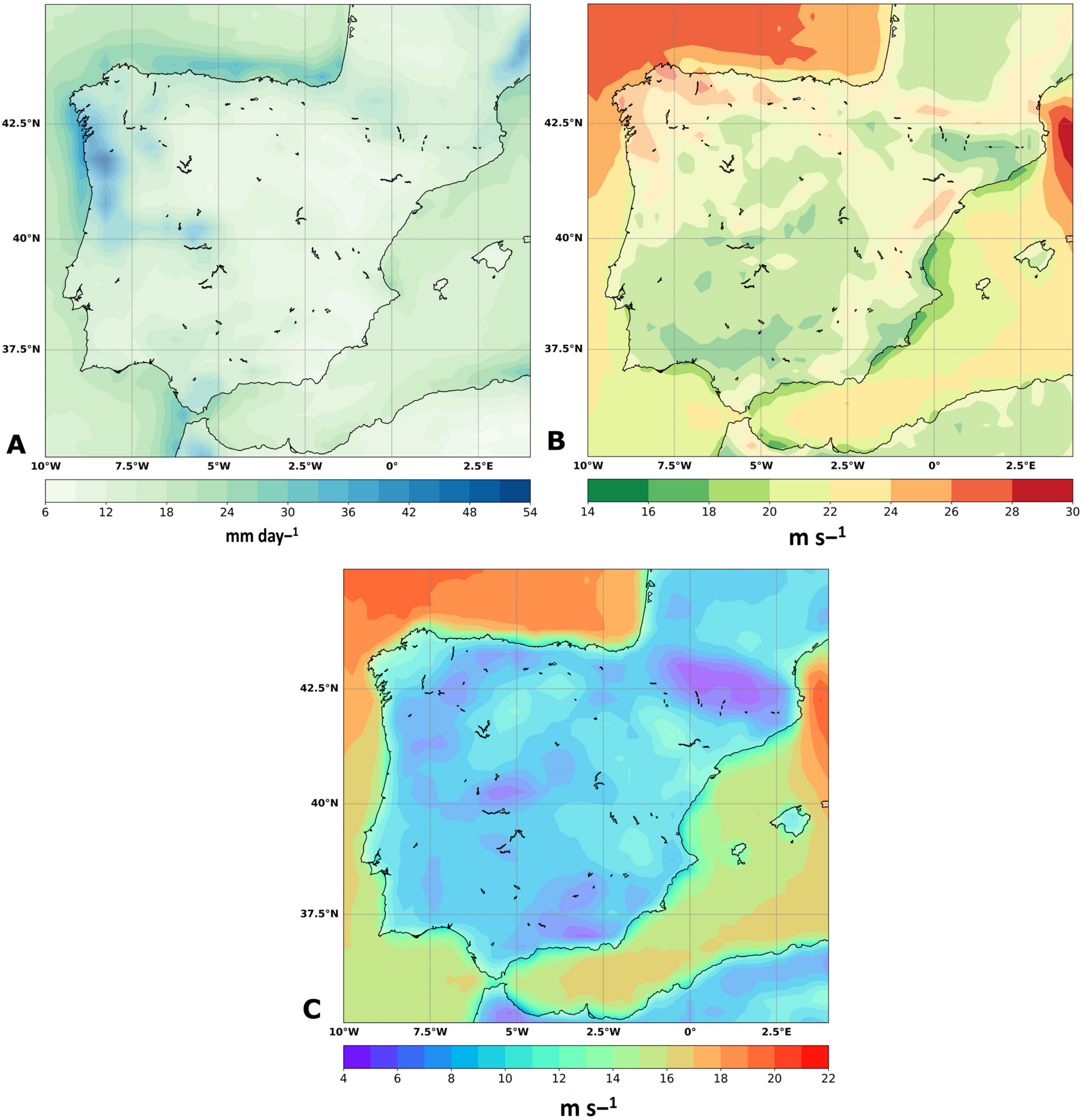

Figure 5. The 98th percentile values of the period of 1991–2020 for (**A**) daily accumulated precipitation (mm day^{-1}), (**B**) instantaneous 10 m wind gust (m s^{-1}), and (**C**) wind speed at 10 m (m s^{-1}).

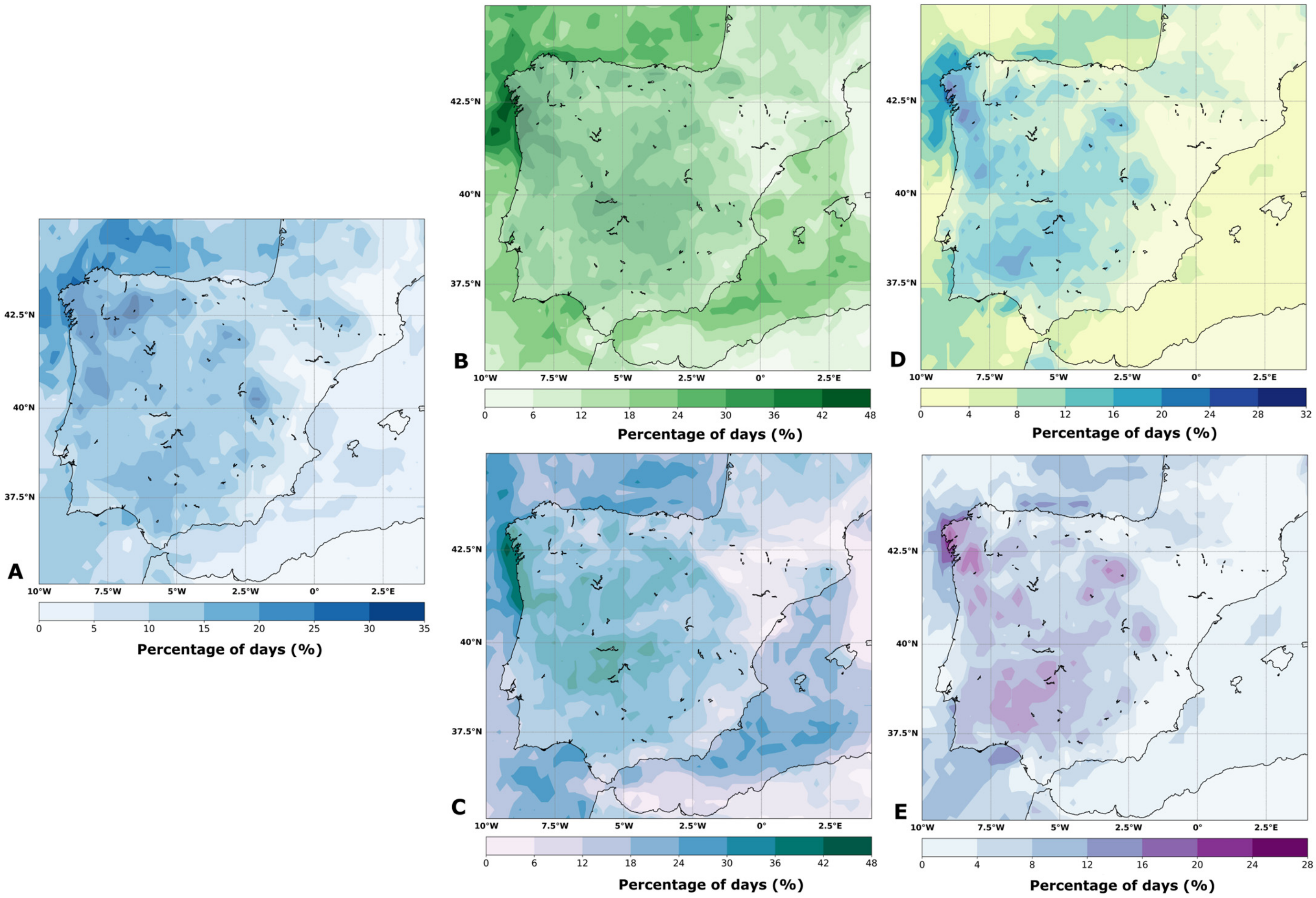

Figure 6. Percentage of days (%) (a total of 94 days) in which the 98th percentile for the period 1991–2020 was surpassed, for (**A**) daily accumulated precipitation; (**B**) instantaneous gusts of wind at 10 m; (**C**) wind speed at 10 m; (**D**) concurrent extremes of daily accumulated precipitation and instantaneous wind gusts at 10 m; (**E**) concurrent extremes of daily accumulated precipitation and wind speed at 10 m.

Figure 5A shows the 98th percentile values of daily accumulated precipitation with a maximum value of 53.80 mm day^{-1} in the northwest region (NW) of the IP. For the i10fg (Figure 5B), the maximum value was reached again in the NW IP (29.40 m s^{-1}), the Pyrenees, and the Mediterranean coast. The wind speed at 10 m (Figure 5C) presents the highest percentile values on the NW and west coast of the IP, as well as the east coast (in the Mediterranean), with a maximum value of 20.05 m s^{-1}.

Out of a total of ninety-four days of storm, the percentage of days in which the variables were greater than the 98th percentile values are shown in Figure 6, with the NW region of the IP presenting the higher percentage, and therefore, it is the area most affected by the storms under study. Figure 6A shows that in the NW of the IP, for 34.1% of the days of storms, the value of daily accumulated precipitation was higher than the 98th percentile, ranging from 30 to 54 mm day^{-1} (Figure 5A). For the i10fg (Figure 6B), it is verified that 45.7% of the storm days' values were higher than the 98th percentile in the NW IP. For that region, the values of the 98th percentile range from 22 to 28 m s^{-1} (Figure 5B). Figure 6C indicates that in 46.8% of the storm days (maximum), the value of wind speed at 10 m was higher than the values of the 98th percentile, on the NW coast of the IP. Figure 5C shows that in this region, the values of the 98th percentile range from 10 m s^{-1} (onshore) to 22 m s^{-1} (offshore).

For the concurrent events (W + P)—daily accumulated precipitation and the i10fg (Figure 6D)—it is verified that in 28.7% of the storm days, the obtained values were higher than the 98th percentile values. Figure 6E shows the analysis of concurrent events—daily accumulated precipitation and wind speed at 10 m—in which for 25.5% of storm days, the values were higher than the 98th percentile values.

4.3. Climatological Analysis

This section presents the climatology for MSLP, IVT, θe at 850 hPa, wind speed at 250 hPa, and SST for the period of reference 1991–2020 and the respective anomalies of the twenty-eight storms composite. The climatology of MSLP (Figure 7A) presents the typical MSLP pattern, with low pressures in the north and high pressures in the south, including the Azores region and the IP. This observation confirms the known fact that low-pressure systems, such as ECs, commonly occur or reach the northern region of the British Islands. However, when we analyze the anomalies of MSLP for the composites of the twenty-eight events (Figure 7B), it is observed that the IP was under the influence of low-pressure systems centered over the British Isles, with values that range between −4 hPa to −12 hPa. The lowest mean values reached −21.6 hPa (Figure 7B) in the British Isles and the Scandinavia region. On the coast of North America, there is a minimum that is related to the low-pressure systems that are verified in that place on the same days that the northeastern coast of the Atlantic is affected by the studied ECs. The MSLP analysis results confirm the intensity of the four winter events, and those ECs that reached the IP and Southwest Europe in the last four winters were very intense, with a minimum value of pressure reaching too low, as also shown in Figures 1 and 2.

Regarding moisture transport, the IVT climatology (Figure 7C) presents a long strip of the coast of North America, from the region of Florida to the east and the north of the Atlantic, with an inclination to the northeast. Moreover, the highest values are near the east coast of North America (ranging from 80 to 200 kg $m^{-1}s^{-1}$). The region of the IP and the British Isles has lower values up to 80 $kgm^{-1}s^{-1}$. When we analyzed the results of the anomalies (Figure 7D), we immediately verified that there was a large transport of water vapor associated with these storms. The storms that occurred in the winters of 2018–2021 show positive anomalies with very high values (up to 320 kg $m^{-1}s^{-1}$), which appear on the Atlantic Ocean, the Azores Islands, all of the coast of the IP, and northwest of France. In the IP, France, and the Mediterranean region, the values reached up to 240 kg $m^{-1}s^{-1}$, but with a major impact in Iberia.

Figure 7E displays the climatology of θe at 850 hPa, which is used to analyze its behavior and impact on storm development. The average θe values range from 20 °C to 40 °C across the IP. The high values, in the order of 50 °C to 60 °C, are observed in the region of the Gulf of Mexico and the Caribbean Sea. In Figure 7F, the anomaly values for the composite of all storms show a strong positive anomaly over the Atlantic Ocean, Europe, and northeast of North America, with values up to 19.1 °C, and there is an exception in the Gulf of Mexico and the Caribbean Sea regions, as well as in the North Pole. Moreover, this analysis shows that all events contained high moisture and latent heat during its development which contributed to its intensification [15,88].

Concerning the jet stream, analyzing the climatology for the 250 hPa wind speed (Figure 7G), it is observed that the highest values occur on the east coast of North America (28 to 44 m s^{-1}). The values in southwest Europe, more specifically in the IP, are of the order of 12 to 20 m s^{-1}. When we calculated the anomalies of the wind speed at 250 hPa of the studied storms (Figure 7H), the results showed a very strong positive anomaly at the west and in the IP, with a maximum of 29.6 m s^{-1}. This strong positive anomaly along the Atlantic Ocean between the east coast of North America and the southwestern region of Europe, which includes the IP, the north of France, the south of the British Isles, and the Mediterranean region—confirms that the storms which reached these regions were very intense with very strong winds, i.e., windstorms. It is also possible to confirm that the jet stream, and then the wind speed, became more intense in lower latitudes, justifying the strong winds that hit the Iberian region in the passage of storms.

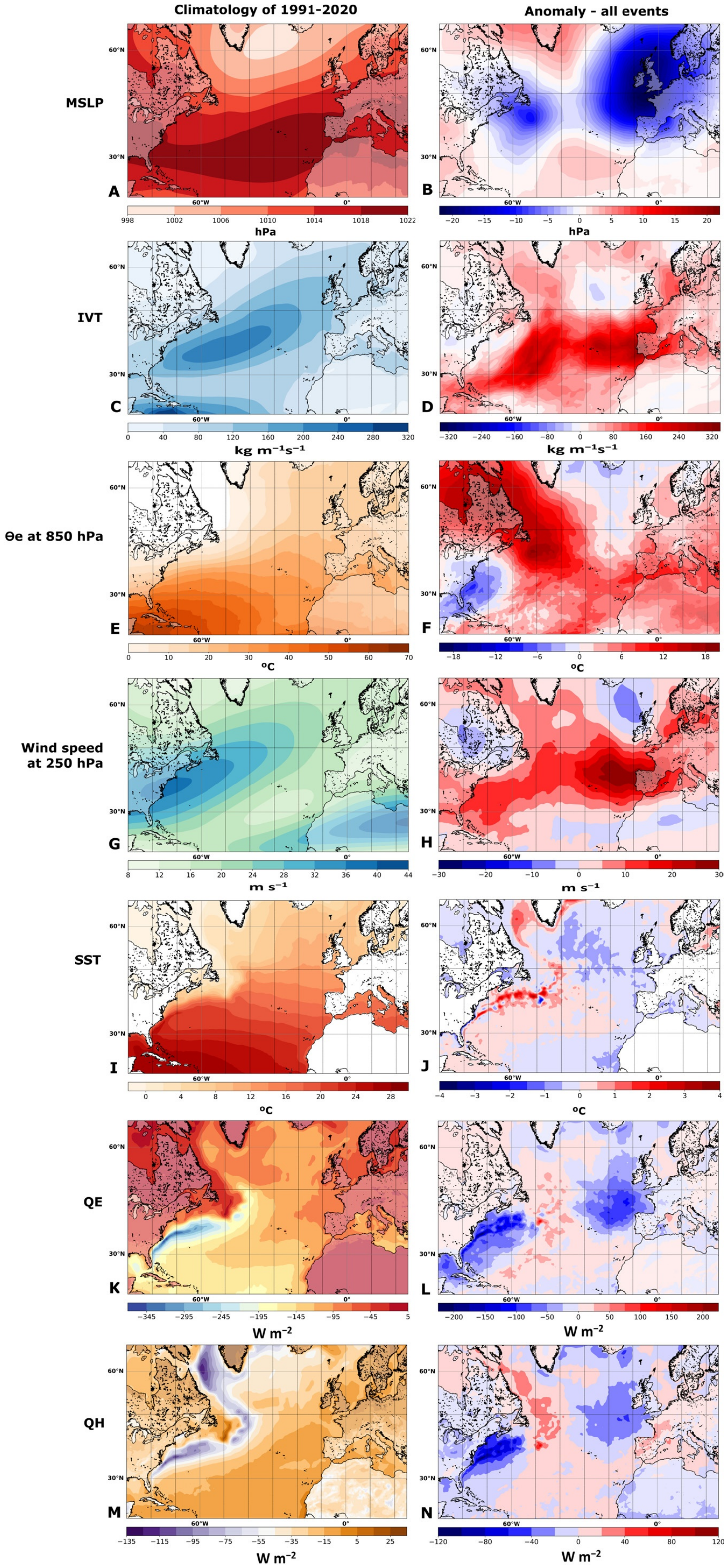

Figure 7. Climatology for extended winter months (ONDJFMA) of 1991–2020: (**A**) mean sea level pressure (MSLP) (hPa); (**C**) integrated vapor transport (IVT) (kg $m^{-1}s^{-1}$); (**E**) equivalent potential temperature (θe) at 850 hPa (°C); (**G**) wind speed at 250 hPa (m s^{-1}); (**I**) sea surface temperature (SST) (°C); (**K**) surface latent heat flux (Q_E) (W m^{-2}); (**M**) surface sensible heat flux (Q_H) (W m^{-2}). anomaly for the composite of 2017–2021 extended winter storms (28 events): (**B**) MSLP (hPa); (**D**) IVT (kg $m^{-1}s^{-1}$); (**F**) θe at 850 (°C); (**H**) wind speed at 250 hPa (m s^{-1}); (**J**) SST (°C); (**L**) Q_E (W m^{-2}); (**N**) Q_H (W m^{-2}).

Figure 7I presents the climatology of SST, and the average values in the eastern North Atlantic Ocean offshore the IP are in the range of 12 °C in the northern regions to 18 °C in the southern regions. The high values (from 24 °C to 28 °C) are observed in the regions of the Gulf of Mexico and the Caribbean Sea. Concerning the anomaly analysis for the SST composite of the storms (Figure 7J), the results highlight the Gulf Stream, with a positive anomaly with values up to 3.5 °C and extending to 40° W. Additionally, the strong positive anomaly of SST is verified in a large part of the North Atlantic Ocean basin, which extends to 20° W (including the Azores and Madeira archipelagos), limited by the parallels between 30° N and approximately 45° N, with values that range from 2 °C to 0.5 °C. Along the North Atlantic Basin, the anomalies of SST are positive (up to 1 °C) between the Gulf Stream region to the Azores and Madeira archipelago. On the other hand, the values of SST anomalies reached −1 °C on the coast of the IP, the British Isles, France, and the African coast.

Figure 7K presents the climatology of Q_E where the average values vary between −360 W m^{-2} and 3.6 W m^{-2} in the same region of the North Atlantic Ocean, that is, in the regions of the Gulf of Mexico and the East Coast of the United States of America. On the other hand, along the coast of the IP, British Islands, and France, the average Q_E values are relatively low, varying between −95 W m^{-2} and −25 W m^{-2}. The anomaly analysis for the Q_E composite of the 28 storms is presented in Figure 7L, and it reveals a strong negative anomaly with values up to −150 W m^{-2} in the northwest of the IP and France and southwest of the British Islands. The highest values are presented in the Gulf of Mexico and the East Coast of the United States of America, with −223.2 W m^{-2}.

The Q_H follows the same pattern as Q_E, but with lower values. Figure 7M presents the climatology of Q_H, where the values range from −120.5 W m^{-2} to 33.9 W m^{-2} along the East Coast of the United States of America. On the other hand, in the IP region, British Islands, and France, the average Q_H values are lower, varying between −35 W m^{-2} and 5 W m^{-2}. Figure 7N shows the anomaly values of the composite of the storms, where a negative anomaly up to −40 W m^{-2} located to the northwest of the IP and France, and southwest of the British Islands, was observed. In addition, a positive anomaly is verified over the IP and France (up to 40 W m^{-2}). The highest and lowest values are found on the east coast of the United States of America and over the Atlantic Ocean, with values of −117.9 W m^{-2} and 69.3 W m^{-2}, respectively. The climatology of the Q_N is present in the Supplementary Material (Figure S2A), where the average values vary between −442 W m^{-2} and 85 W m^{-2} in the same region of the North Atlantic Ocean, that is, in the regions of the Gulf of Mexico and the East Coast of the United States of America. On the other hand, along the coast of the IP, the British Islands, and France, the average Q_N values are relatively low, varying between −75 W m^{-2} and 25 W m^{-2} (Figure S2A). The anomaly analysis for the Q_N composite of the 28 storms is presented in Figure S2B (supplementary material), and it reveals a strong negative anomaly with values up to −350 W m^{-2} in the regions of the Gulf of Mexico and the East Coast of the United States of America. In addition, it is verified that a negative anomaly is located to the northwest of the IP and France, and southwest of the British Islands, with values that range from −40 W m^{-2} to −160 W m^{-2}. The anomaly values are linked to the composite of the storms that affected the IP, and so reveal the heat fluxes (Q_E, Q_H, Q_N) between the ocean and the atmosphere, which favor the development of these high-impact storms with explosive development.

5. Discussion

Concerning the high-impact storms that affected the Iberian Peninsula (IP), we found that out of the twenty-eight events, ten of them presented explosive development.

The analysis of the trajectories of the events (Figure 1) and subsequent classification into groups (Figure 2) allowed us to understand their behavior and their intensity over the IP. It is observed that the North and Hybrid groups exhibited lower minimum pressure values compared to the findings of Karremann et al. [72]. Specifically, the North group recorded a mean minimum pressure of 967.31 hPa, while the Hybrid group recorded

976 hPa. In contrast, Karremann et al. [72] reported mean minimum pressure values of 976 ± 13.1 hPa for the North group and 983 ± 15.8 hPa for the Hybrid group. Of the thirteen events belonging to the North group, seven present an explosive development, which justifies the low average value of minimum pressure, and thus high intensity. In addition, it was possible to observe that the events of the North group had reached the maximum intensity along the coast of northern Europe or over the British Islands, becoming more impactful. It is also possible to justify this fact by analyzing anomaly values (Figure 7), where high values of wind speed at 250 hPa, IVT, θe at 850 hPa, Q_E, Q_H,, and Q_N are verified over the Atlantic Ocean (Azores), south of the British Islands and along the coast of the IP and from France.

The variability analysis (Figure 3) allows us to understand how the events studied were characterized by their intensity (minimum pressure value), duration (lifetime), distribution over the winter months, and deepening rate classification by Zhang et al. [78]. So, the results show that the values of minimum pressure (Figure 3A) reached by the events in the study range from 955 hPa and 985 hPa, where ten events with explosive development were identified. Concerning the duration of each high-impact storm (Figure 3B), the results demonstrate that the events had a duration of two to four days of lifetime, including nine events with explosive development. The distribution by month of the occurrence of each high-impact storm (Figure 3C) demonstrates that the month of January is the month in which the most storms occurred (eight events), two of them with explosive development. According to the classification by Zhang et al. [78], out of the 10 events with explosive development, 3 are considered weak, 4 as moderate, and 3 events as strong. This classification reinforces the intensity of the events studied.

The analysis of the conditions of the dynamics of the atmosphere (Figures 4 and 7) permits us to justify its behavior and the impacts associated with strong wind and intense precipitation. Thus, by analyzing the meteorological fields for the case study of storm Ana, we obtained values of θe at 850 hPa up to 50 °C in the IP region, wind speeds at 250 hPa that reached 90 m s^{-1}, IVT with values more than 1200 kg m^{-1}s^{-1}, and SST with values between 10 °C and 20 °C on the coast of Iberia. In the region of the IP and the southwest of the British Islands, the Q_E values reached −680 W m^{-2}, Q_H presents values of −175 W m^{-2} and Q_N with values up to −810 W m^{-2}.

In addition, when we analyze the anomalies related to the climatology of the 1991–2020 period, it is verified that when considering the instants of maximum intensity of the storms, they presented low MSLP values (up to −21.6 hPa), and high values of water vapor (up to 327.6 kg m^{-1}s^{-1}) and wind speed at 250 hPa (up to 29.6 m s^{-1}) close to Iberia. In addition, the θe at 850 hPa presented values up to more than 19.1 °C over the ocean, Iberia, and throughout Europe. The relative positioning of an extratropical storm and the upper-level jet, which can influence the storm's direction, is widely recognized as another significant factor in its explosive development [15,89]. In this sense, the high values of wind speed at 250 hPa close to Iberia can clarify the intensity of the events, and the strong winds at the surface. On the other hand, the θe of an air parcel increases with increasing temperature and increasing moisture content. Therefore, the gradient of θe at 850 hPa and the high baroclinicity in the region confirms the maximum availability of latent and sensible heat in the lower troposphere at the instant of maximum intensity of the storms, which supports the contribution of moist diabatic processes in the case of intense storms, such as latent heat release by cloud condensation processes, and in the intensification of the windstorm [13–15,71,88,90]. Thus, θe at 850 hPa is often used as an indicator to identify and track these warm and humid air masses [71], in addition, during the occurrence of explosive cyclogenesis, particularly during events like Klaus and Xynthia, extensive areas with θe values exceeding 320 K (46.85 °C) were observed [13,14,88]. So, our results are in line with the literature, in which at times of maximum intensity of the storms, the IP region had high θe at 850 hPa values (up to 50 °C).

The analysis of the net surface heat flux (Q_N) for the case study indicates negative values up to −810 W m^{-2} (Supplementary Material, Figure S1) in the IP region (northwest of the IP and southwest of the British Islands). At the same time, the Q_N anomaly analysis (Figure S2B) presents negative values that range from -40 W m^{-2} to -160 W m^{-2} in the IP region. So, it is verified that in the region where the center of pressure was located, the values of the heat fluxes between the ocean and the atmosphere are higher (more negative). Additionally, this indicates the transfer of heat between the ocean and the atmosphere during periods when the ocean supplied energy to the atmosphere, thereby supporting the formation and intensification of high-impact storms. These results follow the findings of Dacre et al. [80], in which heat and moisture exchanges between the ocean and atmosphere in the cold sector behind the cold front of the ECs can lead to ocean cooling for the strongest cyclones.

On the other hand, the negative anomalies of SST (up to -1 °C) on the Iberia coast (Figure 7J), and the results presented for $Q_{E,}$ Q_H, and Q_N (Figure 4, 7, S1 and S2) suggest that the ocean temperature contributed to the formation and intensification of storms, indicating a contribution of latent heat and energy to the formation and development of these storms [90–92]. Additionally, Zhang et al. [81] show that the surface latent heat flux (QE) has some contributions to the initial development of super explosive cyclones.

Furthermore, the SST and Q_N results also suggest a cooling of the ocean associated with the passage of ECs, which is caused by the heat exchanges between the ocean and atmosphere. Therefore, the strengthening of the SST gradient and associated increased baroclinicity in the central North Atlantic could be a factor that contributes to the storm track intensification [93].

The concurrent extreme events analysis (Figures 5 and 6) revealed that the values on the days of the storms were considered extreme. That is, in the 94 days considered for the study (28 events), more than 34.1% of the days had daily accumulated precipitation values higher than the 98th percentile (Figure 5), 46.8% of the days had wind speed values at 10 m, and 45.7% of the days had instantaneous gusts of wind at 10 m with values above the 98th percentile. Furthermore, when we analyzed the events together, we found that 25.5 to 28.7% of the storm days occurred simultaneously, with daily accumulated precipitation values and wind speed/instantaneous gust at 10 m with values greater than the value of the 98th percentile. Henin et al. [36] studied extreme meteorological events associated with extreme precipitation and wind and analyzed the IP domain and the main Iberian hydrographic basins. In that study, it is concluded that 85% of the studied events with precipitation and wind extremes at the same time are associated with cyclonic characteristics. In addition, the areas most affected by the simultaneous events of precipitation and wind extremes are in the northwestern sector of the IP. In this sense, our results (Figure 6) agree with those obtained by Henin et al. [36], as the areas affected by precipitation and extreme wind events appear in the same regions and with high percentages, even though the number of cases in our study is smaller (28 storms) and associated only with ECs.

Moreover, the study by Owen et al. [45] has identified extreme precipitation and extreme wind events in the ERA5 reanalysis dataset using a definition of extremes of the 99th percentile. The results show that over Europe, high co-occurrence is found over western coasts and low co-occurrence is found over eastern coasts. In addition, the results show that given an extreme co-occurring event, the chance of a cyclone being within 1110 km is more than 70% for much of Europe. Regions with low co-occurrence have extremes caused by different weather systems and regions with large co-occurrence have both extremes caused by the same weather system. Therefore, cyclones linked to extreme events, particularly co-occurring precipitation, and extreme wind, have larger intensity than those not, and for most of Europe, these cyclones also have faster mean speed. Thus, the obtained results agree too with the study of Owen et al. [45] for our study region, where extreme co-occurring events are more associated with cyclones than non-extreme events, and with more intense development and impacts associated.

In this work, data from ERA5 reanalysis [94] are used, and as such, these have associated errors. Thus, it is considered that the ERA5 reanalysis data have errors in the wind gust field, which according to Brasseur [95] range from 5 m s^{-1} to 8 m s^{-1}, in the case of events with explosive cyclogenesis. However, we acknowledge that the ERA5 reanalysis data employed in this research are more current and inclusive of recent information. These data are predominantly utilized in climatological analyses and demonstrate a high level of trust in the description of the wind speed pattern [96–99]. Nevertheless, it remains crucial to consider the possible associated errors. In this sense, we consider that the results obtained for the concurrent extreme events analysis (Section 4.2) are acceptable.

Other studies, such as those conducted by Roberts et al. [18] and Ramos et al. [23], provide valuable resources for understanding these extreme weather events (EWEs) in Europe. The work of Roberts et al. [18] provides storm tracks and wind-gust footprints for 50 severe winter windstorms in Europe between 1979 and 2012, available in the eXtreme WindStorms (XWS) catalog. On the other hand, Ramos et al. [23] developed a database ranking daily precipitation events for the IP from 1950 to 2008, considering factors such as affected area, intensity, and deviation from climatology. These resources are beneficial for academia and the (re)insurance sectors as they enable users to characterize and understand extreme events in Europe, and for evaluating and improving the predictions of weather and climate models [18].

Climate change (CC) studies reveal that extreme precipitation events simultaneously with extremes of wind may increase in the future, that is, moisture transport in the Northeast Atlantic is expected to increase dramatically in future scenarios [26,100], along with an increase in the intensity of cyclone-related fronts affecting Western Europe [1,32]. Hawcroft et al. [101] expect that, by the end of the century, the frequency of extreme ECs—the present-day 99th percentile of precipitation intensity—will significantly increase, and the number of these severely precipitating ECs will more than triple by the end of the century in both Europe and North America. In addition, it is known that CC leads to the occurrence of more frequent and intense EWEs (i.e., changes in weather patterns, temperature, and precipitation), with intense precipitation, strong winds, and snowstorms, or on the other hand severe heatwaves and droughts. These events provoke numerous adverse impacts on ecosystems, people, infrastructures, and related losses, beyond natural climate variability [102,103].

Therefore, studies for future scenarios [1,26,32,100,101] contrast with the older studies [68–71], where few high-impact and extreme storms are affecting the IP region. The present study also shows that in the extended winters of 2018–2021, there were a high number of events that intensely affected the IP. The high-impact storms, and in particular, the storms with explosive development, presented more intense values of humidity and wind speed (Figure 4), which can justify the strong and numerous impacts associated with their passage, first in the IP and then in the rest of Europe [54–56].

Although the climatological analysis reveals changes in the values of the studied variables (Figure 7), it is inconclusive whether these changes are attributable to anthropogenic climate change or simply natural climate variability. Nevertheless, further study of these events over a longer period of historical data will facilitate a more comprehensive investigation of their variability. Additionally, studying CC will enable the assessment of future trends in the frequency and intensity of these events.

6. Conclusions

Extratropical storms are associated with numerous socioeconomic impacts caused by strong winds and heavy precipitation. The region of the Iberian Peninsula (IP) is affected by a few high-impact and extreme storms; however, in the extended winters of 2018–2021 there was a high number of events, and therefore, this work intended to analyze the characteristics of these events.

The main conclusions of this study are:

- Of the events named since 2017 by the meteorological institutes of the countries of the Southwest European Group (SW Group), twenty-eight had impacts on the IP, and of these events, ten had an explosive development.

- The storms lasted for a period of two to four days, with January being the month that had the highest frequency of occurrences (Figure 3).
- For the IP region, the meteorological field analysis for storm Ana (Figures 4 and S1) on the coast of the IP presents values of θe at 850 hPa up to 50 °C, wind speeds at 250 hPa that reach 90 m s^{-1}, IVT with values up to 1200 kg $m^{-1}s^{-1}$, SST with values between 10 °C and 20 °C, Q_E values of −680 W m^{-2}, Q_H values of −175 W m^{-2}, and Q_N values of −810 W m^{-2}.
- The examination of simultaneous extreme events revealed that the recorded values on storm days were classified as extreme (Figures 5 and 6). Specifically, the Northwest region of the IP experienced the most significant impact from these events, where the value of the 98th percentile was higher in 34.1% of storm days for daily accumulated precipitation, in 45.7% of storm days for instantaneous gusts of wind at 10 m, and 46.8% of storm days of wind speed at 10 m.
- In the IP region, the anomaly analysis (Figure 7) related to the climatology of the 1991–2020 period shows low MSLP values (up to more than −21.6 hPa), high values of IVT (up to more than 327.6 kg $m^{-1}s^{-1}$) and wind speed at 250 hPa (up to more than 29.6 m s^{-1}), high values of θe at 850 hPa (up to more than 19.1 °C), Q_E with values up to −150 W m^{-2}, Q_H with values up to –40 W m^{-2}, and Q_N values up to more than −160 W m^{-2}.
- The heat flux analysis (Q_E, Q_H, and Q_N) and the anomalies of SST with values up to −1 °C at the Iberian coast (Figure 7J), as well as the heat flux anomaly values (Q_E, Q_H, and Q_N) (Figure 7 and Figure S2) suggest a cooling of the ocean during the passage of the storm. These results reveal the heat exchangers between the ocean and atmosphere, and their contribution to the development of high-impact storms.
- The results in the present work revealed that the high values of upper-level wind speed and lower-level moisture (Figures 4–7) in the instant of maximum intensity had great importance for the development and intensification of the storms, being responsible for extreme precipitation events and flooding, as well as the strong winds associated with several destructive impacts.

In this sense, the naming of storms by the SW group has led to greater attention from the population to events affecting the region, but also greater availability of information and warnings by the competent authorities. Although the forecasts of the meteorological systems are more and more accurate, it is not yet possible to predict with total certainty its trajectory and the intensity of meteorological impacts. So, the information about these meteorological systems and the associated impacts must be clear, forecast, and in real-time, so that the general population can understand and take measures to minimize the damage.

Moreover, in future work, we consider applying the storm-centered composite analysis [85,104,105] to continue the study of high-impact storms that have affected the Iberian Peninsula. This approach allows us to obtain a different study perspective, with a different localized analysis.

In addition, the study of these events must be continued and considered in future works to understand the development, intensity, and frequency of these meteorological systems that affect the middle latitudes, in particular the IP, with higher values of precipitation and wind speed associated.

Thus, it is essential to improve knowledge of the mechanisms associated with the development of high-impact storms to promote population awareness of this kind of natural hazard and be able to act properly.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14091353/s1, Table S1. High-impact storms with explosive development. Figure S1: Analysis of the Net surface heat flux (Q_N) (W m^{-2}) for storm Ana at 24 hours (A) and 12 hours (B) before the instant of maximum intensity (0 h) (C). MSLP (black contours at intervals of 4 hPa) is plotted in all figures. Figure S2: Climatology for extended winter months

(ONDJFMA) of 1991–2020: (A) Net surface heat flux (Q_N) (W m^{-2}). Anomaly for the composite of 2017–2021 extended winter storms (28 events): (B) Q_N (W m^{-2}).

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Wind Energy Assessment during High-Impact Winter Storms in Southwestern Europe

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Abstract: The electricity produced through renewable resources is dependent on the variability of weather conditions and, thus, on the availability of the resource, as is the case with wind energy. This study aims to assess the wind resource available and the wind energy potential (WEP) during the December months for the three years 2017, 2018, and 2019, in southwestern Europe, when several high-impact storms affected the region. Additionally, a comparison of Prandtl's logarithmic law and Power-law equations for extrapolation of the vertical wind profile is performed for onshore conditions, to evaluate the differences in terms of energy production, with the use of different equations. To assess the effect of the strong winds associated with the storms, 10 m wind components are used, with a 6-hourly temporal resolution, for the December months over the southwestern Europe region (30° N–65° N; 40° W–25° E). Results are compared to the climatology (1981–2010) and show an increase of wind intensity of 1.86 $m \cdot s^{-1}$ in southwestern Europe during December 2019, and a decrease up to 2.72 $m \cdot s^{-1}$ in December 2018. WEP is calculated for the selected wind turbine, 4 MW E-126 EP3—ENERCON, as well as the values following the wind resource record, that is, (i) higher values in December 2019 in the offshore and onshore regions, reaching 35 MWh and 20 MWh per day, respectively, and (ii) lower values in December 2018, with 35 MWh and 15 MWh per day for offshore and onshore. Differences in WEP when using the two equations for extrapolation of wind vertical profile reached 60% (40%) in offshore (onshore) regions, except for the Alps, where differences of up to 80% were reached. An additional analysis was made to understand the influence of the coefficients of soil roughness and friction used in each equation (Prandtl's logarithmic law and Power-law), for the different conditions of onshore and offshore. Finally, it is notable that the highest values of wind energy production occurred on the stormy days affecting southwestern Europe. Therefore, we conclude that these high-impact storms had a positive effect on the wind energy production in this region.

Keywords: renewable energy; wind energy potential (WEP); wind vertical profile; extreme events; windstorms; Northeast Atlantic

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1. Introduction

In recent decades, the continuing demand for renewable and clean energy has increased, which has allowed a significant reduction in greenhouse gas emissions [1,2], and in this sense, the decarbonization of the electricity sector represents one of the main measures to slow the step of climate change [3].

The renewable energy sector (such as hydroelectric, wind, and solar energy) is heavily impacted by atmospheric variability: energy demand and supply are dependent on atmospheric conditions at several time scales ranging from small-scale turbulence through day-ahead weather or seasonal anomalies and up to climate change impacts [4].

Therefore, it is important to understand the availability of the resources and their vulnerability to weather and climate conditions [1,2]. Wind has proven to be a renewable, efficient, and clean energy source, with a high potential for reducing greenhouse gas emissions [5,6]. In general, wind energy resources can be divided into two types: onshore wind and offshore wind, and as a result, wind power generation is composed of onshore and offshore wind farms. Until then, most of the wind power has been generated by onshore wind farms, where the technique for the usage of onshore wind power is well proven. Nevertheless, offshore wind power is getting more attractive for its stable wind resources, generally less environmental impact, and fewer constraints on wind turbine size [6,7]. Wind energy is one of the fastest-growing technologies to produce renewable energy and it has become increasingly attractive, presenting a successful economic development [5,8]. In Europe, the wind energy capacity was 205 GW at the end of 2019, where 15.4 GW of capacity was installed during 2019. Three-quarters of the new wind installations in 2019 were onshore, and Spain installed the most capacity, with 2.2 GW of new onshore wind farms. Onshore wind continues to be the main technology and still makes up 89% of all capacity. This value of new wind power capacity is 27% higher than in 2018, but less than the record in 2017. In 2019, wind energy represented 15% of the electricity consumed by EU-28 countries. In terms of the share of wind in its electricity demand in 2019, Denmark had the highest share (48%), followed by Ireland (33%) and Portugal (27%) [9]. This energy has a high potential of expansion, with capacity scenarios to 2030 that range from 251 to 392 GW production. Thus, by 2030, it could reach 350 GW, supplying up to 24% of electricity demand in Europe [10,11].

Wind energy potential (WEP) is sensitive and strongly dependent upon the strength of near-surface winds which are determined by synoptic-scale variability and local processes, such as those related to orography, which can change the available wind resources [2,12,13].

The vertical gradients of the mean wind speed and wind direction must be known, as well as the turbulence intensity above the surface layer [14], since the wind speed increases as we move away from the ground. This variation in wind speed is essentially due to the irregularity of the soil, vegetation, buildings, and other types of obstacles. The effect of the frictional force fades until it is practically cancelled at a height of approximately 200 m. This area of the atmosphere characterized by the variation of the wind speed with the height is called the atmospheric boundary layer, and above this zone, it is said that the atmosphere is free. Thus, the wind speed, at the presumed average hub height of the installed wind turbines, needs to be corrected [15] and the measured wind speed needs to be extrapolated to hub-height. Several mathematical expressions describe the vertical wind profiles in the surface layer, which allow for reliable vertical interpolations and extrapolations for flat and homogeneous terrain [14], among which are the logarithmic law and the power-law [16].

Thus, the influence of the terrain topography and the soil roughness in the wind speeds profile can be adequately represented by Prandtl's logarithmic law (LogL) [8,17,18], and this law has been used in many studies of wind energy analyses [19–24] with different applications. The Power-law (PL) mathematical relation was normally used to extrapolate the wind speeds at higher heights [6]. This law characterizes the impact of the roughness of the earth's surface on wind speed and it is recognized as a reasonable approximation of the wind vertical profile in the surface layer characterized by neutral conditions and smooth areas [8]. Several studies [5,6,13,16,25–27] used the PL as reference.

Several authors [19,28–31] presented a review of wind resource extrapolation models applied on wind energy, where they highlighted the differences between the various models and equations used in the calculation of wind extrapolation. However, there is no uniform analytic expression for wind speed variation with height, which could be valid for all stability conditions [28] and the formulations only provide a first approximation to the variation of wind speed with elevation; nothing is better than real site measurements [32]. According to these studies, the LogL and the PL equations are the two main approaches to achieving wind speed extrapolation. PL was found to give a reasonably accurate and better representation of wind speed profiles than LogL, at least under unstable and neutral conditions [19,29]. Thus, PL is identified as a reasonable approximation of the wind vertical profile in the surface layer characterized by neutral conditions and smooth areas [8].

The PL indicates the increment of surface wind speed concerning height z. The PL neither satisfies the upper boundary nor the lower boundary conditions [31]. However, the log law model fits well for the wind speed profile at a larger height, which is one of the critical reasons for its preference. Thus, it has been found that the power-law does not fit well at the higher height ranger (typically more than 150 m), and the LogL produces better results at a higher level [31].

The operation of wind turbines is determined by weather, and thus, strongly depends on the regional atmospheric conditions; it could be potentially affected by climate change [33,34]. Modifications, for example, in the intensity and frequency of intense extratropical cyclones, with the origin being in the North Atlantic, that reach Europe and affect the near-surface wind conditions, as the weather is controlled by the passage of these systems and their associated fronts [35], can lead to changing frequencies of calm or strong wind periods. Consequently, this would imply stronger fluctuations of generated electric power [12,34,36,37].

Moreover, the variability and uncertainty in the renewable resource (as wind energy) availability must be properly accounted for in the complex decision-making processes required to balance supply and demand in the power system. Thus, it is becoming increasingly evident that forecasting is a key solution to efficiently handle renewable energy in power grid operations [38]. The variability and uncertainty in renewable resources such as wind power present new challenges from a long-term planning perspective; however, the system reliability must be maintained while trying to minimize the total cost of meeting the electricity demand [39]. This factor is especially important in the long-term planning of new windfarms given the need for the timing of power generation to match the timing of demand, due to the lack of largescale energy storage [2,12]. In this context, ref [3] analyzed the impacts of energy storage systems and the variability and uncertainty of variable renewable energy on power system decarbonization in 2050. On the other hand, the increasing offshore wind deployments will further elevate the concerns that are emerging regarding the challenges of grid integration and system reliability with the rise of variable renewables [40]. These concerns vary from system to system; however, one mechanism to mitigate any issues related to variability and uncertainty is energy storage. Advanced energy storage technologies, such as batteries, can provide the grid with a variety of system-level services, which includes the added flexibility needed to reliably accommodate much higher levels of variable renewable generation [40,41].

The increase in electricity production through renewable energy sources, such as onshore and offshore wind energy, makes energy systems more sensitive to weather and climatic conditions and their variability [42,43]. Extreme weather conditions, such as extreme winds, are a challenge to the normal and safe operation of wind turbines, and because of the entire European electrical system, considering the weight of wind energy in the energy mix [44,45]. In the study of Cutululis et al. [44], the impact of critical weather periods, with very high wind speeds, on the stable operation of the power system was assessed. The wind turbine has a storm control system to protect itself and to stop when the wind speed exceeds a certain value, which leads to the sudden loss of wind power due to the way the wind turbines operate. The obtained results show that, with the present storm controller, during critical weather conditions periods, significant amounts of wind power production will be lost in periods ranging from 10 minutes to over an hour. Those amounts, in the worst case, can go up to 50% of installed capacity in 30 min and around 70% in an hour. That means that losses in production are highly significant [44]. In this way, it is important to consider the spatial and temporal variations in production and demand of energy and the design and operation of power systems of renewable sources [42], to guarantee a continuous and secure energy supply in the future [46].

High-impact storms (storms associated with extreme precipitation and strong winds) are an example of these extreme weather events, which, when they are intense and persist for several days, cause serious impacts on the sector of production and consumption of electricity. These situations are considered a serious risk for the power production sector of electricity and its facilities, which can provoke disruption, supply cuts, and affect other infrastructures depending on the energy supply [42,43,47–49].

In the three December months (2017, 2018, 2019), southwestern Europe was affected by several high-impact storms that caused major adverse impacts [50–52]: in December 2017, three high-impact named storms (Ana, Bruno, and Carmen storms [50–52]); in December 2018, another three storms affected these regions (Etienne, Flora [50,51] and Oswalde [53] or Deirdre [54]); and in the last considered December month (2019), three additional storms (Daniel, Elsa, and Fabien storms [50,51]) affected southwestern Europe, which had strong winds.

This study has the objective of providing a first assessment of the available wind resource and wind energy potential (WEP) during the considered months of December 2017, 2018, and 2019, and understanding the influence of high-impact storms in the production of electricity through wind energy technology in this region.

For this assessment, an analysis comparing two different equations of extrapolation of the vertical wind profile (Prandtl's logarithmic law and Power-law) for onshore conditions is done, to evaluate the differences in terms of WEP. An additional analysis is made to understand the influence of the coefficients of soil roughness and friction used in each equation (Prandtl's logarithmic law and Power-law), for the different onshore and offshore conditions, and in WEP values posteriorly obtained.

2. Materials and Methods

2.1. Meteorological Data

The analysis of wind resource and the availability of the WEP during the three months of December of 2017, 2018, and 2019 was performed through the use of ERA5 Reanalysis 10 m wind components (10-m U and V wind components) retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) [55]. The fields were extracted at 00, 06, 12, and 18 UTC (6-hourly data), over a geographical sector that covers the Northeast Atlantic and southwestern Europe region (30° N–65° N; 40° W–25° E) and compared to the climatological average of 6-hourly values for the December months for the 1981–2010 period. Anomaly composites, namely the departures of arithmetic mean over each month of the considered fields from the respective grand means computed over December 1981–2010, are analyzed. The availability of wind resources is assessed for each of the three months separately.

2.2. Methodologies for Calculating the Wind Potential

For WEP calculations, ERA5 10 m wind velocities (V10) are extrapolated to 135 m, which is the height of the onshore wind turbine considered in this study [55–57]. The wind speed must be corrected [15] and extrapolate measured wind speed to hub-height of the installed wind turbines. For that, the LogL and the PL [16] were used to describe the vertical wind profiles in the surface layer, which allow for reliable vertical interpolations and extrapolations in flat and homogeneous terrain [14]. Wind speed variation is essentially due to the irregularity of the soil, vegetation, buildings, and other types of obstacles. Prandtl's logarithmic law can adequately represent the influence of the terrain topography and the soil roughness in the wind speeds profile [8,17,18], and it is expressed in Equation (1):

$$\bar{v}(z) = \frac{v_r}{k} \ln(\frac{z}{z_0}) \quad (1)$$

where $\bar{v}(z)$ is the average wind speed at height H, v_r is the friction speed, k is the Von Karman constant (with value 0.4), and z_0 (m) is defined by the characteristic length of the roughness of the soil [15,32]. It is usual to use Equation (1) for the extrapolation of the wind speeds to different heights [18,19]. Wind extrapolation is carried out using a logarithmic wind profile that assumes a neutrally stratified atmosphere [15]. In this study, a value of 0.03 m is considered for the coefficient of soil roughness, z_0, considering a type of soil with "open areas with a few windbreaks"; this value was obtained from Table 6.4 in [32]. Moreover, the LogL is more complicated to use than the PL because the latter is simpler to apply in this type of studies [58].

The PL is the only method without a physical basis, and it seems to give a better fit to most of the data over a greater height range and for higher wind conditions [16]. In general, it is customary to adopt a height (H_0) of 10 m above the ground as a reference and for this height also a reference speed (v_r). Therefore, it is necessary to estimate the harvested wind energy at wind speeds magnitude at greater heights, with appropriate equations that predict the wind speeds at one height in terms of the measured speed at another height. PL characterizes the impact of the roughness of the earth's surface on wind speed [8] and it can be expressed by Equation (2):

$$v_h = v_r(\frac{H}{H_0})^{\alpha} \quad (2)$$

where α is the power-law exponent, which depends on such factors as the nature of the terrain (surface roughness), typically 0.20 for onshore areas [13,32,58,59], considering a terrain with "high crops, hedges and shrubs"; this value was obtained from Table 6.3 in [32]. However, to understand the influence of the type of soil in the extrapolation of the vertical wind profile, the various coefficients mentioned in [32] were used in the calculation of the WEP, and the results are shown in Figures S1 and S2 (see Supplementary Materials).

The wind energy density (WED), wind potential (WP), or power output of a wind turbine measures the energy contained in the winds, i.e., the kinetic energy flux associated with the winds, which is proportional to the third power of wind speed [8]. The wind potential (WP) depends on air density (the standard near-surface value of 1.225 kg·m^{-3}), turbine radius, R (m), wind speed, V (m·s^{-1}), and rotor power coefficient, Cp, i.e., the Betz limit (Cp = 16/27), which describes the maximum amount of energy a turbine can theoretically extract from the wind. Moreover, that is the ratio of the rotor power density (mechanical power at the turbine shaft per unit of swept area) to the wind power density [19,60]. However, the real-world values of Cp are well below the Betz limit with typical values in the order of 0.35–0.50 [61–63].

Between the turbine specific cut-in and rated wind velocity, the WP is proportional to the cubic power of wind speed:

$$\text{WP} = (1/2) \times C_p \rho \pi R^2 V^3 \quad (3)$$

Hence, the sensitivity of WP to wind speed is particularly high and depends on the power coefficients of a given turbine model [13]. The wind energy potential (WEP), or gross energy output (E), for a period (t) is calculated as follows:

$$\text{WEP} = WP \times t \quad (4)$$

In 2019, in Europe (EU-28), the average power rating of new onshore wind turbines was 3.1 MW, and it was 7.2 MW for new offshore turbines. The largest turbine in the world is GE's Haliade-X, the industry's first 12-MW onshore turbine. The first prototype was installed at the Port of Rotterdam in 2019 for testing and its commercialization is expected in 2021 [9].

For this study, the turbine ENERCON of the model 4MW E-126 EP3 is used, and the characteristics are presented in Figure 1 and Table 1 [56,57].

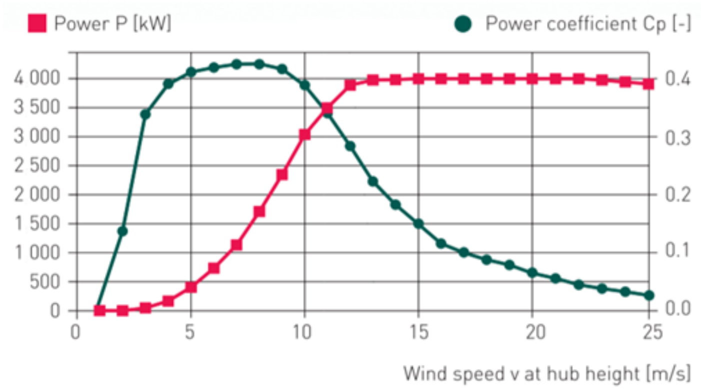

Figure 1. The power curve (in kW) of the selected wind turbine (4 MW E-126 EP3, ENERCON) for wind speeds ranging from 0 to over the cut-out velocity (25 $m.s^{-1}$). Note a rated (maximum) power of 4000 kW, wind-rated speed of 13 $m.s^{-1}$, rotor diameter of 127 m, and cut-in velocity of 3 $m.s^{-1}$. Adapted from [56,57].

Table 1. Characteristic of the selected wind turbine (4 MW E-126 EP3, ENERCON). Adapted from [56,57].

Turbine Characteristics	
Rated power	4000 kW
Wind rated speed	13 $m{\cdot}s^{-1}$
Rotor diameter	127 m
Cut-in velocity	3 $m{\cdot}s^{-1}$
Cut-out velocity	25 $m{\cdot}s^{-1}$
Cut-out velocity storm	28–34 $m{\cdot}s^{-1}$

2.3. Energy Data

To confirm and to compare the obtained results, the European reports of renewable energies—wind energy—are used for the years of 2017 to 2019 [9–11,64–74]. These reports present the production of wind energy in the countries of Europe (EU-28) as well as the installed capacity of wind energy, for the years and months under study.

3. Results

The wind resource and wind energy potential (WEP) analysis for the considered December months of 2017, 2018, and 2019 are presented in Figures 2–4.

3.1. The Wind Resource

To evaluate the wind resource availability in the December months of 2017, 2018, and 2019 and to understand how the wind resource varies spatially and temporally, the climatological average of the 10 m wind speeds for the month of December for the period 1981 to 2010 was calculated (Figure 2A). The mean wind speeds at 10 m over southwestern Europe ranged from 1 to 5 $m{\cdot}s^{-1}$. Then, respective anomalies (departures from year n to the climatological average) were calculated for each considered year (Figure 2B–D). In December 2017 (Figure 2B), the obtained results showed an increase of wind intensity of up to 0.7 $m{\cdot}s^{-1}$ over southwestern Europe in onshore areas, except for the west coast of the British Isles and the Nordic countries (Sweden and Norway). In offshore areas, in the Atlantic Ocean on the north of the Iberian Peninsula (IP), Mediterranean Sea, in the North Sea, and Baltic Ocean, it reached up to 1.43 $m{\cdot}s^{-1}$. North of the Azores Archipelago, there is a region with positive anomalies that also reached up to 1.43 m·s⁻¹. On the other hand, to the west and south of the Azores Archipelago, a strong negative anomaly was observed, reaching −2.16 m·s⁻¹. On the west coasts of the Iberian Peninsula and the British Isles, the values of negative anomalies ranged from 0 to −2.16 m·s⁻¹. In December 2018, it was verified that there was a decrease in wind speed overall southwestern Europe, with a special impact on Iberia, where the negative anomalies reached −1.4 m·s⁻¹ and were even larger on the Mediterranean Sea and southwest coast of Portugal, where the difference reached −2.72 m·s⁻¹ when compared with the respective climatology for the 1981–2010 period (Figure 2A). However, in the region of northern France, Germany, and Poland, an increase of 0.7 m·s⁻¹ was verified. On the Atlantic Ocean, on the north of Azores Archipelago, there was a well-marked positive anomaly, with values reaching 1.76 m·s⁻¹, as well as on the west coast of Norway, over the Norwegian Sea. Concerning December 2019, from Figure 2C, the increase in resource availability was obvious, showing the map positive anomalies across southwestern Europe and over the Atlantic Ocean. In some regions, positive values reached up to 1.86 m·s⁻¹, as is the case of the Atlantic Ocean and the Mediterranean Sea, with the exception on the Balearic Sea region that presents negative anomalies (−1.78 m·s⁻¹). It can be concluded from Figure 2 that, in general, December 2019 presented an increase in available wind resource, while December 2018 presented a clear decrease, highlighted in the Iberian Peninsula region.

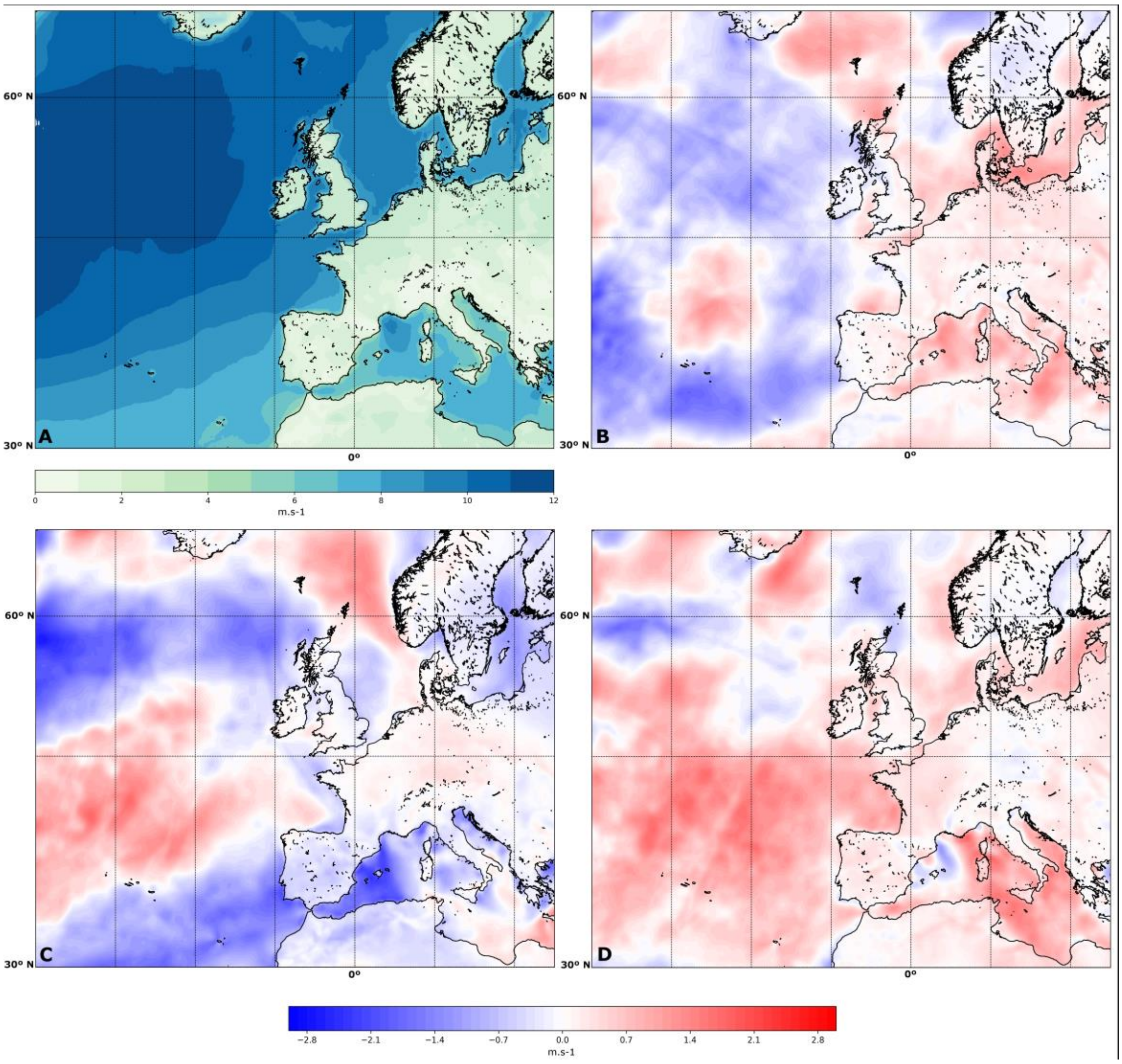

Figure 2. (**A**) Climatological average of ERA5 wind speed at 10 m (m·s⁻¹), for the December months of 1981 to 2010. (**B–D**) Anomalies of wind speed at 10 m (m·s⁻¹) for the December months of 2017, 2018, and 2019, respectively.

3.2. The Wind Energy Potential (WEP)

The Wind Energy Potential (WEP) was calculated using two different equations (Equations (1) and (2)) for the extrapolation of the vertical wind profile, by Equation (1), which uses the LogL (with $z_0 = 0.03$ m), and Equation (2), which uses the PL (with $\alpha = 0.20$), with coefficients to onshore conditions. Figure 3 illustrates the WEP for the months of December in 2017, 2018, and 2019. The first column shows the results calculated with Equation (1); the second column shows the results obtained with Equation (2). The third column shows the difference (in percent) between the results of WEP obtained by both equations (Equations (1) and (2)), to understand the influence of the vertical wind profiles on the surface layer and the roughness of the terrain. Equation (1), Prandtl's logarithmic law, was used as a reference.

In December 2017 (Figure 3A,B), the WEP values in onshore regions varied between 5 and 20 MWh·day^{-1}. The northern coast of Europe (France, Germany, the Netherlands, Denmark, Poland, and countries in the east), as well as the British islands, had the highest values, while in offshore regions, it ranged from 15 to 40 MWh·day^{-1}. These values were higher (up to 35 MWh·day^{-1}) on the North Sea and Baltic Ocean and on the Atlantic Ocean on the north of the Azores archipelago. The direct differences of the WEP for December 2017 in percentage (Figure 3C) verified that the differences reach −80% of energy production on onshore areas, as in Alpes and Norway, and over up to −50% in all Europe. On the other hand, an increase in energy production occurred in the north region of the Atlantic Ocean, north of the Azores Archipelago, north of the Iberian Peninsula, and the entire west coast of France and the British islands, with up to 20% more energy and in the region of the Mediterranean Sea.

In December 2018, a decrease in wind production occurred (Figure 3D,E), especially in the Iberian Peninsula, south of France, and the British Isles. The highest WEP values were reached in the region north and west of Europe, reaching 35 MWh·day^{-1} on offshore regions and 15 MWh·day^{-1} on onshore regions. The differences of the WEP for December 2018 (Figure 3F) were more visible between the onshore and offshore regions as in 2017 (Figure 3C), but with higher values of WEP in the offshore regions for 2018, which reach up to 50% more, over the Atlantic Ocean (at northern latitudes of Azores Archipelago) and the west coast of the British Islands.

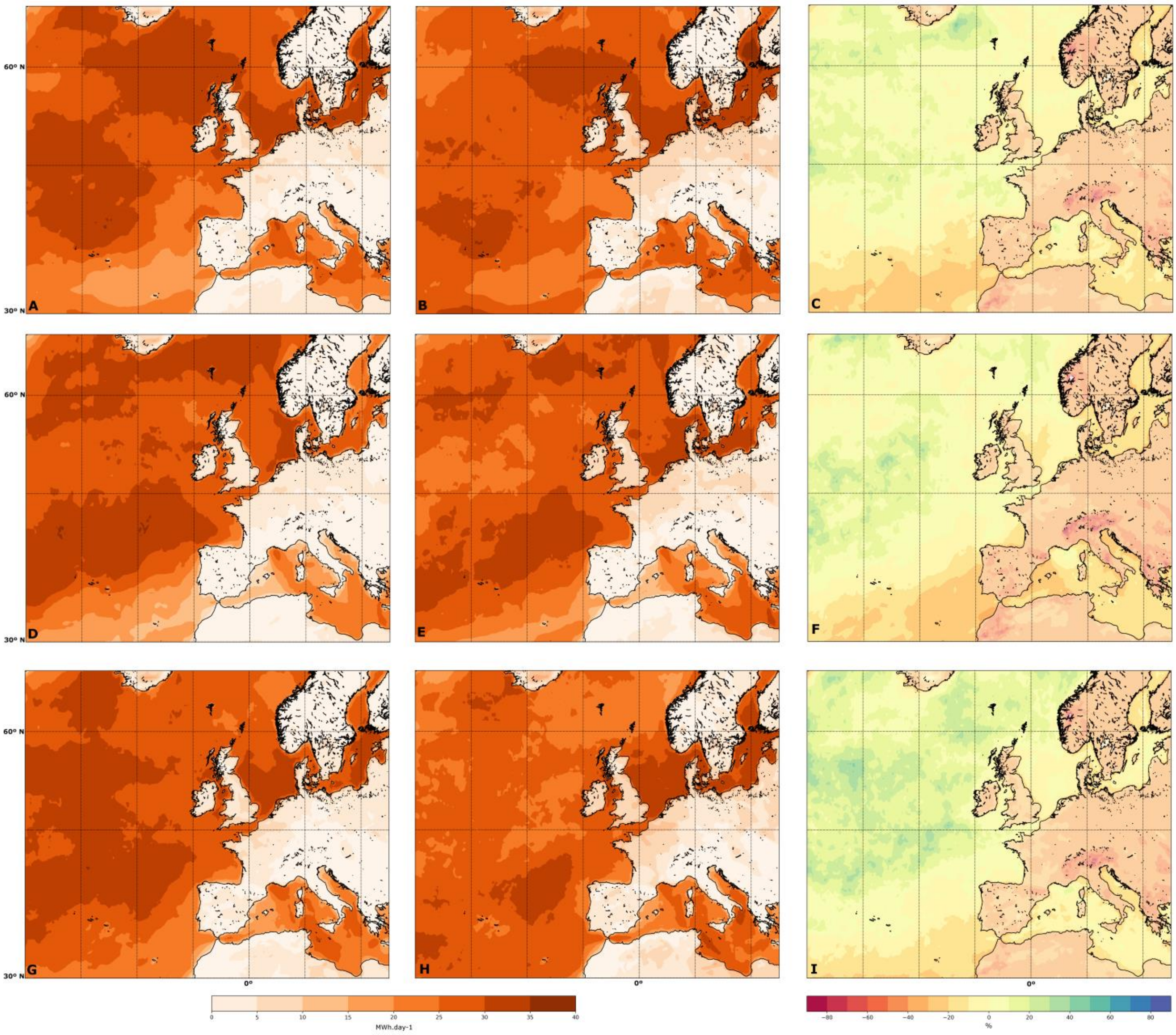

Figure 3. Wind Energy Potential (WEP) (MWh·day^{-1}): December 2017 (**A**,**B**); December 2018 (**D**,**E**); December 2019 (**G**,**H**); (**A**,**D**,**G**) calculations made using Equation (1) (LogL, z_0 = 0.03 m); (**B**,**E**,**H**) calculations made using Equation (2) (PL, α = 0.20); (**C**,**F**,**I**) percentage difference of WEP between the use of Equations (1) and (2), for the respective months of each year.

On the other hand, in the onshore regions, as in the case of the Iberian Peninsula, the Pyrenees, and the Alps region, there were differences in WEP varying between −40% and −80%. Concerning December 2019, there was a particular increase in onshore production compared with the previous years. The WEP values in the onshore regions reached 25 MWh·day^{-1}, while the WEP values in the offshore regions was 35 MWh·day^{-1}. Areas on the northern coast of Europe (such as the British Isles, Denmark), France, Germany, the Netherlands, and Poland recorded the highest WEP values, in the order of 15 MWh·day^{-1} (Figure 3G) and up to 25 MWh·day^{-1} (Figure 3H). In the offshore regions, the values reached 35 MWh·day^{-1} over the northern region of the Atlantic Ocean, in the Baltic Ocean and the North Sea (Figure 3G,H). Additionally, in the offshore regions, the differences between the application of wind extrapolation equations are notable. On the Atlantic Ocean, in the North Sea, the Baltic Ocean, and the Mediterranean Sea, differences between 10% and 60% more than WEP were verified, using the LogL. On the other hand, using

LogL as a reference, the differences in onshore regions reached −80% WEP in the Alps (Figure 3I). However, there was a difference between −20% to −60% in all onshore regions (Figure 3I).

Thus, considering the results obtained, using Equation (1) (Prandtl's logarithmic law) in the calculation of the extrapolation of the vertical wind profile, showed the highest values of WEP for offshore regions. Nevertheless, when Equation (2) (the PL) was used, the WEP values were higher in the onshore regions. This pattern was consistent and similar in the three December months under study. Moreover, the differences in the values of WEP obtained were observed in the same regions, even considering the roughness and fiction factors of the soil for onshore conditions.

3.3. The Anomalies of Wind Energy Potential (WEP)

The anomalies of the WEP values for December 2017, 2018, and 2019 were calculated and compared with the climatological WEP values for all December months of the 30-year period from 1981 to 2010 (Figure 4), using, respectively, Prandtl's logarithmic law (Equation (1), with z_0 = 0.03 m; Figure 4A) and the PL (Equation (2), with α = 0.20; Figure 4E) in the extrapolation of the wind profile.

Analyzing the climatological average of WEP (Figure 4A,B), there are differences in the production of WEP in several offshore and onshore regions in concordance with the analysis performed in Section 3.2. Figure 4A shows high average values, on offshore areas, over the Atlantic Ocean and on the west coast of the British Isles, in the order of 35 MWh·day^{-1}. For the onshore regions, the highest average values (15 MWh·day^{-1}) are found in the British Isles and the north of the countries of France, Germany, Poland, Denmark, and Sweden. When the power-law equation is applied (Figure 4E), higher WEP values were found in the onshore regions (up to 20 MWh·day^{-1}), except for the Baltic Ocean, which presented higher values (reaching 35 MWh·day^{-1}) than in Figure 4A.

In the Iberian Peninsula and over the north countries (France, Germany, and British Isles) (Figure 4E), the highest WEP values are very noticeable when compared to Figure 4A. Thus, it is possible to conclude that the PL (Equation (2)) allows obtaining higher values of WEP in onshore regions.

The anomalies show how the WEP availability varies (Figure 4B,F). In December 2017, the values of WEP presented an increase of around to 3 MWh·day^{-1} on onshore areas, except for the British Isles and Scandinavia Peninsula that have experienced a reduction in WEP of up to −3 MWh·day^{-1}. Moreover, in the west region of IP, there was also a reduction of WEP of up to about −3 MWh·day^{-1}. These values are valid for both approaches, that is, for the values obtained through the two different wind extrapolation formulas (Figure 4B,F). On offshore areas, it is possible to observe an increase and a decrease in WEP. Thus, an increase was verified that ranges from 6.80 MWh·day^{-1} (Figure 4B) to 8.14 MWh·day^{-1} (Figure 4F) on the Mediterranean Sea and Baltic Ocean, north and east of the British Islands, and north of Azores Archipelago region. On the other hand, the reduction in WEP is more pronounced on the west coast of Portugal and in the region of the Gulf of Biscay and in the English Channel, where the values varied between −7.53 and −8.51 MWh·day^{-1}, Figure 4B,F, respectively.

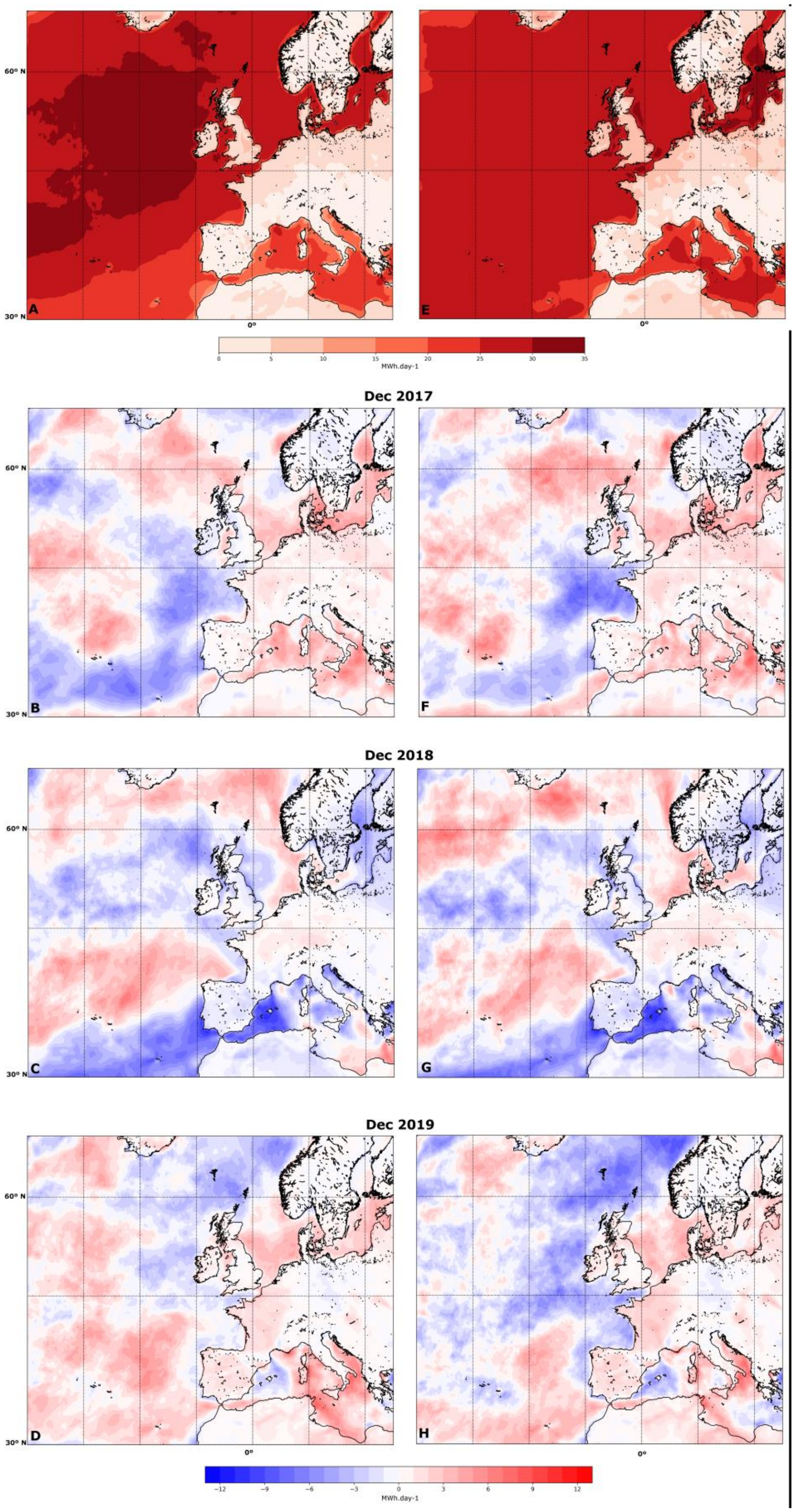

Figure 4. (**A**,**E**) Climatological average of the Wind Energy Potential (WEP) (MWh·day^{-1}) for the December months of 1981 to 2010. Anomalies of WEP (MWh·day^{-1}) for the December months of (**B**)

and (**F**) 2017; (**C**,**G**) 2018; (**D**,**H**) 2019. (**A**–**D**) calculations made using Equation (1) (the LogL, z_0 = 0.03 m); (**E**–**H**) calculations made using Equation (2) (the PL, α = 0.20).

Concerning December 2018, this month showed the lowest values of WEP when compared with the other two. The reduction in WEP is more pronounced in onshore areas (Figure 4C,G), where practically the whole of Europe presents negative anomalies, with values ranging from −6 to −3 MWh·day^{-1}, considering the two equations for extrapolating the wind. However, in onshore regions, there was an increase in the production of WEP in the north of France, Germany, and the Netherlands, where the values are up to 3 MWh·day^{-1} higher than the climatology. Moreover, the highest values of positive anomalies are present in offshore regions and the values range from 6.85 to 7.70 MWh·day^{-1} (Figure 4C,G, respectively). Concerning negative anomalies, the highest negative values were obtained for the offshore regions and the values vary between −10.64 and −11.01 MWh·day^{-1} (Figure 4C,G, respectively), over the Balearic Islands and on the west and southwest coast of Iberia. Along the coast of the British Isles and in the Baltic Ocean, there is also a slight decrease in WEP (−6 MWh·day^{-1}). Additionally, in the Atlantic Ocean, the region south of the Azores Archipelago and the Macaronesia islands, as well as on the Italian and Greek coast, there are negative anomalies with values ranging between −3 and −9 MWh·day^{-1}, for the two approaches.

Finally, the month of December 2019 showed a general increase in energy production (WEP) compared with the climatology. This increase is in line with the greater availability of wind resources, shown in Figures 2D and 3G,H. The highest values of positive anomalies obtained for the two situations plotted in Figure 4D,H, are 8.10 MWh·day^{-1} and 8.30 MWh·day^{-1}, respectively, and these are observed for offshore regions (the North Sea, the Baltic Ocean, and in the Mediterranean Sea). For the onshore regions, this increase in WEP is most noticed in the Iberian Peninsula and France, where the values reach 6 MWh·day^{-1}. It should be noted that although in the Iberian Peninsula and France there is an increase in WEP, the west and north offshore coast of both regions present negative anomalies that range from −6 to −3 MWh·day^{-1} (Figure 4D,H). In the Atlantic Ocean, the region of the Azores Archipelago presents negative anomalies over the islands (in the order of −3 MWh·day^{-1}) and positive anomalies in the region surrounding it, and around the Madeira Islands. The highest values of negative anomalies are shown in offshore regions over the Norwegian Sea and in the northern region of the Atlantic Ocean, where the values are up to −6.36 and −9.13 MWh·day^{-1} (Figure 4D,H, respectively).

When the PL is considered for the extrapolation of the wind (Equation (2)), there are more pronounced positive and negative anomalies, so the values are higher than those calculated using LogL. However, it is also shown that LogL (first column) presented higher values of WEP in the offshore regions, and on the other hand, the PL (second column) presents higher values of WEP in the onshore regions.

Thus, considering the results obtained (in Figure 3), it appears that, when we use Equation (1) (LogL) in the calculation of the extrapolation of the vertical wind profile, the highest values of WEP correspond to offshore regions. Nevertheless, when we use Equation (2) (the PL), WEP values are higher in onshore regions. This pattern is consistent and similar in the three months of December under study. Moreover, the differences in the values of WEP obtained are observed in the same regions, for the different studied months.

In the analysis of anomalies of the WEP (Figure 4), when the PL is considered for the extrapolation of the wind (Equation (2)), there are more pronounced positive and negative anomalies, and the values are higher than those calculated when LogL is used. Furthermore, it is also shown that LogL (first column) presented higher values of WEP in the offshore regions, and on the other hand, the PL (second column) presented higher values of WEP in the onshore regions.

Although in this analysis only the coefficients of roughness and soil fiction for onshore conditions were used, the values obtained in Figures 3 and 4 show that if we consider the onshore regions for the study, it is better to use Equation (2) (the PL). On the other hand, if the objective is to study the WEP in the offshore regions, Equation (1) (Prandtl's logarithmic law) presents better results.

To understand the effect of the coefficients of soil roughness and friction used in each equation (LogL (z_0) and PL(α)), an additional analysis was done and the WEP values were then calculated. The values of the coefficient used follow the tabled values of Table S1 and S2, and the results are presented in Figures S1 and S2 (see Supplementary Materials).

When we analyze the obtained results with the different coefficients, we identify the same pattern in the two figures, that is, when we increase the value of z_0 (Figure S1) or α (Figure S2), the roughness of the land or the friction of the terrain, respectively, is devalued allowing the increase of WEP in the onshore regions. On the other hand, a decrease is observed in WEP values in the offshore regions. This pattern is similar for the 3 months under study. The low WEP values in the mountainous regions of the Pyrenees and Alps should be highlighted, with this pattern being maintained in all figures (Figures S1 and S2).

4. Discussion

To compare and validate these results calculated using ERA5 wind values, we used the electricity production reports available for the December months in the study. When these reports are analyzed, the values obtained for Europe, using the EU-28 statistics, allow confirming and understanding the results presented in Figures 2–4. The reports show high values of wind energy produced in the months under study, with emphasis on December 2017 and 2019, where there was a greater production of wind energy, and a comparative decrease in the December 2018. This fact is confirmed with the values obtained in this study, in which the availability of wind resources and the WEP show the same pattern—an increase in the months of December 2017 and 2019 and a decrease in December 2018. In 2017, wind energy generated enough electricity to meet 11.6% of the EU-28's total electricity demand. Denmark was the EU country with the highest penetration rate (44%), followed by Portugal (24%) and Ireland (24%). Germany registered the highest increase from the previous year, now covering over 20% of its annual demand. Ten out of the twenty-eight Member States had a wind penetration rate of more than 10%. Thus, the total EU electricity consumption was 2906 TWh, of a total wind energy production of 336 TWh, of which 292 TWh was onshore wind energy production and 43 TWh was offshore wind energy production [64].

In 2018, wind energy generated enough electricity to meet 14% of the EU's electricity demand. This is a 2% share higher than in 2017 levels, in part due to the lower electricity demand registered. Denmark had the highest share of wind (41%) in Europe, followed by Ireland (28%) and Portugal (24%). Germany, Spain, and the UK followed with 21%, 19%, and 18%, respectively. Nine Member States had a wind share of 10% or more. Throughout 2018, wind power plants produced a stable output, with peak production (98 GW of average output during the day) on 8 December. On that day, wind energy supplied one-third of Europe's electricity needs. The year 2018 was a less windy year than 2017. This is reflected in a decrease of the capacity factors both for onshore (22%) and offshore energy production (36%). Thus, the total of EU Electricity consumption was 2645 TWh, of a total wind energy production of 362 TWh, of which 309 TWh was onshore wind energy production and 53 TWh was offshore wind energy production. In 2018, wind energy represented 14% of the EU's electricity demand. According to data on wind energy production (onshore and offshore) from the EU member states, the months of January, February, March, November, and December had the highest energy production, with the remaining months having a very low wind energy production. It is worth mentioning that the month of December showed high values of wind production, with a record value of almost 100 GW (onshore) and almost 90 GW offshore on 8 December [65]. The strong winds recorded since 7 December caused hundreds of flight delays and cancellations on 8 December at the Amsterdam airport. Wind speeds were 32–40 km·h^{-1} (8.9–11.1 m·s^{-1}) and the highest gusts were forecast for the Amsterdam region by the end of the day [66]. Figure 5 shows a wind speed at 10 m for 8 December 2018, and by analyzing the figure, it is possible to confirm the strong winds that affected the northern region of Europe, with the coast of the British Isles, France, Germany, Netherlands, and the entire North Sea region showing values between 10 and 20 m·s^{-1}. The pattern of wind speed suggests that strong gusts of wind affected those areas; despite these strong winds, the wind turbines were not forced to be stopped.

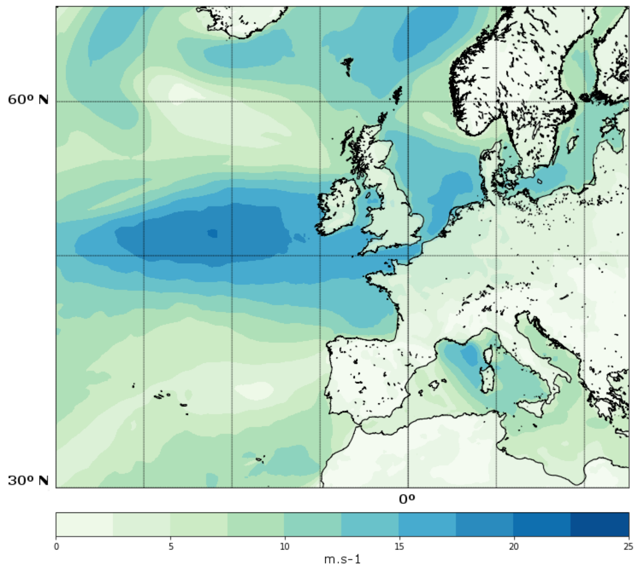

Figure 5. Wind speed at 10 m (m·s^{-1}) on 8 December 2018.

Figure 6A,B allow us to confirm the high WEP on December 8, with values varying from 50 to 175 MWh·day^{-1} on the northern coast of Europe, in countries such as the British Isles, the north of France and Germany, the Netherlands, and the entire North Sea region. Figure 6 also presents the results obtained with the two equations (Equations (1) and (2)) for extrapolating the vertical wind profile. The results are shown in Figures 3 and 4, that is, showing higher WEP values in offshore regions (Figure 6A, Equation (1)) and higher WEP values in onshore regions (Figure 6B, Equation (2)).

The obtained results shown in Figures 5 and 6 permit us to understand the values mentioned in the reports for 8 December 2018, which was a record day for wind production (both onshore and offshore). In other words, according to our calculations and the data obtained, 8 December had a high wind potential. This wind potential was captured by the wind turbines, which suggests that the wind speed values were not as destructive for the wind turbines as to be necessary to force the cut-off of the turbines, and thus, it was possible to take advantage of the wind resource and the production of electricity.

In 2019, wind energy generated enough electricity to meet 15% of the EU's electricity demand. This is one percentage point higher than in 2018, and results from the new installations as well as windy conditions around Europe throughout 2019. Denmark had the highest share of wind in its electricity mix (48%), followed by Ireland (33%), Portugal (27%), and Germany (26%). Twelve Member States had a wind share above 10%.

In 2019, Europe's wind farms produced a stable output throughout the year with daily peak production of 102 GW registered on 13 March. March was the month with the highest average hourly generation. In March, wind energy generated more than 34 GW of electricity an hour 90% of the time in the EU. From June to August, the amount of electricity produced by wind energy generation peaked in the winter months, although in winter, the variation in the hourly generation is higher than in summer. Although March was the month with the highest wind production, there were high values of wind production throughout the month of December, ranging from 40 to 80 GW [9].

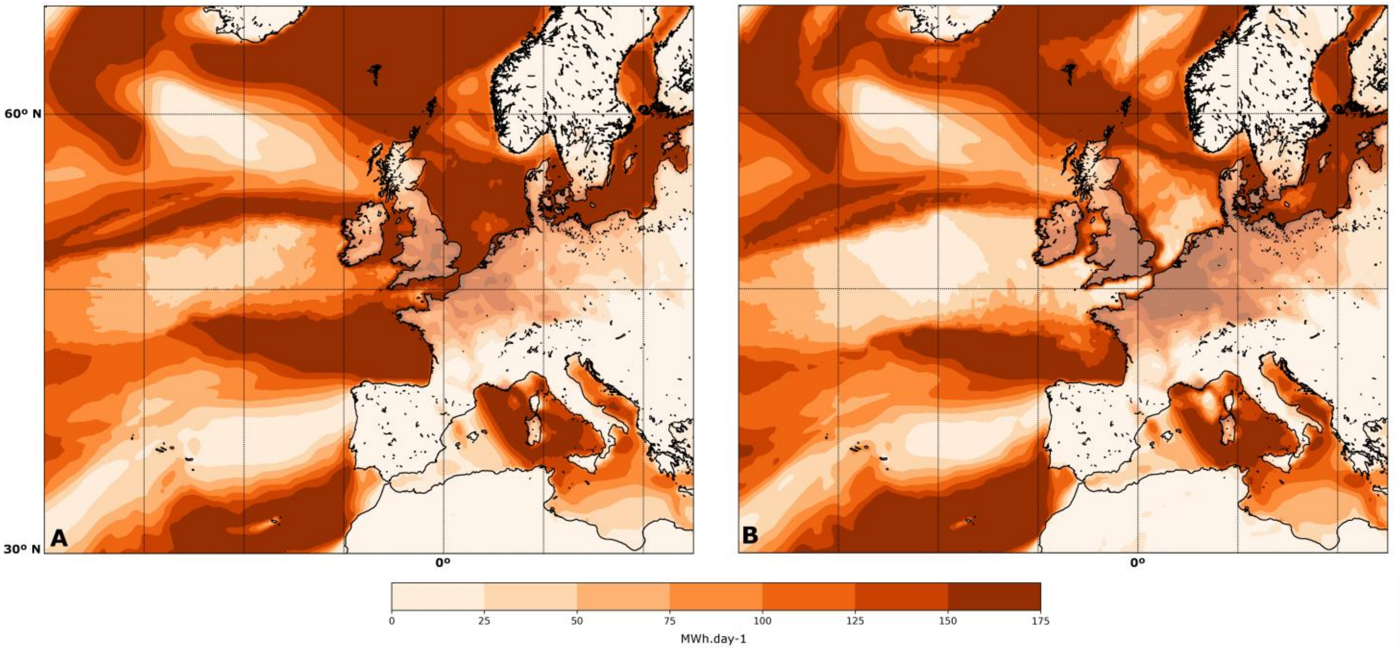

Figure 6. Wind energy potential (WEP) (MWh·day^{-1}) on 8 December 2018. (**A**) Calculations made using Equation (1) (the LogL, z_0 = 0.03 m); (**B**) calculations made using Equation (2) (the PL, α = 0.20).

During the three December months assessed in this study, southwestern Europe was affected by many severe storms, which caused serious impacts on the population. In December 2017, two storms first reached the Iberian Peninsula and then the rest of Europe, namely, the Ana storm on 9–11 December and the Bruno storm on 25–27 December. The passage of these two storms represented an increase in wind energy production in the IP [67,68]. In December 2018, more than two high-impact storms affected, simultaneously, the IP and the other countries of southwestern Europe. Storm Flora on 13 December and storm Oswalde on 16 December hit the southwestern European countries with strong winds, which caused high values of wind energy production during the days when the storms passed. However, a reduction was verified in the monthly wind productivity in December 2018, when compared to the previous months and the values of the previous year [69,70]. Although 8 December is considered a record day for wind energy production, there is no record that the favorable conditions (high wind speeds) for this increase in production were related to the passage of a low-pressure system or a high-impact storm that affected southwestern Europe.

In December 2019, three consecutive storms (Daniel, Elsa, and Fabien) affected southwestern Europe, but firstly the IP, where it caused strong impacts due to extreme winds and heavy precipitation. From 12 December until 23 December, renewable production (wind and hydroelectric energy) reached a new historic record. This corresponded to a consecutive period of 5 and a half days (uninterrupted period of 131 h), between 18 and 23 December, when the production of renewable electricity was enough to satisfy consumption needs in mainland Portugal. In total, 331 h of 100% renewable consumption were recorded in December 2019 [71,72]. The values obtained for Spain show a new historic maximum of wind power was reached in the peninsular electricity system on 12 December and the maximum daily wind energy on 13 December [63].

Thus, the reports of energy production for the IP and European Union countries, EU-28, confirm the trends of the obtained values with theoretical values of wind speed, and they can demonstrate that the high-impact storms influenced the electricity production favorably in the southwestern Europe region. The values of wind energy production for Europe, EU-28, also reflect the values obtained in this work for WEP, and therefore, in December 2017 and 2019, an increase in electricity production by wind energy was registered (more wind resource available), and in December 2018, there was a decrease (less wind resource available) [9,64,65].

Additionally, our results show that for a comprehensive study, it is necessary to consider the different types of soil and terrain, as well as the type of equation of extrapolation of vertical wind profile when the WEP values are calculated for a wind farm. Indeed, these factors have a great influence on the energy results both for onshore and offshore conditions (see Figures S1 and S2, Supplementary Materials). However, when the objective is to assess the wind energy production in a specific period and region, these differences obtained with the different coefficient values are irrelevant because the most important is to compare the WEP obtained in each month under the same conditions.

Nonetheless, and to the best of our knowledge, there are no previous studies on this question. Therefore, it is necessary to deepen this study and the results obtained here, to understand how the type of terrain and soil can influence the use of wind energy, as well as what is the best equation to use in the prediction of the WEP value obtained in wind farms. This issue is important since wind energy remains one of the biggest bets for the decarbonization of the electricity sector.

5. Conclusions

Wind energy has been extensively utilized to meet the great demands of industrial production and ease the energy crisis in sustainable development [7] and is a key solution to cope with climate change. However, climate change will be more likely to result in the high frequency and intensity of extreme weather events (such as windstorms and high-impact storms), which may have negative effects on wind power generation [45].

Wind energy has an important role in the renewable energy mix of Europe, EU-28, [74]. The installed capacity and the annual participation of wind energy in the energetic system of each country is high, and this is important, because these countries are betting and continuing to bet on wind energy to produce clean energy and reduce CO_2 emissions.

As previously discussed in Section 3.2, the results in Figure 4 illustrate that the use of the two equations for the vertical extrapolation of the wind at the height of the turbine, and later the calculation of the WEP, show that the WEP is sensitive to the variability of wind patterns. Moreover, the effect of the characteristics of the orography is quite remarkable in the transitions between onshore and offshore [8]. The differences between the WEP calculated by the two equations are observed in Figure 3, where it is possible to verify that LogL allows more WEP production in offshore regions and the PL allows greater WEP values in onshore regions, with differences reaching 80%. The values obtained in Figures 3 and 4 also revealed that for onshore regions it is better to use Equation (2) (the PL) and, if the objective is to study the WEP in the offshore regions, Equation (1) (LogL) presents better results, even if, in a first analysis, only the coefficients of roughness and fiction of the soil for onshore conditions were considered.

Although several authors [30,31,75,76] studied the different methods to extrapolate the vertical wind-speed profile, there is no obvious conclusion about which equation is best suited for the onshore and offshore regions. Thus, it is possible to declare that both LogL and the PL are suitable and commonly utilized to calculate the vertical variation of mean wind speeds in the atmospheric boundary layer. However, most authors agree with the fact that the PL is widely used due to its simplicity, and it seems to give a better fit to most of the data over a greater height range and for higher wind conditions, compared to LogL [28,58,77]. Thus, to the best of our knowledge, this is the first time that this pattern is highlighted—further research should be performed in the future to confirm these results for a larger dataset and diverse conditions.

The obtained results for WEP can be confirmed and compared with other studies. For example, Santos et al. [13] performed a study on the potential of wind energy of the

Iberian Peninsula, in which the values obtained for WEP and for the mean annual patterns and the mean patterns for the winter months (December, January and February), where the highest values ranged from 8 to 16 MWh per day on the northwest and north of the IP region, on the southeast region of the IP and the Gibraltar strait region. Moreover, while onshore daily WEP varies between 2 and 16 MWh per day, in winter, offshore values are never below 16 MWh per day [13].

Regarding the results obtained with the theoretical values, these were followed by the real reported values of the production of electricity from wind energy in the countries, that is, an increase in production in the months of December of the year 2017 and 2019, and a decrease in December 2018. Moreover, it was also verified that the occurrence of high-impact storms with associated strong winds influences the available wind resource for energy production in the studied months, due to the high WEP values observed during the days of the storm's passage.

The event of 8 December 2018 (Figures 5 and 6) is classified as a record day in terms of onshore and offshore wind production in Europe. The remaining high-impact storms that hit Europe with strong winds during the months of December, studied here, have become a positive factor to produce renewable energy. In other words, this study suggests that high-impact storms and events with strong associated winds have a positive impact on the renewable energy sector, thus allowing an increase in electricity production through wind energy. Nowadays, wind energy technology is so evolved (more resistant and efficient materials) that storms and extreme wind events can contribute to a greater wind potential, considering that the wind turbines do not need to be shut down and maintain energy production during these periods.

Nevertheless, the kind of data available to perform this study, without information from wind energy plants, did not allow us to verify whether the passage of these high-impact storms caused the cut-off in the wind turbines, due to the high values of the wind speed and strong gusts with different directions. This can be discussed in future work.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4433/12/4/509/s1, Figure S1: Wind Energy Potential (WEP) (MWh.day^{-1}): December 2017 (A), (B), (C), (D) and (E); December 2018 (F), (G), (H), (I) and (J); December 2019 (K), (L), (M), (N) and (O); Calculations made using equation 1 (LogL); (A), (F) and (K) calculations made using 0.0002m as z_0 coefficient; (B), (G) and (L) calculations made using 0.003 m as z_0 coefficient; (C), (H) and (M) calculations made using 0.1 m as z_0 coefficient; (D), (I) and (N) calculations made using 0.4 m as z_0 coefficient; (E), (J) and (O) calculations made using 1.6 m as z_0 coefficient, for the respective months of each year, Figure S2: Wind Energy Potential (WEP) (MWh.day^{-1}): December 2017 (A), (B), (C), (D), (E) and (F); December 2018 (G), (H), (I), (J), (K) and (L); December 2019 (M), (N), (O), (P), (Q) and (R); Calculations made using equation 2 (PL); (A), (G) and (M) calculations made using 0.10 as α coefficient; (B), (H) and (N) calculations made using 0.15 as α coefficient; (C), (I) and (O) calculations made using 0.20 as α coefficient; (D), (J) and (P) calculations made using 0.25 m as α coefficient; (E), (K) and (Q) calculations made using 0.30 m as α coefficient; (F), (L) and (R) calculations made using 0.40 m as α coefficient, for the respective months of each year, Table S1: Roughness coefficient (z_0). Adapted from [32], Table S2: Friction coefficient (α). Adapted from [32].

Author Contributions: Conceptualization and methodology, M.L.R.L. and A.G.; formal analysis and investigation, A.G.; writing—original draft preparation, A.G.; writing—review and editing, M.L.R.L. and R.N.; project administration, funding acquisition, M.L.R.L. All authors have read and agreed to the published version of the manuscript.

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Disruption risk analysis of the overhead power lines in Portugal

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ABSTRACT

The growing increase in frequency and intensity of extreme weather events (EWEs) has a wide impact on energy systems and consumers, as energy transmission infrastructures - overhead power lines (OPL). The main objective of this work is to present the methodology of risk analysis of the EWEs on OPL in Portugal. The level of risk associated with each of the identified events is classified according to the probability of occurrence and consequences, in a risk matrix, and through the cause-and-effect analysis. It is concluded that, in Portugal, the extreme wind – corresponding to level 11 of the Beaufort Wind Force Scale, that is, values equal to or higher than 105.1 km h^{-1} (29.22 m s^{-1}) – is the main factor that provoked the OPL disruption, between 28% and 40% of analyzed events associated with windstorms. Considering the occurrence of compound events - wind and rain - the probability of damage to OPL is between 21% and 30%; for wind and ice, it is 3%–5%. EWEs represent a serious risk for electrical systems, and it is necessary to develop effective solutions to minimize the associated impacts, such as the modification and upgrade of the current design and engineering standards, and electrical network monitoring.

1. Introduction

Extreme weather events (EWEs) are associated with strong extratropical cyclones (ECs) that originate in the North Atlantic and reach Europe as one of the major natural catastrophic systems in mid-latitudes. The European weather is primarily controlled by the passage of these systems and their associated fronts [1]. Some of these specific events have already been studied – such as windstorms Klaus on 23–24 January 2009, Xynthia on 27–28 February 2010, or Gong on 18–19 January 2013 [2–4], – as well as strong ECs occurred in recent winters [5,6], which all crossed the North Atlantic heading Europe with an explosive development at lower latitudes and an uncommon intensity [4,7]. These events can produce extremely high surface wind speeds over a large footprint region [8].

When the weather events are extreme and persist across several days, they are considered a serious risk for the Energy sector and its facilities, and they can cause supply cuts and affect other infrastructures that depend on the energy supply [9–11]. EWEs present a significant impact on critical infrastructures with a typically long life [12] and are considered one of the main causes of wide-area electrical disturbances worldwide. Weather-related power interruptions often tend to be of high impact and sustained duration, ranging from hours to days, because of the large damage to transmission and distribution facilities [13–17]. EWEs influencing overhead power lines (OPL) are important factors causing power transmission grid breakdowns. Extreme winds, ice storms, and wet snow deposition on OPL are some of the major causes of structural failures worldwide in transmission and distribution lines. Ice storms and wet snow deposition can cause overloads exceeding the mechanical endurance of even new, well-designed lines [14,15,18]. Although many studies assess the impacts of CC on different infrastructures in the energy sector qualitatively, very few provide a quantitative assessment of the effects of CC on the reliability of structures, especially on power transmission and distribution lines [16,19,20]. Some authors studied these types of events and their impacts. Rezaei et al. [14] suggest that the intensity and frequency of ice storms and hurricanes may, in the future, increase in several regions, with the increase in global temperatures. These changes in the frequency and intensity of wind and ice storms (snowfalls or freezing rain) can have

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considerable adverse effects on applied loads and consequently affect the probability of structural failure of different components of the line and trigger a set of cascading disruptions [14]. The work developed by these authors showed that power lines are more sensitive to increased extreme wind intensity than to increased intensity of extreme ice thicknesses. In detail, it is shown that a 20% change in the mean value of extreme wind speed and extreme ice thickness can reduce the reliability index of the line under study by more than 30% and 17%, respectively [14]. Panteli et al. [21] propose a probabilistic methodology to assess the resilience degradation of transmission networks subject to extreme wind events. Matko et al. [22] studied the potential for spatial planning to improve the reliability of electric power infrastructure, and to reduce the risks of electric power outages due to EWEs, such as ice storms, by proper siting of installations. For Poland, Tomaszewski and Ruszczak [15] analyzed the frequency of occurrence of weather conditions favoring deposition of wet snow on OPL and aimed at specifying the probability of failures of a power system occurrence caused by icing. Ward [19] studied the effect of weather on-grid systems and the reliability of electricity supply in Europe and North America, it is concluded that the effects on the high voltage transmission networks are different from the effects on lower voltage distribution networks and that generally, the most significant extreme weather is high winds. Therefore, enhancing the grid resilience to such events is becoming increasingly important [13], as well as checking the possibility of functioning of power systems during the occurrence of extreme events, through measures of adaptation and control of the systems [20,23].

Moreover, with the growing importance and impact of EWEs in the energy sector, there is a gap in this research area in Portugal. Therefore, the aim of the present paper is to propose a methodology for analyzing the risk of disruption of OPL caused by EWEs that affected Portugal in the four extended winters of 2017–2021. Additionally, adaptation measures and recommendations for managing the risk associated with EWEs are analyzed. Thus, the workflow in this study is as follows: (i) to classify EWEs associated with high-impact EC in Portugal and characterize the events; and (ii) to identify which impacts were caused – especially if there was OPL disruption (fall of electrical lines/poles/supports that caused the cut in the electricity supply to consumers), (iii) to identify a threshold for the wind speed gusts that caused OPL, and finally (iv) to propose a methodology to do the risk analysis of the OPL disruption in Portugal caused by EWEs. Finally, strategies to minimize or even eliminate the disruption risk to the electricity transmission and distribution system in Portugal are considered.

In this paper, the work is structured as follows: the background is presented in section two. Then, section three shows the data and methods used in the risk analysis. In section four, extreme weather events (EWEs) and their impact on mainland Portugal are assessed. Section five discusses the results of the risk analysis, with the two tools applied in the study – The cause - and - effect diagram and the risk matrix. Section six presents the discussion, limitations of the study, and conclusions, as well as the significance of the work.

2. Background

2.1. Risk concepts

Individual natural hazards can interact resulting often in high-impact events leading to heavy socio-economic losses [24–26]. When they occur as compound events (CEs) [4,27,28] they may also exacerbate socioeconomic impacts on vulnerable populations. CEs are defined as an extreme impact that depends on multiple statistically dependent variables or events, and, thus, also defined as (i) two or more extreme events occurring simultaneously or successively, (ii) combinations of extreme events with underlying conditions that amplify the impact of events, or (iii) combinations of events that are not themselves extreme but lead to an extreme event or impact when combined (i.e., clustered multiple events) [29,30]. Examples of these events are thus the ECs that are associated with CEs and which can also refer to as simultaneous, concurrent, or coincident extremes, (e.g., the concurrence or succession of multiple extremes events), which can lead to larger impacts on human society and the environment than those from individual extremes alone [24,27–32]. Zscheischler et al. [26] show that a better understanding of complex CEs may improve future projections of potential high-impact events. In addition, consecutive disasters [33] are also associated with compound [26] and cascading events [34]. Consecutive disasters are events whose impacts overlap both spatially and temporally, while recovery is still underway [33]. The United Nations Office for Disaster Risk Reduction (UNDRR) defined them as "(1) the selection of multiple major hazards facing a country, and (2) the specific contexts in which hazard events may occur simultaneously, cascade or cumulatively over time, and taking into account the potential interrelated effects" [35]. On the other hand, de Ruiter et al. [33] defined "consecutive disasters" as two or more disasters that occur in succession, and whose direct impacts overlap spatially before recovery from a previous event is completed. This can include a broad range of multi-hazard types, such as CEs and cascading events, and the latter are considered dependent hazards which are commonly defined as a primary hazard triggering a secondary hazard [34], such as landslides triggered by a flood [33]. These events thus occur when a hazard coincides with exposure and vulnerability, and these three risk components are dynamic [35], with the potential to increase or decrease in response to the occurrence of a previous hazard or disaster [33,36]. Thus, disasters are sudden events, such as earthquakes, tropical cyclones, or landslides. In most cases, disaster risk accumulation is slow and continuous over time and is the ultimate cumulative consequence of incremental changes resulting from day-to-day actions arising from inappropriate decisions [36,37]. These events have associated with extreme risk, and this is related to the dependence structure of the driving variables, i.e., a higher dependence between drivers can increase the risk of a compound event [38]. In this way, Lavell et al. [24] defined the risk as

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure} \quad (1)$$

Therefore, the hazard comprises the probability of a climate extreme with a potentially large impact, and thus, a change in the likelihood of the hazard directly affects the risk [25,39]. UNDRO [40] defines risk with three components: natural hazards, elements at risk (expected number of losses), and vulnerability. This recognizes that disaster events result from a series of independent components, including hazard types which vary in frequency, intensity, duration, rapidity of onset; type and number of exposed elements (assets, population, environmental features); and the vulnerability of the exposed elements arising from various physical/structural, social, economic, and environmental factors [36,40]. The 2020 Global Risk Report [41] considered extreme weather, climate action failure, and human-led environmental damage to be among the most likely risks over the next ten years. It is known that climate change (CC) leads to the occurrence of more frequent and intense EWEs (i.e., changes in weather patterns, temperature, and precipitation), which lead to extreme precipitation events, intense wind, and snowstorms, or on the other hand severe heatwaves and droughts [42,43]. These events cause widespread adverse impacts on ecosystems, people, settlements, and infrastructures, and related losses, beyond natural climate variability. However, CC impacts and risks are becoming increasingly complex and more difficult to manage. In this way, the progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits and there is growing public and political awareness of climate impacts and risks, including the adaptation of climate policies and planning processes. So, decision support tools and climate services are increasingly being used and are being implemented in different sectors [42,43].

Concerning risk management, it is an iterative process that helps organizations to define strategy, achieve objectives, and make informed decisions. Thus, it contributes to the improvement of management systems and is part of all activities associated with an organization, including interaction with stakeholders [44]. Therefore, risk management plays a decisive role in adaptation to CC and presents itself as an efficient and effective way of responding to the adverse consequences of extreme phenomena, such as the EWEs. Thus, risk management involves different main steps that include estimating the level of risk, identifying possible risk mitigation strategies, and reassessing the risk to verify mitigation strategies. Moreover, estimating the level of risk requires the process of risk assessment, which includes risk identification, risk analysis, and risk assessment [45,46].

2.2. Scope of the analysis for the disruption of overhead power lines

In the electric energy sector, risk management is present in several steps, such as energy trading, the operation and dispatch of power plants, and energy asset management, such as transmission lines and the OPL.

Thus, identifying the potential risks and their consequences is an essential task of the sector, as it allows for risk management and analysis, and then allows for better decision-making on strategies and measures to minimize these risks [47].

Risk assessment of the electricity network as an essential part of natural disaster risk management is currently an important issue. Zlateva and Velev [48] propose an approach for the risk assessment of Bulgarian electricity transmission and distribution network in case of natural disasters is proposed, based on guidelines and techniques of risk management standards ISO 31000:2009 and EN 31010:2010, and using the risk matrix. In this work, the causes of a natural hazard corresponding to a natural disaster are considered to have four levels of intensity. The results obtained from the risk assessment can support all key stakeholders to make more informed decisions – with precise decision criteria – on the effective protection of the electricity networks from natural disasters for the safety and adaptation of the electricity network and its elements.

Additionally, Reinoso et al. [18] proposed a methodology to assess the wind risk of electrical transmission towers by considering the coupling of the tower with the cables and a capacity-based failure mechanism. The results of this study showed that risk tends to vary significantly according to the location of the exposure. At the same time, the risk also varies when the transmission line is considered as a set of points rather than as a cluster, considering the variability of wind speed over distance and the possible differences between the towers in the same transmission line.

Thus, as it was mentioned above, this article aims to analyze the risk of OPL disruption caused by EWEs using an integrated approach to identify and establish the risk level. However, it is necessary to consider the tools and techniques used in the risk analysis and apply the most appropriate ones to this study to obtain useful results and conclusions. A method of combining two risk analysis tools will be proposed to realize a quantitative conclusion and minimize subjectivity. The qualitative causality analysis tool (cause-and-effect diagram) allows for the organization of the complex systems and the quantitative tool (risk matrix model) is used to determine the risk level through a combination of risk probability and severity of the consequences. The use of these tools allows the application of different methodologies and results/conclusions that complement each other [49].

An important motivation for this study was the high number of high-impact storms that affected mainland Portugal and caused damage to power lines, but there is still no analysis of them.

3. Data and methods

To build a methodology for mitigation of the disruption risk to the electricity transmission and distribution system in Portugal due to EWEs and suggest mitigation measures and strategies under current CC conditions, we first need to characterize the EWEs under consideration (section 3.1). The assessment is performed using meteorological and socioeconomic impact data, described in section 3.2. Risk assessment methodologies are then discussed in section 3.3.

3.1. Extreme weather events (EWEs)

For this study, we consider EWEs as those extreme events associated with extratropical cyclones (ECs) and accompanying fronts that may cause OPL disruption, namely strong winds, heavy precipitation, and snow or ice rain. The need to increase public awareness of extreme ECs and their impacts led that, since 2017, the names of high-impact storms that may affect Portugal, Spain, and France, which are part of the namely meteorological Southwest European Group (SW Group), have been assigned by their national meteorological services [50–53]. From the 2019–2020 and 2021 seasons, the meteorological services of Belgium and Luxembourg, respectively, joined the initiative [54,55]. The named storms can affect all five SW Group countries, simultaneously or only one of them. Additionally, these meteorological services are also in coordination with the Western European Group formed by the United Kingdom [56], Ireland [57], and the Netherlands [58]. From these datasets, 29 storms that provoked serious impacts over mainland Portugal in the four recent extended winters (2017–2021, from October to April, ONDJFMA) are selected (Table 1). In the season of 2017–2018 (from a total of 9 named storms), 6 of them had serious adverse impacts; in 2018–2019 we considered 6 from a total of 13; in 2019–2020 we analyzed 8 from 15; in 2020–2021 we selected 9 from 12. For all these storms the main characteristics were studied, with a special interest in the instant of maximum intensification – the position where the low-pressure system attains the minimum pressure.

Some of these extreme events have been extensively studied, with the synoptic characterization of high-impact storms and associated impacts in mainland Portugal, the Azores islands, and mainland Spain [5,6,59,60].

Table 1
High impact storms affecting mainland Portugal in the recent four extended winters (2017–2021), with the date for the highest impact in Portugal.

Season	Name of the storm from the *SW Group*	Date (dd/mm/yyyy UTC)
2017–18	**Ana**	December 11, 2017 00
	Carmen	January 01, 2018 06
	Emma	February 28, 2018 06
	Félix	March 11, 2018 00
	Gisele	March 14, 2018 12
	Hugo	March 23, 2018 18
2018–19	**Beatriz**	November 11, 2018 00
	Carlos	November 18, 2018 00
	Diana	November 29, 2018 12
	Gabriel	January 29, 2019 06
	Helena	February 01, 2019 12
	Laura	March 06, 2019 00
2019–20	**Cecilia**	November 22, 2019 12
	Daniel	December 16, 2019 12
	Elsa	December 19, 2019 18
	Fabien	December 21, 2019 12
	Gloria	January 18, 2020 12
	Jorge	February 29, 2020 12
	Karine	March 02, 2020 00
	Leon	March 01, 2020 06
2020–21	Alex	October 02, 2020 06
	Barbara	October 20, 2020 12
	Dora	December 04, 2020 06
	Ernest	December 07, 2020 12
	Gaetan	January 20, 2021 06
	Hortense	January 21, 2021 06
	Ignacio	January 23, 2021 12
	Karim	February 20, 2021 12
	Lola	April 23, 2021 18

3.2. Meteorological and socioeconomic impacts data

To analyze the synoptic conditions and the large-scale dynamics of the storms, the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 Reanalysis [61] meteorological parameters have been used for the Euro-Atlantic region (40°W–5°E; 30°N–50°N), namely: wind at 27 pressure levels (from 100 to 1000 hPa), mean sea level pressure (MSLP), total column water vapor (TCWV) and integrated vapor transport (IVT). These fields were extracted for the extended winter months (ONDJFMA), for the climatological period of 1991–2021, a monthly time step with a horizontal spatial resolution of 0.25° (31 km) on a latitude/longitude grid was retrieved. For the period of our study, the 2017–2021 period, fields were retrieved to the 6-hourly time steps (00, 06, 12, and 18 UTC), with the same horizontal spatial resolution (0.25° (31 km)), to analyze the large-scale conditions associated with the development of the storms. This characterization also includes the analysis of composites and their anomalies (deviations of the arithmetic means of the fields considered from the respective climatology over 1991–2020).

The weather charts [62], satellite images [63], and the climatological bulletins of the IPMA [50] were checked and analyzed to best identify the high-impact storms presented in Table 1. To account for the several impacts (mostly socioeconomic) associated with the landfall of the storms, these are identified and collected from news on media and visits to the affected places [64–74]. The information about the impacts of electrical infrastructures and overhead power lines was obtained from EDP reports [75–78].

3.3. Risk assessment

Risk assessment may be performed using several tools and techniques as identified in NP ISO 31000:2018 [44], NP 31010:2016 [79], and following the IEC/ISO 31010: 2009 [80]. Risk assessment is the overall process of risk identification, risk analysis, and risk assessment. This should be conducted in a systematic, iterative, and collaborative way, based on the knowledge and data acquired for the process. So, performing risk assessment involves several steps:

- identification of the reference situation;
- risk identification;
- risk analysis;
- risk mitigation measures and strategies.

3.3.1. Identification of the reference situation

In this study, when considering the disruption of energy infrastructure, it must be taken into consideration that mainland Portugal is frequently affected by EWEs, more specifically ECs, accompanied by heavy rain and strong wind phenomena that generate important consequences in terms of damage to structures, infrastructure, networks, and electricity lines, falling trees and, in some cases, human casualties. These events have both a geographically broad impact (usually associated with winter storms and ECs) and a potential to reach relatively small areas of the territory (extreme wind events, with localized impact, such as the occurrence of tornadoes) [81].

Thus, the reference situation is the one considering the ECs that affected mainland Portugal during the four extended winters (2017–2018 to 2020–2021), and that caused impacts on the electricity network, that is, disruption of OPL.

3.3.2. Risk identification and characterization

The purpose of risk identification is to find, recognize and describe risks that can help or prevent an institution from achieving its objectives. Therefore, it is important to have relevant, adequate, and up-to-date information to identify risks. At this stage, several techniques can be used to identify uncertainties that may affect one or more objectives, so it is important to consider the general factors and their interrelationship, which include: the tangible and intangible sources of risk; causes and events; threats, and opportunities; vulnerabilities and capabilities; changes in external and internal contexts; emerging risk indicators; the nature and value of assets and resources; the consequences and their impact on the objectives; the limitations of knowledge and reliability of information; the temporal factors; and the biased judgments, assumptions, and convictions of those involved. With the identification of risks, it should be considered that there may be more than one type of outcome and that it may result in a variety of tangible or intangible consequences [44,79,80].

Thus, risk characterization is the second step, which aims to increase knowledge of the risk factors that affect the territory (people, material goods, or the environment), identifying their location, severity of potential damage, and the probability of occurrence of the event. Hazard and risk characterization should preferably be quantitative and qualitative, descriptive, consistent with available data, and broad enough to include a range of options that allow for risk reduction [44,79,80,82].

3.3.3. Risk analysis

Risk analysis aims to understand the nature of the risk and its characteristics including, where appropriate, the level of risk. Risk analysis involves detailed consideration of uncertainties, risk sources, consequences, likelihood, events, scenarios, controls, and their effectiveness. An event can have multiple causes and consequences and may affect multiple goals. Thus, risk analysis can be carried out with varying degrees of detail and complexity, depending on the purpose of the analysis, the availability and reliability of the information, and available resources. The quality of the information used, the assumptions and exclusions considered, the limitations of the techniques, and the way they are performed also influence the risk analysis. In addition, events with high uncertainty can be difficult to quantify, which can be a problem when analyzing events with severe consequences. Thus, risk analysis provides input for risk assessment, decision-making on whether and how to address the risk, and on the most appropriate risk management strategy and methods. Finally, the results provide insights for decision-making, where choices are being made and options involve different types and levels of risk [44,79,80].

From the literature review, we found that risk management is an area of wide applicability and that there are numerous risk analysis tools. Therefore, it is necessary to choose the most appropriate tool for our work, considering the type of data we have and the type of study in question. Considering the numerous tools and techniques for risk assessment in the standard “Risk Management Techniques for Risk Assessment (ISO/IEC 31010:2009)” [79,80], we concluded that the most suitable for our case study is the cause-and-effect diagram and the consequence/probability matrix. Considering the stages of the risk assessment process, they are divided into risk identification, risk analysis (consequence, probability, and risk level), and risk assessment. The tools and techniques are classified according to their applicability in assessing risk as: Strongly Applicable, Not Applicable, and Applicable. Thus, the cause-and-effect diagram is presented as “strongly applicable” in the risk identification and risk analysis steps (only in the consequences identification step), the remaining steps are classified as “not applicable”. Regarding the consequence/probability matrix, it is presented as “strongly applicable” in the risk identification and risk analysis stages (consequence, probability, and risk level), and as “applicable” in the risk assessment stage. The quantification of risks, in the form of a matrix (risk or consequence/probability matrix) in which the probability and severity (expected damages) are considered, allows us to find the priority of the intervention (population, goods, and environment). In addition, the cause-effect diagram is also used in the risk analysis to relate the several factors that led to the risk situation [79,80,82].

So, the risk assessment process was carried out using a cause-effect diagram [44,79,80,83] and a risk matrix (or a consequence/probability matrix) [44,79,80].

•**Cause-effect diagram (Ishikawa diagram):** is a tool for identifying the root causes of quality problems and is an analysis tool that provides a systematic way of looking at the effects and causes that create or contribute to those effects, as it is also called a cause-and-effect diagram. This diagram mainly represents a model of suggestive presentation for the correlations between an event (effect) and its multiple causes. The structure provided by the diagram helps team members think in a very systematic way, and this tool helps to locate the cause of the problem [49,79,80,83–86].

This technique makes it possible to appreciate all possible scenarios and causes and establish a consensus on the most likely causes, which can then be tested empirically or by evaluating the available data. It is particularly useful to use a cause-and-effect diagram when it is needed to: identify the possible root causes for a certain problem; select and list some of the interactions between the factors that affect a given process; analyze existing problems so that corrective actions can be taken. The advantages of constructing a cause-and-effect diagram include: helping to determine the root causes of a problem using a structured approach; using an orderly and easy-to-read form to represent cause-and-effect relationships; identifying the areas where data should be collected for further study. Among the main advantages of applying this technique are the consideration of all probable scenarios, the illustration of the results in an easy-to-read form, and the identification of areas where it is essential to obtain additional data [87–89]. So, the information can be presented in a diagram, as in Fig. 1.

The cause-and-effect diagram (Ishikawa Diagram) allows the identification of dangerous situations and the interconnection between the different factors (causes) that potentiate a certain risk situation, the disruption of OPL. It is another way of contextualizing the issue and is characterized by its easy interpretation of the situation presented, the interconnection between the different causes (hazards), and the final effect (disruption of OPL). It is a qualitative scenario analysis, in which an outcome may have a set of contributing factors that can be grouped into different categories. Contributing factors are often identified in brainstorming (group discussion to identify potential failure modes and hazards, risks, decision criteria, and/or treatment options) and presented in a tree structure or fishbone diagram. In terms of the relevance of factors influencing this analysis, resources and capacity are low, as are the nature and degree of uncertainty. It also has a medium complexity level and only one qualitative result [44,79,80].

•**A risk matrix (consequence/probability matrix):** is a qualitative or semi-quantitative risk assessment technique, based on the degree of consequence (severity) and probability associated with the risk under analysis [16,49,90–97]. Depending on the scenarios chosen and the elements identified in the situation under study, the aim is to estimate the degree of severity associated with the occurrence of each scenario considered in the scope of the risk characterization [89]. In this context, the probability is defined as the potential/frequency of occurrences with negative consequences for the population, environment, and socioeconomic, and the severity is defined as the consequences of an event, expressed in terms of the scale of intensity of the negative consequences for the population, property, and environment. Associated with the degree of severity is the concept of vulnerability, which can be defined as the potential to generate casualties, as well as economic losses for citizens, companies, or organizations, as a result of a given event [82]. The criteria for defining the different degrees of severity and probability under study are described in the standards NP ISO 31000:2018 [44], ISO/IEC 31010:2009 [79], and NP EN 31010:2016 [80], in tables with the severity (consequence) and probability criteria (adapted in Tables A1 and A2 of the supplementary material). In Table A1, it is possible to verify that the high probability level corresponds to an event that is expected to occur in almost all circumstances, or that can occur once a year or more. While the medium-low probability level corresponds to an event that is unlikely to happen, or that can happen once every 100 years. As shown in Table A2, a low level of severity is an event that causes a small impact on the environment and has no lasting effects, as well as some financial loss. Concerning a critical level of severity, events are characterized by significant environmental impacts and/or permanent damage, in addition to significant socio-economic damage.

Once the respective criteria have been identified, the risks are positioned on the matrix, which allows for the identification of the associated degree of risk. Table 2 shows a symmetric matrix, with a 5-level consequence (severity) scale and a 5-level probability scale. However, the risk levels assigned to the cells will depend on the definitions of the probability/severity scales. These can be designed to give extra weight to severity or probability. This technique is often used as a screening tool, as it allows to define which risks can be analyzed further (or in more detail) and which ones need priority treatment. The use of this tool is relatively easy, providing a quick raking of risks at different levels of importance. However, the definition of scales often leads to problems of ambiguity [44,79,80,82]. Following the ranking of the degrees of severity and probability, the risks are placed on the matrix (Table 2), identifying the associated risk degree: Extreme, High, Medium, Medium Low, and Low [82]. Risk levels are usually depicted using different colors: red typically marks the unacceptable risk level, yellow or orange marks risks reduced, and green generally represents acceptable risks [90–92,98]. The level of risk identified can be used to identify the need for further assessment or appropriate risk management measures [92, 93].

The consequence/probability matrix is a way of combining the qualitative or semi-quantitative classification of consequence and probability to define a risk level or risk classification. The format of the matrix and the definitions applied to it depend on the context in which it is used, and an appropriate design for the circumstances must be used. This tool is used to classify risks, sources of risk, or treatments of risk based on the level of risk. In addition, it is also widely used to determine whether a given risk is broadly acceptable or not, according to the zone of the matrix in which it is located. A consequence/probability matrix configuration can also be used in situations where there is insufficient data for a detailed analysis or when the situation does not justify the time and effort for more quantitative analysis. The consequence/probability matrix has the advantage of being relatively easy to use and providing a quick ranking of risks at different levels of importance [44, 79,80].

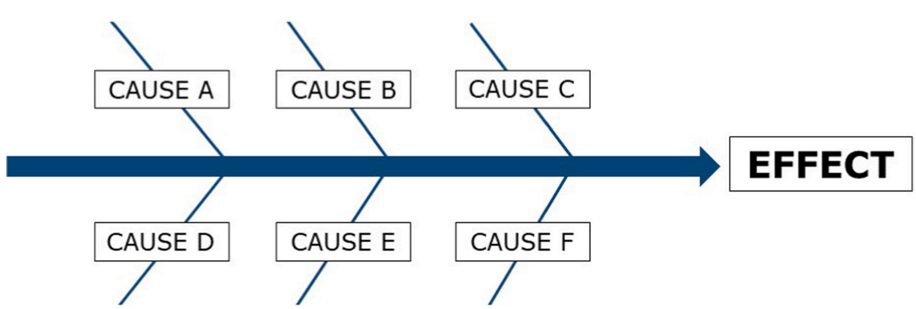

Fig. 1. Cause-effect diagram [44,79,80].

Table 2
Risk matrix (Adapted [44,79,80,82,90–92,98]).

Probability \ Severity	Residual (1)	Reduced (2)	Moderate (3)	Accentuated (4)	Critical (5)
High (5)	Medium	High	High	Extreme	Extreme
Medium-high (4)	Medium	Medium	High	Extreme	Extreme
Medium (3)	Medium Low	Medium	Medium	High	High
Medium-low (2)	Low	Medium	Medium	Medium	High
Low (1)	Low	Low	Medium Low	Medium	Medium

- **Probability computation:**

To calculate the probability (P) values (0–100%) the 5 risk levels are considered (Table A1), i.e.: level 1, $P \leq 20\%$; level 2, $20\% < P \leq 40\%$; level 3, $40\% < P \leq 60\%$, level 4, $60\% < P \leq 80\%$, and level 5, $80\% < P \leq 100\%$.

Once the levels were defined, the probability values of the risk of disruption of OPL were calculated, considering the 29 EWEs that affected Portugal in the four 2017–2021 extended winters. In the previous analysis of the damages caused by these events, it was possible to find out which and how many events caused power outages and failures in the electricity supply, that is, disruption in the OPL [75–78,99–107].

In addition, the events were classified according to three different scenarios: snowstorm events; windstorm events; compound events (i.e., wind and precipitation).

Thus, the probability of OPL disruption was calculated considering these scenarios for the first three extended winters (2017–2020) of our study period, as for the last one (2020–2021) no reliable data are yet available for mainland Portugal.

The probability (P) of OPL disruption can be expressed and calculated as:

$$P = \frac{number\ of\ events\ that\ disrupted\ OPL}{total\ number\ of\ events\ considered\ in\ the\ study} x\ 100\% \quad (2)$$

The number of events that disrupted the OPL considers the three previously defined scenarios independently. After calculating the probability values and constructing a table (see Table 3 in our case presented below in section 5.2), the levels of severity (consequence) were assigned considering the damage caused by the events under study (Table 4, section 5.2). With these tables created, the risk matrix is made, and the risk levels associated with each extreme event are studied.

3.3.4. Risk mitigation measures and strategies

The purpose of risk assessment is to support decisions and involves comparing the results of the risk analysis with the established risk criteria to determine whether additional actions, i.e., mitigation measures and strategies, are required. Thus, decisions should consider the broader context and the real and perceived consequences for external and internal stakeholders. In addition, the outcome of the risk assessment must be recorded, communicated, and then validated at the appropriate levels of the organization. The objective of risk treatment, through the action of defined measures and strategies, is to select and implement options to address the risk. This is an iterative process involving the formulation and selection of risk treatment options; the planning and implementation of risk treatment; the assessment of the effectiveness of the risk treatment; the decision on whether the residual risk is acceptable; if not, a complementary treatment is undertaken. When selecting risk treatment options, the organization should consider the values, perceptions, and potential involvement of stakeholders, as well as the most appropriate ways to communicate and consult with them. While equally effective, some risk treatments may be more acceptable to some stakeholders than others. Even with careful design and implementation, risk management may not produce the intended results and may have unintended consequences. Monitoring and review are necessary as an integral part of the implementation of risk treatment to ensure that different forms of treatment are working and remain effective. Thus, monitoring and review are intended to ensure and improve the quality and effectiveness of the design, implementation, and results of the process. Ongoing monitoring and periodic review of the risk management process and its results should be a planned part of the risk management process, with clearly defined responsibilities [44,79,80].

Therefore, after identifying and analyzing the degree of risk, the last step of risk assessment is the identification and application of measures and strategies to be implemented for risk mitigation.

Risk mitigation can be defined as "any sustained action to reduce or eliminate long-term risks to people and property, hazards and their effects". Strategies for risk mitigation include several instruments such as the implementation of measures within the scope of spatial planning; the implementation of warning and alert systems; raising public awareness; developing civil protection emergency plans; or performing training exercises and drills [22,82,89,108].

4. Occurrence of extreme weather events and their impacts on mainland Portugal

In this section, the high-impact storms that affected mainland Portugal during the four extended winters from 2017–18 to 2020–21, which caused severe damage to OPL are characterized. Of the 29 events considered in the study (named storms with a high impact on mainland Portugal), 9 of them were identified as causing damage to the energy transmission and distribution network, more specifically OPL. Additionally, other impacts caused by these storms are also identified, such as the fall of structures and trees, the occurrence of floods, cut and conditioned roads, and even displaced people. For this analysis, the highest value of wind gusts and precipitation in 24 h for each region of mainland Portugal (north, centre, and south), according to the monthly IPMA bulletins [75–78,99–107], were also considered to better understand the causes of these damages.

The synoptic and large-scale assessment for the 9 events (high-impact storms) is illustrated in Fig. 2 in the instant with the highest impact in mainland Portugal, for the fields of wind speed at 900 hPa, IVT, and TCWV. The composite for the 9 events in the left column, and the anomalies relative to the 1991–2020 period in the right column.

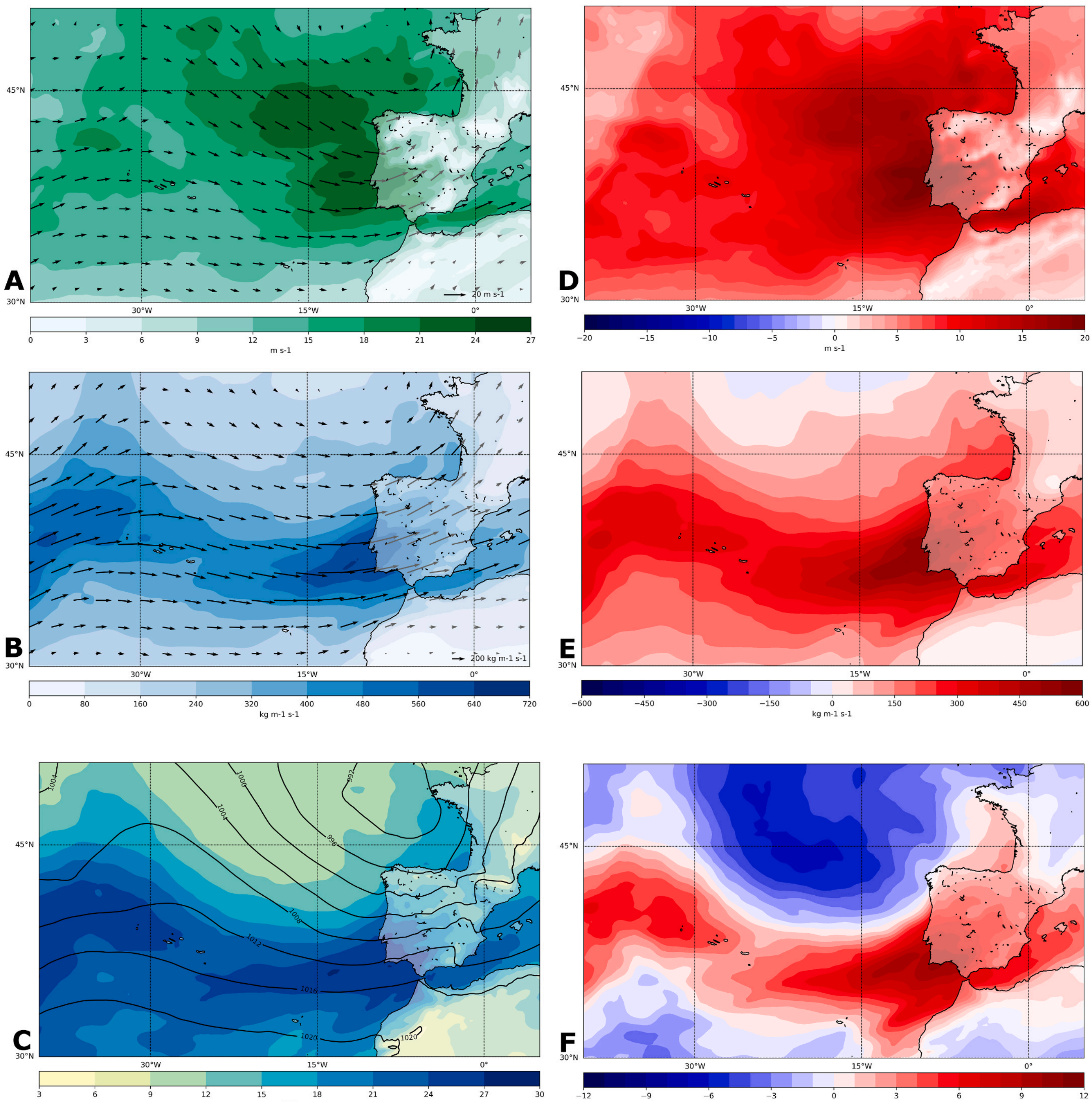

Fig. 2. Composites of the 9 storms, in the instant with the highest impact in mainland Portugal, that caused damage to overhead power lines: **A)** Wind speed (shaded; ms^{-1}) and the vector wind at 900 hPa; **B)** Integrated Vapor Transport (shaded; IVT; kg m^{-1} s^{-1}) and the vector IVT; **C)** Total Column Water Vapor (shaded; mm) and MSLP field (contour interval 4 hPa). Anomaly for the composite of 9 storms concerning extended winter months (ONDJFMA) of the period 1991–2020: **D)** Wind speed (shaded; ms^{-1}) at 900 hPa; **E)** Integrated Vapor Transport (shaded; IVT; kg m^{-1} s^{-1}); **F)** Total Column Water Vapor (shaded; mm).

Fig. 2A shows the composite of wind speed at 900 hPa, with high values (18–24 m s^{-1}) reaching mainland Portugal, with the west coast and central regions being the most affected. The anomaly (Fig. 2D) verifies that wind speed composite values are 20 m s^{-1} higher than the climatological values. The amount of moisture and water vapor associated with these storms is represented in Fig. 2B and 2. C, with the IVT (kg.ms^{-1}), the TCWV (mm), and MSLP (hPa) composites, respectively. Thus, very high values of humidity and water vapor were advected over mainland Portugal, reaching values between 580 and 720 kg ms^{-1} (Fig. 2B) and from 27 to 36 mm (Fig. 2C). These high values are also confirmed with the analysis of the anomalies (period 1991–2020) for the same variables, in which ITV anomaly values of more than 550 kg ms^{-1} (Fig. 2E) reached mainland Portugal and values of more than 10 mm of TCWV (Fig. 2F) were obtained. Therefore, these high values of wind speed and associated moisture can justify the strong impacts of these events and the damage to OPL.

These figures highlight the unusual and abnormal synoptical and large-scale conditions associated with these events during this period. During the events, recorded wind speeds are classified as level 11 (with gusts from 103 to 117 km h^{-1} [28.61–32.5 m s^{-1}]), level 12 (with speed range of 118–132 km h^{-1} [32.78–36.67 m s^{-1}]) or higher according to the Beaufort Wind Force Scale [109]. The maximum gust values recorded for the storms under study were: Ana - 144.4 km h^{-1} (40.14 m s^{-1}) in Cabo da Roca and 129.2 km h^{-1} (35.92 m s^{-1}) in Mogadouro; Emma - 117.7 km h^{-1} (32.72 m s^{-1}) in Cabo da Roca; Gisele - 110 km h^{-1} (30.58 m s^{-1}) in Ponte de Lima; Helena - 115.2 km h^{-1} (32 m s^{-1}) Guarda; Elsa - 150.1 km h^{-1} (41.73 m s^{-1}) in Pampilhosa da Serra; Fabien - 136.8 km h^{-1} (38.03 m s^{-1}) in Guarda; Gloria - 124.9 km h^{-1} (34.72 m s^{-1}) in Pampilhosa da Serra; Karine - 116.64 km h^{-1} (32.43 m s^{-1}) in Miranda do Douro and Leon recorded a high of 136 km h^{-1} (37.81 m s^{-1}) Tondela. These values thus show the intensity of the events under study and highlight that, for mainland Portugal, a threshold for extreme winds that provoked the disruption of the OPL corresponds to level 11 of the Beaufort Wind Force Scale [109], that is, values equal to or higher than 105.1 km h^{-1} (29.22 m s^{-1}).

Most of the events under study also affected Spain and the British Isles, where they caused substantial damage, such as Storm Emma and Gloria. According to reinsurance companies, the Emma storm and adverse conditions generated €84 million in insurance payouts in 2018 in Ireland [110]. In Spain, the insurance sector received more than 11, 600 claims worth €76 million due to the Gloria storm in January 2020. Total economic losses were estimated to be around €200 million, mainly in Catalonia and Valencia [111].

It is worthwhile noting that, according to IPCC [42], it is expected to substantial increase in several extreme events types, in particular, heavy precipitation and associated flooding are projected to intensify and be more frequent in several regions of Africa and Asia (high confidence), North America (medium to high confidence depending on the region), and Europe (medium confidence). Moreover, heavy precipitation associated with tropical cyclones and extratropical storms is projected to be higher at 2 °C compared to 1.5 °C global warming (medium confidence).

In addition, it is projected that the total number of tropical cyclones decreases under global warming, while the most intense (categories 4 and 5) cyclones are projected to occur more frequently. In this way, these very intense storms are projected to be associated with higher peak wind speeds and lower central pressures under 2 °C versus 1.5 °C of global warming [42]. In the study of Catto et al. [1], the results are in line with IPCC [42], where the precipitation intensity will most likely increase, along with associated increased latent heating, however, it is unclear to what extent and for which climate conditions this will feedback to increase the intensity of the cyclones.

5. Risk analysis

After the synoptic characterization of the EC, and their influence on OPL in mainland Portugal, the risk analysis is performed using two methods: Cause-and-effect analysis (Ishikawa diagram) and matrix risk (or consequence/probability).

5.1. Cause-and-effect analysis

For the situation under study, a new diagram is built to better understand the causes and effects provoked by the occurrence of an incident on the line through the verification of damage both in the structure and in the environment (Fig. 3). These damages can be due to environmental conditions, through the occurrence of EWEs, such as severe extratropical storms, which are often associated with episodes of strong wind, intense snowfall, formation of large ice sheets throughout conductors, and/or their deposition on the supports, episodes of thunderstorm originating from electrical discharges, among several others. On the other hand, changes in weather patterns can also cause system complications. One example is the decrease in the carrying capacity of the conductor caused by the increase in ambient temperature, another, is the increase in the number and intensity of forest fires during large heat waves and prolonged periods of drought. Moreover, the geographic conditions of the location where the line is installed acquire additional value when combined with other factors. Thus, the occurrence of an episode of intense precipitation combined with a place with a very steep terrain can easily lead to a landslide capable of causing damage to the respective supports, and, subsequently, the disruption of OPL.

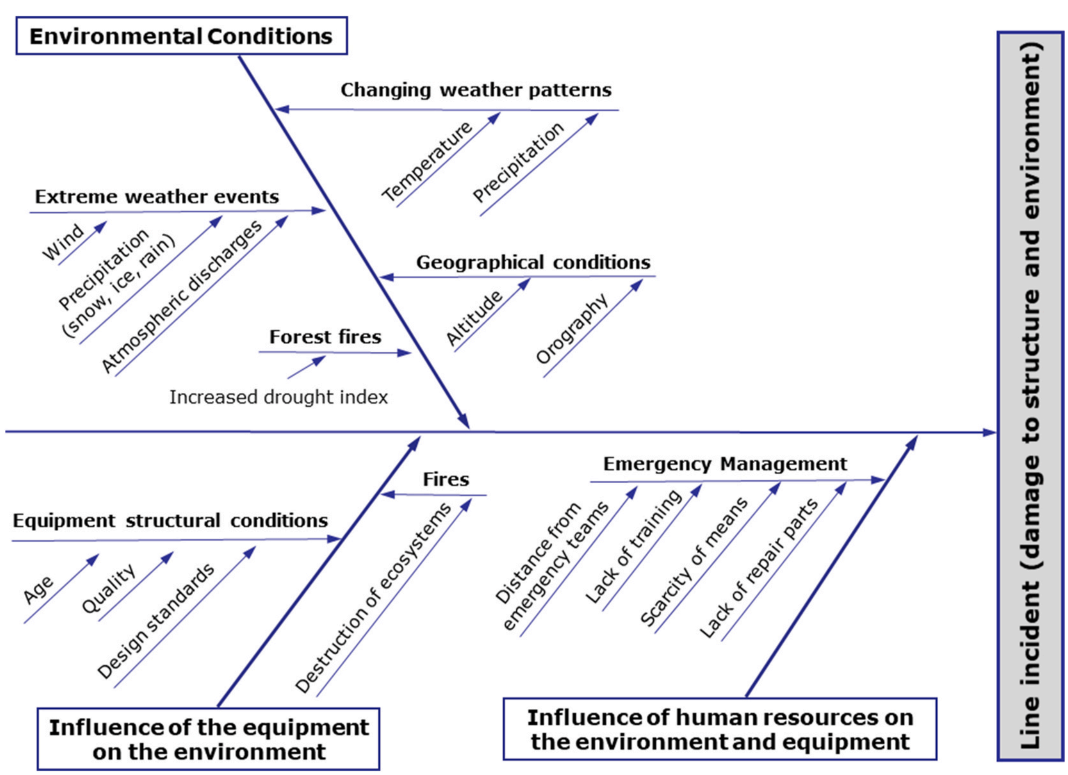

Fig. 3. Ishikawa diagram relating to the risk analysis understudy.

The structural conditions of the equipment are highly influenced by their age, the quality of the materials they are made of, and the values considered in the design project. This, together with the lack of vegetation maintenance, is one of the main causes of disruption of OPL, due to strong winds and intense precipitation. In the case of failure, the subsequent fall of the line could lead to an ignition capable of causing a forest fire which, among several other constraints, will inevitably lead to the destruction of ecosystems.

Furthermore, all the above aspects may be aggravated by failures in the emergency management process. This can be hampered by the distance of the teams and the difficulty of access to the affected places due to obstructed roads, resulting in increased response time, lack of training, inadequate training, lack of operational resources, and possible lack of spare parts and repair.

In this way and by analyzing the different factors, it is possible to relate the causes (factors) that influence and affect the state of OPL. This diagram allows a quick interconnection of factors, which leads to the final effect, the risk of disruption of OPL.

This diagram sets out a number of factors that despite not having had a direct impact when the EWEs understudy took place, may have already been risked factors in the places and on the OPL in question. Examples of this are the increase in temperature and forest fires, which occur more in the hot summer season, however, they can leave marks and damage that will have effects during the winter, combined with extreme weather conditions such as strong winds and heavy precipitation.

Thus, the risk analysis through this diagram and the consequent schematic representation (diagram, Fig. 3) allows a better interpretation of the study in progress. It can be seen as a summary of the study, that is, it allows knowledge of the topic, relating the research questions, as well as the connection between the various factors that cause the disruption of OPL in Portugal. Therefore, it is possible to carry out a qualitative quick risk analysis and manage them with the identification of mitigation measures and strategies.

However, this study only focuses on the impacts of EWEs (EC and high-impact storms) that affected mainland Portugal and which caused the OPL disruption. So, Fig. 4 presents the specific diagram of the EWEs and the causes identified in this study that led to the OPL disruption. Thus, windstorms, with extreme gusts, cause trees to fall on OPL, which are one of the main causes of disruption, as well as damage to electrical infrastructure. At the same time, floods and landslides associated with heavy rainfall in unstable areas also disrupt the OPL, in addition to making electrical infrastructure more vulnerable to future damage events. Moreover, when snowstorms occur with ice accumulating in OPLs, the risk of disruption is higher. Furthermore, atmospheric discharges, with lightning on electrical infrastructures or fires caused by them, which can occur during extreme events are thus an important cause of the disruption of OPL. In this way, it is possible to identify the main causes of OPL disruption with the passage of EWEs, which resulted in power cuts that affected countless people across the country caused by significant damage to high and medium voltage posts, and the fall of OPL.

Thus, all the factors indicated in Figs. 3 and 4 when combined represent serious risks for OPL, requiring their analysis and intervention by those responsible for each sector, to minimize the risk of disruption of OPL caused by EWEs.

5.2. Risk matrix analysis

The second method used for risk analysis is the probability/consequence matrix, with information from the storms that directly affected mainland Portugal in the recent winters, and distinguishing the storms that caused damage to OPL, through the collection of damage data in official reports.

For the analysis through the risk matrix, the probability values are calculated and presented. So, Table 3 presents the values of the probability of the events that disrupted OPL. As explained in section 3.3.3, the events considered for this study are classified into 3 scenarios, snowstorms, windstorms, and compound events (with wind and precipitation). After calculating the probability values of disruption, the levels of severity (consequences) are identified, as it is shown in Table 4. That said, the risk matrix is built, associating the levels of probability and levels of severity (consequence) of the events under study, previously calculated and identified.

In a first assessment, the 29 storms with a high impact on mainland Portugal in the recent four extended winters (2017–2021) were considered, among which 9 storms caused damage to OPL, representing the 31% of the storms understudy.

Of these 9 storms (in 29 storms) understudy, one was considered a snowstorm (Emma: 1/29, i.e., 3%), and 8 storms were considered windstorms (Ana, Gisele, Helena, Elsa, Fabien, Gloria, Karine, and Leon: 8/29, i.e., 28%). When considering the 8 identified windstorms, 6 storms were characterized by compound events - wind and rain - (Ana, Gisele, Elsa, Fabien, Karine, Leon: 6/8, i.e., 75% or 6/29, i.e., 21%, of the storms had wind and rain in their development). The other 2 storms were characterized only by the wind (Helena and Gloria: 2/8, i.e., 25% or 2/29, i.e., 7% of the storms had the wind in their development).

This analysis is based on probability calculations presented in Table 3 and the severity level (Table 4) is identified through the impacts associated with each storm and based on severity levels in table S2. These results are then synthesized in the risk matrix (Fig. 5) with each probability and severity associated with each storm, and the respective caption of risk levels (colors).

The Helena and Gloria storms are considered twice in the risk matrix, as the risk is assessed considering that it is characterized as a compound

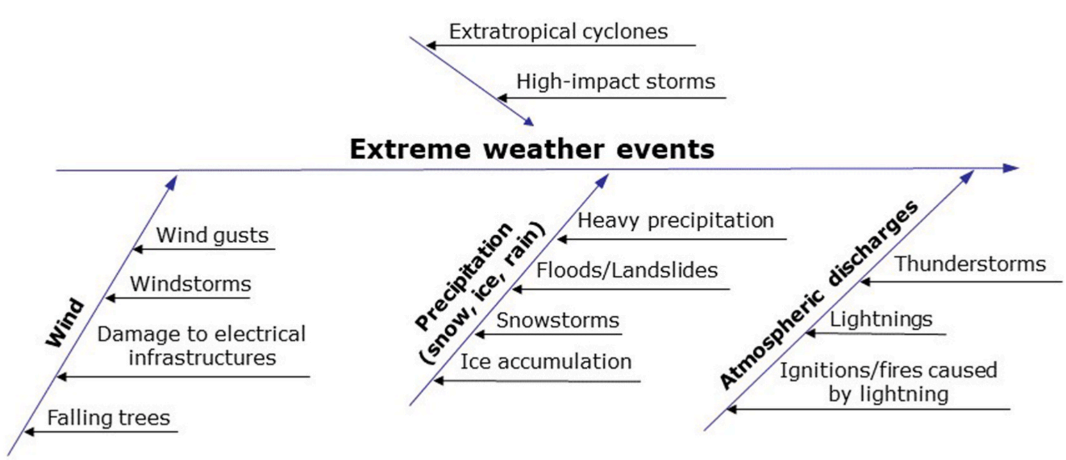

Fig. 4. Ishikawa diagram relating to the risk analysis understudy – Extreme weather events.

Table 3
Probability results for each storm analyzed in the study. The * identifies the only snowstorm. A total of 29 storms is considered.

	Probability				
Risk level	1	2	3	4	5
Frequency (%)	< 20	20-40	41-60	61-80	81-100
	Emma (E1) *	Ana (A)			
	Helena (H)	Gisele (G1)			
	Gloria (G2)	Helena (H)			
		Elsa (E2)			
		Fabien (F)			
		Gloria (G2)			
		Karine (K)			
		Leon (L)			

Table 4
Severity results for each high-impact storm analyzed in the study. The * identifies the only snowstorm. A total of 29 storms is considered.

Impact \ Risk level	Severity				
	1	2	3	4	5
		Gisele (G1)	Ana (A)	Emma (E1) *	
		Helena (H)	Gloria (G2)	Elsa (E2)	
			Karine (K)	Fabien (F)	
			Leon (L)		

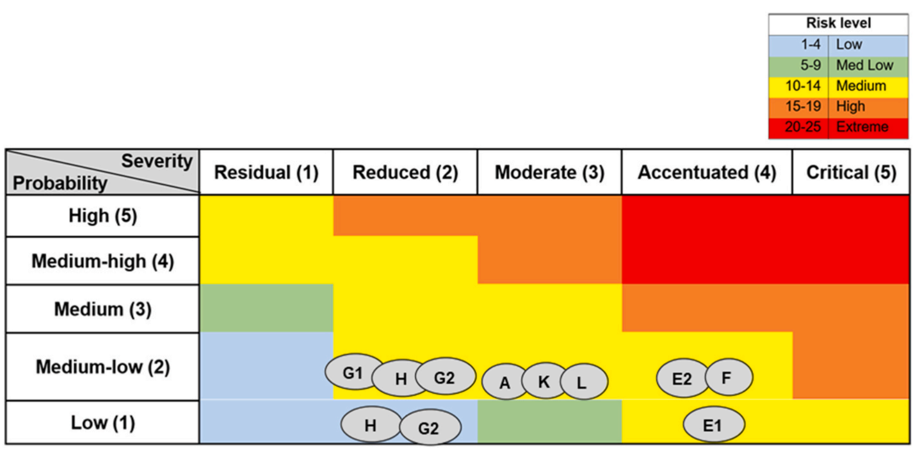

Fig. 5. Risk matrix of high-impact storms analyzed in the study. The risk level caption is shown in the box above. Emma (E1) storm corresponds to the only snowstorm considered.

event (wind and rain in their development) and only a windstorm event. These results are assessed for a different period, only 3 extended winters in which the 9 storms that caused damage to OPL occurred, therefore considering 20 storms. In this case, the risk matrix is the same, despite the values of likelihood being higher and different. In this way, of the 9 storms (in 20 storms) understudy, one was considered a snowstorm (Emma: 1/20, i.e., 5%), and 8 storms were considered windstorms (Ana, Gisele, Helena, Elsa, Fabien, Gloria, Karine, and Leon: 8/20, i.e., 40%). Of the 8 identified windstorms, 6 storms were characterized by compound events (wind and rain) (Ana, Gisele, Elsa, Fabien, Karine, Leon: 6/8, i.e., 75% or 6/20, i.e., 30%, of the storms had wind and rain in their development). The other 2 storms were characterized only by the wind (Helena and Gloria: 2/8, i.e., 25% or 2/20, i.e., 10% of the storms had the wind in their development).

Thus, the obtained results show that the probability of occurrence of disruption on OPL due to windstorms was 28% when considering the analysis of four extended winters (29 events). When considering only the winters with damages to the OPL (20 events), it is verified that 40% of the analyzed storms had windstorms associated. On the other hand, the probability of occurrence of events accompanied by compound events (wind and rain) with damage to OPL is 21% (considering 29 events) and 30% (considering 20 events). Moreover, the probability of occurrence of disruption associated with a snowstorm is 3% (considering 29 events) and 5% (considering 20 events).

Therefore, it is possible to conclude that, in Portugal, the wind is the main factor that provoked the disruption of the OPL, in the considered winters, and that the compound events (wind and rain) had a higher impact on these damages.

When analyzing the risk matrix (Fig. 5), it can be verified that the Elsa and Fabien storms, with a risk value between 10 and 14, were those that presented the highest risk, having been classified as "Medium Risk". Despite the Emma storm presents also a "Medium risk", the probability of occurrence is "low", but it had "accentuated" and significant consequences that adversely provoked numerous socioeconomic damages during its development and passage.

These results show that with a severity level of "accentuated", a probability level of "medium-low", and the risk level is "medium" these events can provoke impacts with long-term effects on the environment and important socioeconomic damage, with partial community functioning with some services unavailable and significant loss and necessary financial assistance.

With the risk analysis performed through the consequence/probability matrix, it is possible to obtain quick conclusions and better communicate risk to populations because it is a graphical representation of easy interpretation. In other words, this is one of the objectives of the present study, to verify the impact of EWEs on OPL and characterize and quantify the risk associated with each one.

In general, the 9 extreme events that affected mainland Portugal and caused disruption in the OPL, present a "Medium Risk" level, however, the type of consequences and the effects caused is what differentiates them.

5.3. Adaptation strategy and recommendations for risk management

Once the risk analysis is completed, it is important to define the strategy for adapting to climate change and the occurrence of EWEs with impact on OPL, as well as define a set of recommendations and measures capable of boosting the network's resilience.

The implementation of measures to improve the network is capable of significantly increasing the resilience of OPL, which can act both in terms of mitigation and adaptation. These measures seek to answer two questions, on the one hand, the reduction in the magnitude of the immediate impact caused by EWEs and, on the other, the restoration of the network's functionality as quickly as possible after the occurrence of such an event. A similarity can also be made between the mitigation process and the improvement of the physical resistance of the network, and the process of adaptation of the network and its operational capacity [22,89,108,112–114].

Thus, Table 5 presents some identified strategies to promote the resilience of power networks, and these can be divided into two points: physical strength and operational capacity. The first includes measures related to vegetation management, physical revitalization and upgrade, and other measures related to the physical infrastructures. The second includes measures aimed at the operation of the system, that is, linked to emergency generators and mobile substations, the network monitoring system, among others. These strategies to improve the resilience of power lines must be defined and applied considering the factors that were mentioned throughout the study, more specifically in the diagrams (Figs. 3 and 4). Thus, it is necessary to define the action plans/strategies considering the weather conditions that act on the OPL, allied to their geographical location and physical structure of the OPL.

On the other hand, it is necessary to adapt the emergency systems (human resources) for the occurrence of these EWEs that cause significant damage to these systems and affect many people (cutting the electricity supply), but also the environment (such as falling trees, and habitat destruction). Once the measures are defined and applied, it is important to verify whether they are more appropriate for the type of situation in question.

Thus, the rise of the EWEs severity enforces the modification and upgrade of the current design and engineering standards, as well as the operation and maintenance procedures. Consequently, the multi-events assessment must be considered to achieve the most effective and efficient solutions, however, this implementation of network resilience enhancement strategies requires large investments to improve the network capability. On the other hand, a fragile grid may turn into a huge economic loss due to failures in network functionality. In this context, optimal selection of the enhancement strategies is required based on cost/benefit analysis [20,22,108,115].

Table 5
Strategies for improving network resilience.

Type of training	Improvement strategy
Physical robustness	Vegetation management
	Partial burial
	Revitalization and physical update
	Substation replacement and line rerouting
Operational capacity	Emergency generators and mobile substations
	Repair parts and restoration teams' management
	Network monitoring system
	Regulation and update of regulated design standards

6. Concluding remarks

EWEs, such as high-impact storms studied in this work, are associated with numerous socioeconomic impacts caused by strong winds, heavy precipitation, ice, and snow as it is the disruption of OPL, which is also mentioned in some previous studies [6,14,15,17,19] for different regions worldwide. Of the 29 events that affected mainland Portugal with high impact in the four extended winters (2017–2021), 31% of the events disrupted OPL. With this study, it is possible to confirm that the strong winds corresponding to level 11 of the Beaufort Wind Force Scale, that is, values equal to or higher than 105.1 km h^{-1} (29.22 m s^{-1}) are the main factor that provoked the disruption of the OPL and that the compound events (wind and rain) had a higher impact on this type of damage.

Through the analysis of the risk matrix, it is possible to conclude that Elsa and Fabien storms, with a risk value between 10 and 14, were those that presented the highest risk, having been classified as "Medium Risk". Despite the Emma storm presents also a "Medium Risk", with the probability of occurrence "low", it had "accentuated" and significant consequences that affected millions of people during its development and passage. Although these events present a level of risk considered "medium", some impacts with long-term effects on the environment and significant socioeconomic impacts (significant loss and necessary financial assistance) occurred. This is particularly important when we acknowledge that Portugal is one of the most vulnerable countries to climate change [42] and that more frequent and more extreme ECs are expected to occur in the future [1,42].

Moreover, measures and mitigation strategies for the impacts of these events on OPL were identified. The various improvement strategies presented are based on the physical robustness and operational capacity of the network, to reduce the magnitude of impacts, thus aiming at improving the operational capacity and reducing its restoration time. Among the main strategic measures, the management of vegetation, partial burial, revitalization and updating and replacement of the line, network monitoring, and preparation of repair teams, among several others, stand out. The network's resilience framework includes resilience assessment, quantification, and enhancement, thus covering all major aspects. In this way, it is important to minimize the impacts of these EWEs and to do an optimal selection of the enhancement strategies based on cost/benefit analysis to be adequate for each case (OPL, in this case).

In addition, these strategies must be adapted and revised considering the advance of climate change and thus minimize the impacts on power systems and infrastructure.

This work is the first systematic study for the analysis of the environmental risk of the disruption of OPL. Despite the scarce data obtained we were able to elaborate a simple but relevant analysis of the risk of disruption of the OPL caused by the EWEs. In this way, we consider that the applied methodology (cause-effect diagram and the consequence/probability matrix) allowed a clear understanding of the effects, the connection of different factors, and quick and objective conclusions. The

EWEs that affect Portugal head towards Spain and France causing similar damages to a greater or lesser extent depending on the events and regions affected. In other words, these events also disrupt power lines in these countries, as can be seen from the media [116–123] that report the damage caused, more specifically the indication that there was a power outage and cuts in the electricity supply, which affected countless consumers. However, to the best of our knowledge and from the bibliographic research carried out until the moment, no information or similar studies were found for Portugal, Spain, or France, to allow us to compare these results and the applied methodology.

Thus, we can consider this study as a pioneer, in the analysis of the risk of disruption of the OPL caused by the most recent extreme events that have affected Portugal. So, this study presents evidence of the cause and effect between the EWEs and the disruption of the OPL in Portugal. This is extremely relevant when it is expected that, in near future, more frequent and more extreme storms will affect populated areas. It is also important to highlight that the occurrence of 29 high-impact storms in four winters is uncommon in Portugal [3-4,124], and for that, it is a unique work for Portugal and the whole situation in question is unique and different from other studies and countries analyzed in the literature. Therefore, this study may also contribute to future new theoretical studies by justifying the need to develop adaptation methodologies and/or the need to apply new materials to OPL infrastructures giving more resilience to EWEs in Portugal. Additionally, this study justifies the need to develop new managerial approaches to adapt OPL infrastructures to EWEs in Portugal.

However, in this study, an important limitation needs to be considered. The scarcity of data only allowed us to verify how many storms caused failures/cuts in the electricity supply to consumers, caused by the disruption of OPL. Thus, the data we have is the occurrence of disruption of electricity lines in Portugal, in the most affected districts/localities, and the number of customers who were affected by the disruption of OPL. This is a study that was made with a short period of data that we were able to obtain, as it is expected to continue the work from an environmental risk analysis perspective. Furthermore, the Portuguese electricity grid is very heterogeneous. This is an excellent suggestion for a future, more localized study, where it might be possible to normalize the probability values per km. year, per smaller region/locality. However, despite our efforts, until now, we do not have access to this critical data from the energy sector, which prevents us to go into further detailed analysis. In this way, we must keep our study with public information. Moreover, we expect this study highlights the need for and importance of further developing collaboration between energy enterprises and academia, in Portugal.

Under current CC conditions, policymakers in countries like Portugal need to be aware that infrastructures are already subject to such new challenges. This may be generalized to other countries, such as Portugal, where these EWEs were not so common until now.

In other words, we must consider the meteorological conditions, the constituent materials of the OPL, and all electrical infrastructures, as well as the strategic management for the occurrence of EWEs for the Portuguese case study. In addition, it is also necessary to review the strategic management of these events and the measures and strategies of operation, to minimize the impacts caused by these EWEs. The elaboration of these studies is extremely important for companies in the energy sector and infrastructure, to adapt projects to the worst situations, such as extreme wind speeds that affect OPL, and the maximum limits that they can withstand.

Finally, since the energy sector is one of the most affected by CC and the associated increase in extreme weather and climate events, it is important to consider this type of study and approaches to monitor the progress of CC and the impacts caused on power systems, as well as to adapt and implement strategies to minimize the damage to the energy sector and all associated infrastructure. Moreover, the application of risk analysis and assessment methodologies, as well as risk mitigation and resilience measures and strategies of electrical networks, can be generalized and applied to other electrical energy infrastructures and other types of case studies such as the impacts on the production of wind and hydroelectric power.

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Author contributions

Ana Gonçalves: Conceptualization, Methodology, Investigation, Writing-Original Draft; Margarida Correia Marques: Conceptualization, Methodology, Validation, Supervision, Project Administration; Sílvia Loureiro: Writing-Review&Editing, Methodology; Raquel Nieto: Writing-Review&Editing; Margarida Lopes Rodrigues Liberato: Conceptualization, Methodology, Validation, Writing-Review&Editing, Supervision, Project Administration. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

The authors are unable or have chosen not to specify which data has been used.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.125583.

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Sustainable Energy Research

REVIEW **Open Access**

Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures

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Abstract

Energy systems (ES) are seriously affected by climate variability since energy demand and supply are dependent on atmospheric conditions at several time scales and by the impact of severe extreme weather events (EWEs). EWEs affect ES and can cause partial or total blackouts due to energy supply disruptions. These events significantly impact essential infrastructures and are considered one of the main causes of wide-area electrical disturbances worldwide. A comprehensive review is carried out based on 210 published studies using searches from Scopus and Google Scholar databases, to assess the impacts of EWEs—such as extreme storms, wind, and lightning events, heat, or cold waves, and freezing—on ES and their associated infrastructures—production, transmission, and distribution—worldwide, with a particular focus on wind energy systems (WES). Strategies and measures are critically reviewed and synthesized to minimize and mitigate the impact of EWEs, protect, and adapt the systems to maintain regular operations even when these events occur. Finally, physical modifications to systems and the incorporation of new technological solutions such as energy storage systems (ESS), distributed energy systems (DES), and microgrids, can enhance the network resilience and mitigate the EWEs effects.

Highlights

- Extreme weather events (EWEs) have a major impact on energy systems (ES).
- Wind energy systems are particularly affected by EWEs.
- Measures and new solutions are needed to minimize the impacts of EWEs on the ES.
- ES need to be adapted to maintain normal operation during the occurrence of EWEs.
- EWEs are now a great challenge to researchers and engineers.

Keywords Energy sector, Renewable energy, Wind energy, Severe cyclones, Windstorms, Resilience measures

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Introduction

Energy systems (ES)—that is, infrastructures for electricity production, transmission, and distribution—are exposed to natural disasters and extreme weather events (EWEs), such as tropical and extratropical cyclones, windstorms, floods, landslides, lightning, and earthquakes (Waseem & Manshadi, 2020; Hewitt, 1983; Peduzzi, 2019). Heatwaves, droughts, and wildfires may also cause damage to ES and all associated infrastructures. These events foremost affect the physical components of the systems (Bompard et al., 2013; Brás et al., 2023; Jasiunas et al., 2021) and lead to heavy socioeconomic impacts on vulnerable populations (Gonçalves et al., 2023; Liberato, 2014; Otto et al., 2020; Stojanovic et al., 2021; Zscheischler et al., 2020). ES, which include the design and operation of energy infrastructures such as production and distribution systems, are called energy-critical infrastructures. These infrastructures are crucial for vital societal functions, including the health, safety, security, economic and social well-being of people (Kyriakides & Polycarpou, 2015; Mikellidou et al., 2018; Nik et al., 2021). Therefore, the energy supply sector includes all energy extraction, conversion, storage, transmission, and distribution processes (Bruckner et al., 2014; Martinez et al., 2019; Qazi, 2017).

Extreme weather events (EWEs) are rare occurrences that deviate from normal weather patterns in frequency and intensity. These events typically fall within or exceed the statistical rarity thresholds, ranking at or beyond the 10th or 90th percentile on a probability density function derived from observed data. When an extended period of extreme weather lasts, spanning a whole season, it might be categorized as an extreme climate event, particularly if it results in notably high or low average or total (IPCC, 2022a; McPhillips et al., 2018). Thus, certain climate extremes, such as droughts or floods, may result from multiple non-extreme weather or climate events accumulating over time, leading to extreme conditions (Leonard et al., 2014). Additionally, weather or climate events, even if not considered extreme based on statistical measures, can cause severe conditions or consequences. This could happen by surpassing a crucial limit within a societal, ecological, or physical system or by co-occurring with other events (IPCC, 2018). Furthermore, there is an understanding that climate change results in an increased occurrence and intensity of EWEs, which include extreme precipitation events, strong winds, and snowstorms, as well as intense heatwaves and droughts. These events cause extensive adverse effects on ecosystems, populations, and infrastructure, leading to consequential damage that goes beyond that attributed to natural climate variability (IPCC, 2018, 2022b). Consequently, an increase in EWEs can have a direct impact on energy demand in key end-use sectors (Damm et al., 2017; IEA, 2022; Panteli & Macarella, 2015) and affect the energy systems (ES) in the most vulnerable areas (Mikellidou et al., 2018; Otto et al., 2020; Panteli & Macarella, 2015). ES are severely affected by EWEs, which are considered a serious risk for the energy sector and its facilities—implications for the reliability and performance, and the resilience of energy supply systems (Brás et al., 2023; Gonçalves et al., 2023, and references therein, Panteli & Macarella, 2015; Holtinger et al., 2019; Perera et al., 2020) but also in the sectors of production, transmission, distribution infrastructures (Waseem & Manshadi, 2020), and other economic sectors that depend on the energy supply. Moreover, EWEs can also have implications for the reliability and performance of renewable, such as wind energy systems (WES), and non-renewable energy systems (Cronin et al., 2018; Perera et al., 2020; Schaeffer et al., 2012).

Acknowledging the growing occurrence and impact of EWEs in the energy sector, the present paper aims to assess and systematize the impacts caused by extremes of the different atmospheric parameters on energy systems (such as thermal and solar power plants, hydropower plants, power grids), the impacts of these events on energy production systems, on power transmission and distribution systems worldwide. Additionally, this study focuses particularly on wind energy systems through a comprehensive review of the effect of EWE on wind resources and wind technology. Furthermore, a review of measures and recommendations for the mitigation of impacts on energy storage systems, distributed energy systems, and smart grids and microgrids is presented. Adaptation measures and new strategies to mitigate the impacts of extreme events and to maintain the normal operation of the systems and associated infrastructures are described and finally, conclusions are drawn. Thus, the main novelty of this study, in comparison with existing literature, is the fact that it presents a comprehensive review of the impacts of extreme events on different energy systems worldwide, with a special focus on wind energy systems, together with the identification and analysis of measures and solutions that allow to minimize those impacts and increase the resilience of systems to these events.

This study proceeds in the following order: (i) to assess the real impact of the EWEs on ES worldwide; (ii) to focus particularly on the WES; (iii) to identify and assess the need to adapt the WES systems to maintain their normal operation and the stability of the network, even during the occurrence of EWEs; and (iv) to critically review and suggest measures and solutions to minimize the impacts of EWEs on the systems. Therefore, the article's structure is as follows: the background is presented in section two;

section three describes the data and methods used to perform this review. Section four identifies and evaluates EWEs and their impacts on energy systems. In section five the impacts on WES are specifically assessed. Section six analyzes and synthetizes the strategies, measures, and solutions. The results and conclusions are presented in the final section.

Background

Energy systems are heavily impacted by climate variability since the energy availability and supply are dependent on atmospheric conditions (Gonçalves et al., 2021; Jerez & Trigo, 2013; Liberato, 2014; Staffell & Pfenninger, 2018; Trigo et al., 2004) and/or climate change impacts (Damm et al., 2017; Devis et al., 2018; Jasiunas et al., 2021; Lledo et al., 2019; Otto et al., 2020; Santos et al., 2015; Tobin et al., 2016). ES are susceptible to diverse types of events, including EWEs, natural hazards, and climate change as summarized in Fig. 1.

The concept of vulnerability is used to measure the challenges a system faces in supporting its function during and after an unwanted event (Doorman et al., 2006; Sperstad et al., 2020). Power system vulnerability consists of two aspects: susceptibility to threats and the system's ability to cope with such events. It involves the power system operator's technical, human, and organizational factors (Sperstad et al., 2020). Several types of vulnerability, such as in power generation infrastructure, transmission, distribution, and supply chains, are studied by Schweikert and Deinert (2021).

Abedi et al. (2019) further define the concept of vulnerability by dividing it into physical vulnerability, systemic vulnerability, systemic and physical, and measurement-based assessments. These authors discussed vulnerability analysis methods, differentiating between analytical and simulated approaches. Analytical methods provide accurate solutions for simplified problems and are efficient for evaluating similar systems. Simulations, like Monte Carlo methods, generate accurate solutions to more complex, real-world problems, particularly when deriving equations becomes challenging. While analytical methods rely on mathematical solutions for simplified models, simulations replicate actual system behaviors, becoming the preferred choice as systems become more complex (Abedi et al., 2019, and references therein). Moreover, the authors detailed various vulnerability analysis approaches, dividing them into two primary categories: analytical methods and Monte Carlo simulations. The analytical methods include complex network methods (pure complex network method and extended complex networks methods), flow-based methods (deterministic flow-based approach and probabilistic flow-based approach), logical methods (game theory and hierarchical method), functional methods (agent-based

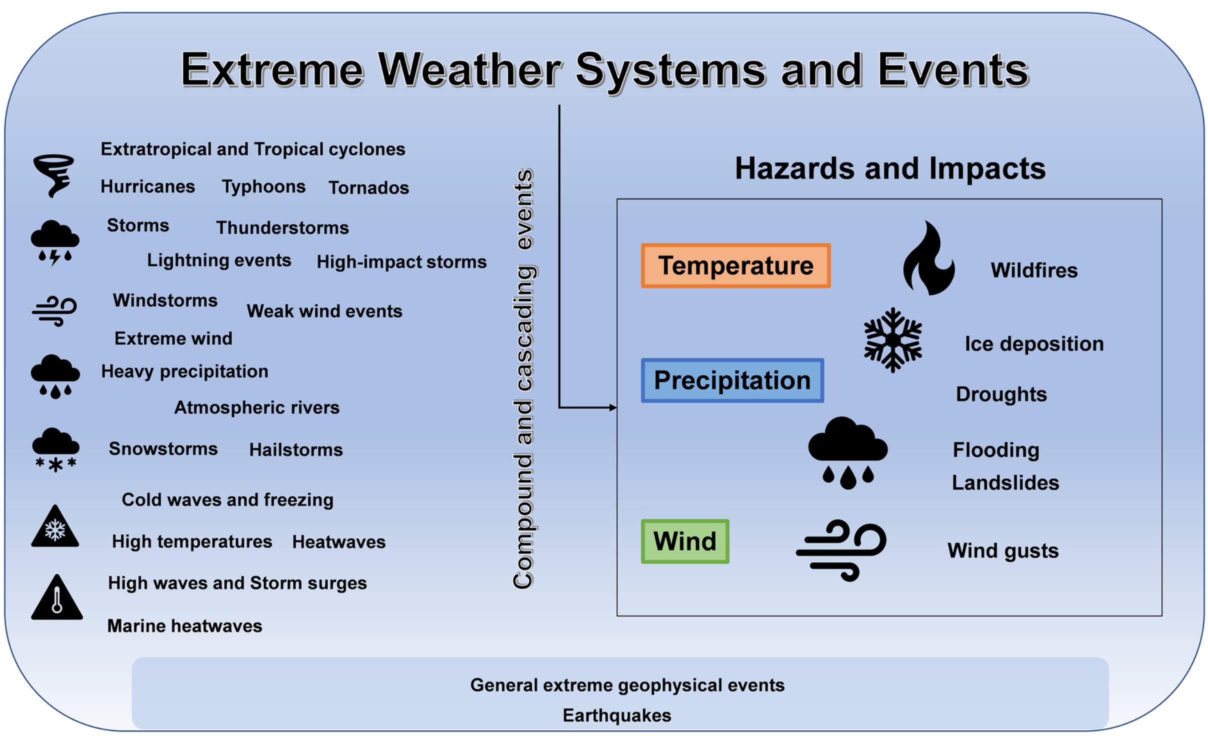

Fig. 1 Extreme weather systems and events that impact energy systems

modeling, dynamic modeling, and multi-objective optimization) (Abedi et al., 2019, and references therein).

The assessment of electrical grid component vulnerability under extreme weather and climate conditions is also considered in the work of Dumas et al. (2019). The authors investigated the impact of extreme weather and climate conditions on different electrical grid components. They identify hazards like temperature changes, water availability issues, storms, flooding, wind pattern variations, and other extreme events such as wildfires. These hazards are assessed within the context of electricity generation, transmission, distribution, and demand. The study employs engineering approaches, including fragility curves, damage functions, and dose–response functions, to evaluate the vulnerability of grid components to environmental threats. Fragility curves and damage functions predict the probability of system or component failure in response to a single extreme event, while dose–response functions quantify how a component reacts to climate stress exposure. These tools help energy planners quantify the climate vulnerabilities of their assets, enabling better risk assessment and mitigation.

In this sense, the rise of power outages caused by EWEs has led to the study of system and grid resilience (Brás et al., 2023; Chen et al., 2022; Dumas et al., 2019; Gonçalves et al., 2023). Resilience refers to a network's ability to rapidly recover from disturbances (Holling, 1973). Energy system resilience depends on the occurrence of severe weather incidents and includes the system's capacity to predict, tolerate, restore, and respond to challenges (Gosh & De, 2022; Panteli & Mancarella, 2015). Various organizations and researchers define resilience with characteristics such as resourcefulness, robustness, adaptability, and rapid recovery, and other features associated with resilience include redundancy, capacity, flexibility, and tolerance (Mahzarnia et al., 2020 and references therein). Standardized definitions, metrics, and evaluation methods for resilience are being developed, and research is ongoing to address gaps and challenges (Bhusal et al., 2020; Bie et al., 2015, 2017). Grid resilience involves anticipating, absorbing, restoring, and adapting to impacts caused by EWEs, to return the grid to normal operation swiftly (Hossain et al., 2021; Jufri et al., 2019). Therefore, developing strategies to enhance ES and grid resilience is crucial for power system planning and operation, considering the significant impact of EWEs on power supply reliability and socioeconomic factors (Bhusal et al., 2020; Jufri et al., 2019; Panteli & Macarella, 2015; Panteli et al., 2017).

Although diverse types of systems are examined, the main emphasis is on renewable energy systems, specifically on wind energy systems (WES), which are particularly vulnerable to the impacts of climate change and the increasing frequency of EWEs (Fernández-Alvarez et al., 2023; IPCC, 2022b; Nogueira et al., 2019; Tobin et al., 2018). Wind resources are extremely sensitive and dependent on weather conditions (Davy et al., 2018; Gonçalves et al., 2021; Ravestein et al., 2018) since wind energy depends on the cube of the wind speed. The changes in the intensity and frequency of extratropical cyclones (Catto et al., 2019; Karremann et al., 2016), for example, can result in varying frequencies of calm or strong wind periods, leading to fluctuations in electricity production (Costoya et al., 2022; Gonçalves et al., 2021; Moemken et al., 2018). Moreover, wind energy is currently experiencing the highest growth rate among renewable energy sources and is projected to have the largest installed capacity by 2030 (IEA, 2022; WindEurope, 2023).

Thus, EWEs pose significant challenges to the secure and reliable operation of energy systems (thermoelectric production technologies) (Panteli & Mancarella, 2015; Zhou et al., 2023), especially renewable energy systems (RES), such as hydroelectricity, photovoltaic, and wind energy systems (Sims et al., 2011; Panteli & Mancarella, 2015; Zhang et al., 2019; Zhou et al., 2023).

In this sense, measures and solutions are needed to adapt these systems and to minimize their impacts which are analyzed in the following sections.

Data and methods

A comprehensive and objective analysis of the current knowledge on the research question "The impacts of extreme weather events on energy systems" is carried out in this article using an interdisciplinary approach. This type of review focuses on contextualization and interpretation, presenting a broad overview and critical analysis of the literature within a subject area, with a more qualitative synthesis of information (Cronin et al., 2008; Grant & Booth, 2009; Green et al., 2006; Machi & McEvoy, 2016; Onwuegbuzie & Frels, 2016). This comprehensive literature review follows the next steps:

- Definition of the research question/objective and selection of the topic: define and narrow the research topic or question; clarify the scope and objectives of the review to guide the literature search.
- Literature search/research strategy and information collection: develop a comprehensive search strategy using relevant keywords and terms; explore multiple reliable sources (databases, journals, books) to gather literature.
- Selection criteria: establish criteria for including or excluding sources based on relevance, publication date, and research quality.

- Screening and selection: review and select collected literature to identify relevant articles, studies, and sources; delete irrelevant material that does not contribute to the review's focus.
- Data extraction: extract key information from selected literature, including key ideas, methodologies, and key findings.
- Synthesis and analysis: analyze and synthesize extracted information to identify patterns, themes, or gaps in the literature.
- Organization and structuring: develop a logical structure for presenting the review, organizing information into themes or categories, or chronologically; synthesize findings to develop a coherent narrative that addresses the research question.
- Critical evaluation: assess the quality, strengths, and limitations of the reviewed literature; discuss conflicting findings, gaps in research, biases, or areas in need of further exploration.
- Writing the review: structure the narrative review by introducing the topic, logically presenting synthesized information, and offering interpretations derived from the literature.
- Conclusion and recommendations: summarize main findings and conclusions drawn from the review; discuss implications for practice, policy, or future research based on the insights gained.
- Revision and finalization: review and revise the review for clarity, coherence, and accuracy before finalizing; make sure arguments are supported by evidence from the literature and the narrative flows logically.

These steps provide a structured method to carry out a narrative literature review, offering a comprehensive presentation and critical analysis of the information collection currently available on the topic in question (Cronin et al., 2008; Green et al., 2006; Pautasso, 2019).

For this review, the information and literature consulted are publications searched from scientific sources available on the internet of scholarly literature—databases Scopus (Scopus, 2022) and Google Scholar (Google Scholar, 2022) and based on research topics and keywords considered representative of the topic under study, and that are summarized in Table 1.

The publications data include multiple reliable sources, such as scientific articles, reports, books, and doctoral theses available and published worldwide in the English language. Selection criteria were established for inclusion or exclusion of sources based on relevance and research quality. With the results obtained in the search screening and selection were made through an analysis to understand whether the collected literature is applicable. That is, deciding whether it fits with the topics under study, by reading the main objectives and conclusions of each document and excluding irrelevant material that does not contribute to the focus of the review. Then, only the documents of interest, consistent with the object of the study, were downloaded. As a result, 210 relevant scientific documents published between 1973 and 2023 were selected and used to review the scientific literature on EWEs and their effects on ES, especially on WES.

From these documents, the main objectives, methods, and conclusions were extracted, which were subsequently synthesized and analyzed to identify a pattern in

Table 1 Topics and keywords of the research

Topics	Research keywords
Extreme weather events (EWEs)	Weather variables EWEs Impact of EWEs on ES
Energy systems (ES)	Vulnerabilities of ES The resilience of ES Renewable and non-renewable ES Energy production and distribution systems Impacts of EWEs on electricity production technologies Impacts of EWEs on energy transmission and distribution infrastructures
Wind energy systems (WES)	Impacts of EWEs on WES Solutions to minimize the impacts of EWEs on WES
Measures and solutions	Mitigation of EWEs impacts on ES Energy storage systems (ESS) Distributed energy systems (DES) Smart grids and microgrids

the type of information collected. That said, the information was organized considering the topics under study, and a coherent narrative was developed. Concerning the impacts of EWEs on electricity production systems, these can be divided according to the type of events that gave rise to them. The studies were analyzed on extreme wind and lightning events, storms, hurricanes, heat waves, and drought events, weak wind events, cold waves and freezing, high temperatures resulting from climate change, floods, compound flood events, and general extreme events. The variation, frequency, and intensification of this type of event significantly affect electricity production. At this point, studies on the most varied impacts on ES were analyzed, such as thermoelectric production technologies, nuclear energy, hydroelectricity, and photovoltaic and wind energy systems. In addition, energy transmission and distribution systems that constitute the energy production system itself are analyzed, as well as energy storage systems, distributed energy systems, and smart grids and microgrids.

During the process of writing the review, it was structured, and the information was presented logically, as well as the results and conclusions of this review. Furthermore, limitations and gaps in the reviewed literature were also identified, and proposals for future work were also identified. Finally, the narrative was revised, to present a clear and precise text, with arguments supported by evidence from the literature and figures were conceived to better systematize the most relevant findings.

Extreme weather events' impacts on energy systems

In this section, the impacts of different atmospheric parameters such as temperature, precipitation, and wind are described to understand their impacts on the energy systems (ES). Then, diverse impacts of extreme weather events (EWEs) on energy production, transmission, and distribution systems are presented in the following points, using a critical analysis of several case studies.

Importance of different atmospheric parameters on energy systems

The atmospheric temperature, precipitation, and wind are extremely important in the power production, the functioning of electricity production systems and their associated infrastructures, since the systems are dependent on their values for efficient functioning and on the resource availability (water, wind, solar radiation), and power demand, as mentioned in the following paragraphs.

Temperature—high temperatures impact the effectiveness of thermal and solar power plants, influencing their cooling needs (Rubbelke & Vogele, 2011; Schaeffer et al., 2012), as well as affecting biomass production, including factors like the duration of the growing season, water availability, and crop diseases (DOE US, 2013; Panteli & Macarella, 2015). Moreover, decreased temperatures can result in ice forming on equipment, such as wind turbines, or on the sea surface, significantly impacting offshore activities (Pryor & Barthelmie, 2010). Conversely, elevated temperatures in permafrost regions can lead to instability in the foundations of sizable structures. Additionally, rising temperatures can decrease the efficiency of power transmission capacity, as well as the grounding efficiency of electricity transmission and distribution lines (DOE US, 2013; Panteli & Macarella, 2015). Heating and cooling needs are greatly influenced by temperature fluctuations, affecting not only overall energy use but also seasonal consumption patterns and the preferred primary fuels for each (e.g., electricity is used primarily for cooling, while heating mainly depends on other energy sources) (Dowling, 2013; Jasiunas et al., 2021). Thus, thermal, and hydroelectric power generation are particularly vulnerable to risks arising from heatwaves and droughts, while transmission, distribution systems, and other renewable technologies are more susceptible to risks associated with cold spells (such as heavy snowfall, ice storms), windstorms, floods, and wildfires (Gonçalves et al., 2023; Panteli & Macarella, 2015; Perera et al., 2020; Yalew et al., 2020).

Precipitation—the precipitated water is used for generating power in hydroelectric facilities, helping in the cooling processes of thermoelectric plants, and cleaning solar panels. However, this dependence on precipitation for energy production undergoes substantial yearly fluctuations, with drought periods posing a significant energy security risk for nations heavily dependent on hydroelectric power (Liberato et al., 2021; Trigo et al., 2004). Thermal energy generation depends significantly on water for cooling purposes (for instance, 43% of the European Union's water consumption is attributed to the cooling needs of energy production). (Jasiunas et al., 2021; Rubbelke & Vogele, 2011). Water is essential for the maintenance and cleaning of solar panels, presenting a significant challenge in arid regions. Furthermore, the presence of clouds impacts the amount of solar radiation, consequently influencing the overall production of solar energy (Dowling, 2013). In addition, most of the capacity for storing electrical energy (more than 99%) relies on pumped hydro storage, which depends on the availability of water in accessible reservoirs. Substantial energy amounts are consumed in the processes of transporting and treating water. With a growing trend towards desalination in energy system applications, water demand could increase if naturally occurring water sources are substituted by transported water (Jasiunas et al., 2021, and references therein).

Wind—severe winds pose one of the most significant threats to electrical grid systems (Rubbelke & Vogele, 2011). The predicted increase in wind speed attributed to climate change is a pressing issue, especially considering the projected expansion of wind energy (Davy et al., 2018; Jasiunas et al., 2021; Santos et al., 2015). These changes have the potential to significantly impact economic aspects, site viability, plant design, operational approaches, and overall system stability (Pryor & Barthelmie, 2010). However, when extreme variations in the availability of these resources occur, resulting from the occurrence of EWEs, energy systems are severely affected (e.g., Gonçalves et al., 2021, 2023). Thus, the energy sector and the respective ES are extremely impacted by EWEs.

The occurrence of compound events, such as wind and snow and/or freezing or high temperatures, heatwaves, and droughts, may constitute a multiplying disruptive factor, as described in the following sections.

Impacts on energy production systems

Overall, EWEs have a significant impact on both electricity demand and generation. These events can manifest as droughts, leading to reduced hydropower output in countries like Brazil and increased reliance on liquefied natural gas imports. Heatwaves can also affect electricity generation by reducing the availability of nuclear power, as observed in France and other regions. Additionally, lower-than-average wind speeds can affect wind generation in Europe. Furthermore, events like Hurricane Ida can disrupt the offshore production of electricity in the United States (Beven et al., 2022; U.S. Energy Information Administration (EIA), 2021; IEA, 2022).

Concerning EWEs affecting energy production systems (renewable and non-renewable), several studies address the topic, including those mentioned in the following paragraphs.

Rocchetta et al. (2015) introduce a multi-objective distributed energy systems (DES) that accounts for extreme wind and lightning events. Their assessment of associated risks considers both regular environmental conditions and extreme scenarios. Environmental variations significantly affect the operation and performance of DES, and security and reliability are key concerns for their future. Panteli and Macarella (2015) investigate the impact of weather and climate change on the dependability and operation of energy system components. They propose a comprehensive modeling framework aimed at understanding and simulating the effects of severe weather on energy systems, offering potential strategies for prevention or mitigation in the future.

EWEs pose challenges to the reliability of power systems, and disruptions in power generation highlight the vulnerability of the systems (Abdin et al., 2019). The recent study of Brás et al. (2023) analyzed the impact of EWEs on European power technologies, emphasizing the substantial increase in hydroelectric energy capacities during floods and storms, contrasted with a decrease in fossil fuel-based technologies. The study reveals that although floods and storms positively influence hydroelectric energy, droughts, and heat waves neutralize these gains. Additionally, the results highlight the varying impact of wind and solar photovoltaic technologies, underlining the need for strategic planning to manage these risks as Europe strives to amplify renewable energy use while maintaining a reliable power supply.

In addition, the study of Van der Wiel et al. (2019) explores meteorological conditions associated with increased risks related to European energy security in a renewable energy-dependent energy system that relies on wind and solar sources. They conducted large ensemble experiments using data from two global climate models (EC-Earth and HadGEM2-ES) to calculate 3 sets of 2000-year daily records of energy production and demand. The weather data reveal extreme events of low renewable energy production and high energy shortfalls, primarily caused by high-pressure systems and atmospheric blocking. These events occur in winter and summer, and redesigning renewable energy distribution or importing energy cannot prevent these high-impact events and it is not enough to mitigate them. Climate change impacts are smaller compared to the interannual variability of these events, emphasizing the need to design future power systems considering their unpredictability.

Storms (Liberato, 2014; Pinto et al., 2010; Priestley et al., 2018) and particularly hurricanes (Che et al., 2014) contribute significantly to power disruptions in the U.S. electrical sector, primarily due to damage inflicted on transmission systems (Gonçalves et al., 2023; Reinoso et al., 2020; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013), as discussed on the following section. The study by Gonçalves et al. (2021) assessed the high-impact storms that affected Southwestern Europe in the December months of 2017 to 2019, and it was concluded that these events had a positive effect on wind energy production, with the highest values of energy production occurred on the stormy days.

However, solar photovoltaic (PV) systems can supply power to local loads during transmission system restoration. In this way, the study by Cole et al. (2020) conducted research examining the projected energy production from PV systems and storage during 18 hurricanes that hit landfall in the US between 2004 and 2017. The findings indicated that solar PV generation during hurricanes varied between 18 and 60% of its potential under clear skies, while post-hurricane conditions allowed PV systems to produce between 46 and 100% of their clear-skies potential. When combined with storage systems, PV can provide a minimum level of energy during and after a hurricane, thus improving the resilience of the PV system.

Another question is the floods and the work of Najafi et al. (2021) introduces a network-oriented framework designed to characterize compound flood risks in coastal areas. This integrated framework, focusing on the complex connections between infrastructure systems, offers a means to analyze risk across multiple global regions. It incorporates these interdependencies into a comprehensive assessment tool to model failures and subsequent cascading impacts.

Heatwaves can affect the operation of power grids by increasing peak loads, reducing generation and transmission capacity, and reducing the thermal capacity of transmission lines. This can reduce gas turbine and combine-cycle gas turbine efficiency and cause severe power shortages and large price spikes. Ke et al. (2016) researched the potential effects of heatwaves on the operation of power grids. Their findings underscore the importance of accurately assessing the capacity of thermal power plants concerning ambient temperature. This assessment is crucial to avoid underestimating capacity reduction during periods of heatwaves. Hourly consideration of derating effects during heatwave periods is also crucial. The study of Abdin et al. (2019) proposes a modeling and optimization framework designed for power systems planning. This framework considers operational flexibility and the ability to withstand extreme heatwaves and droughts, intending to increase resilience within the power system. The results show that implementing a resilient planning framework can lead to substantial enhancements in load supply during extreme events. Although this approach involves higher investment and operational costs, the savings derived from reducing load loss during such events completely offset these expenses (Abdin et al., 2019).

Concerning climate change impacts on energy systems, a comprehensive analysis of how climate change directly impacts the production of solar photovoltaic (PV) energy across the electric grids of European regions, considering a future scenario with high-capacity installed of PV was carried out by Jerez et al. (2015). The results suggest that by the end of the century, the change in solar PV output, compared to current estimations, could range from a decrease of 14% to an increase of 2%. The most significant declines are anticipated in Northern countries, and the consistency of power generation over time might even display a slightly positive trend in Southern countries. So, this indicates that while there might be minor reductions in solar energy production in specific parts of Europe, the European PV sector is unlikely to face substantial threats from climate change.

In the same way, the study of Bloomfield et al. (2016) highlights the need to consider the impact of long-term climate variability on power systems, especially as climate change mitigation policies lead to increased weather-dependent renewable energy generation. By analyzing multi-decadal meteorological records and a simplified power system model for Great Britain, the study shows that inter-annual climate variability affects all aspects of the power system, with the most significant impact on baseload generation. In a 2025 wind-power scenario, the inter-annual range of operating hours for baseloads like nuclear power increases fourfold, indicating the importance of long-term planning. This research suggests that renewable integration studies used in policy and system design should adopt a more robust approach to climate data and expand consideration of climate variability, as this issue is likely to be relevant for power systems in regions with strong climate variability, such as Western Europe.

Periods of high temperatures have resulted in cutbacks in generation, raising concerns about the stability of the power supply. As thermal power generation relies heavily on water for cooling purposes, the potential impact of climate change across the European Union was analyzed on 1326 individual thermal power plants and 818 water basins in 2020 and projected conditions for 2030 (Behrens et al., 2017). Despite efforts aligned with policy objectives and a decrease in the withdrawal of water for electricity production, the results indicate an increase in the number of regions experiencing reduced power availability due to water stress, rising from 47 basins in 2014 to 54 basins by 2030. The most at-risk basins are primarily situated in the Mediterranean region, with additional vulnerable areas identified in France, Germany, and Poland. Additionally, there are plans for constructing more plants in these stressed areas (Behrens et al., 2017).

Moreover, high temperatures can result in reduced efficiency in thermoelectric and nuclear power generation. This decrease in efficiency stems from factors such as decreased access to cooling water, reduced biomass production, limited hydroelectric resources, and decreased effectiveness of renewable electricity technologies (Auffhammer & Mansur, 2014; Nik et al., 2021). Additionally, the higher temperatures caused by climate change can reduce the efficiency of PV cells (Feron et al., 2021; Schaeffer et al., 2012).

The study of Perera et al. (2020) suggests that computations relying on standard weather patterns might capture gradual changes. Nonetheless, their findings highlight that accurately measuring the consequences of climate change and adjusting energy system designs accordingly could potentially increase the renewable energy fraction by up to 30%. This adaptation is crucial to ensure robust and reliable operation. So, increasing resilience to extreme weather is crucial for designing electrical systems with intermittent renewable energy sources (RES).

Thus, providing support to increase the strength of ES components such as structures, conductors, and poles, represents a viable approach to minimize the impact of EWEs (Tari et al., 2021). Additionally, assessing the viability of system functionality during extreme events involves implementing adaptation measures and system control (Tari et al., 2021; Zhang et al., 2019), consequently increasing the resilience of the grid (Panteli & Macarella, 2015).

Impacts on power transmission and distribution systems

The transmission lines are a major part of the ES and are greatly affected by EWEs that cause important power transmission grid interruptions—Hurricane Sandy in 2012, and Hurricane Katrina in 2005—have caused critical blackouts and heavy damages (for example, hurricane Sandy left about 7.5 million customers without power across 15 states in the US) (Che et al., 2014). In Europe, extratropical cyclones stand out as major contributors to insured losses, where individual storms possess the potential to generate billions of EUR in damages (Pinto et al., 2010; Priestley et al., 2018). Notable examples of severe windstorms, characterized by extreme wind speeds associated with intense cyclones, include storms Lothar and Martin in December 1999. These storms resulted in losses of US$8 billion and US$3.3 billion, respectively. Storm Kyril in January 2007 also caused insured losses of more than US$6.7 billion (Roberts et al., 2014), with significant impacts on buildings, utility infrastructure, as well as transport, forestry, and agricultural sectors (Pinto et al., 2010). In addition, storm Klaus, in January 2009, with over US$6 billion in total losses reported in Spain and France (Liberato et al., 2011), and storm Xynthia, in February 2010, with 64 reported casualties, and a total economic loss estimated at least US$4.5 billion over the Iberian Peninsula and France (Liberato et al., 2013), were considered the most expensive weather risk event in the world during 2009, and the 2nd insured loss event in 2010, respectively. Windstorm Gong, in January 2013, caused considerable socio-economic damage and huge insured losses in the Iberia Peninsula. The extreme winds caused transportation disruptions, and structural damage to infrastructures due to the uprooting and downfall of thousands of trees. More than 11,000 km of wires within the national power grid were affected, causing power cuts in numerous areas. Approximately 2.6 million people were left without access to electricity and communication services for several days. Insured losses amounted to over 100 million EUR (Liberato, 2014).

Consequently, several studies discuss these issues and expose their research and results.

Extreme winds, ice storms, and wet snow deposition on overhead power lines (OPL) are some of the major causes of structural failures in transmission and distribution lines (Reinoso et al., 2020; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013). These events have the potential to surpass the mechanical capacity of even recently constructed and well-engineered lines, leading to overloads. While numerous studies qualitatively assess the influence of climate change on various elements of the energy system, quantitative assessments are scarce regarding the effects of climate change and EWEs on the dependability of structures, particularly on power transmission and distribution lines (Matko et al., 2017; McMahan & Gerlak, 2020; Panteli et al., 2017; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013; Ward, 2013). Gonçalves et al. (2023) present a risk analysis methodology focusing on EWEs' impact on OPL in Portugal. Their study found that extreme winds are the main factor disrupting OPL, accounting for approximately 28 to 40% of the examined events linked to windstorms. In instances of compound events—wind and rain—the probability of damage to the OPL varies from 21 to 30%, while for wind and ice events, it fits between 3 and 5%. Consequently, the development of effective solutions is essential to mitigate these impacts. Guo et al. (2020) present a model that evaluates the probability of transmission line failures during typhoon weather conditions. This model considers both the wind speed and the load of the lines. Their findings reveal that the Monte Carlo simulation and the DC model based on OPA can simulate the fault propagation path and identify the crucial components of the power grid during a typhoon. The work of Waseem and Manshadi (2020) discusses the impact of various natural disasters on the operational planning of the electricity grid. They examine the challenges that arise during such events and explore the strategies to mitigate and ideally prevent any negative effects on the grid's operation. Zimba et al. (2020) described the tropical cyclone Idai which hit on March 14th, 2019, on the power grid across southern Africa. Their findings underscore the significance of reinforcing electric power infrastructure during design and planning phases. In addition, the authors advocate the implementation of multifaceted emergency preparedness protocols within power utilities and emphasize the need for coordinated preparedness efforts with other sectors such as transportation, telecommunications, meteorology, and security. Scherb et al. (2019) propose an efficient procedure to assess component importance and network reliability in wind-exposed power grids. Their method accounts for cascading failures and islanding caused by load redistribution after the first failures caused by windstorms. Applied to the Nordic Grid, the results prove its effectiveness in planning network enhancements to mitigate wind impacts and enhance line abilities to limit cascading failures. In the same way, Caro et al. (2019) propose an advanced methodology to enhance grid resilience during severe events by employing flexibility tools. A real case study in northeast Italy proved the potential of demand response policies to mitigate cascading outages during a severe weather event. This method strategically reduces the cascade effect of numerous outages on a power network when faced with severe weather conditions. It achieves this by making minimal adjustments to market, load, and generation programs, effectively resolving an optimization problem. Gunduz et al. (2017) conducted a comprehensive analysis of Sweden's power system reliability, addressing climate change-related natural disasters. They proposed updating the power policy and investing in underground cables to mitigate the severe impacts of EWEs, such as the Gudrun storm of 2005, which caused significant economic damage. Chen et al. (2022) developed a hybrid simulation approach to model the connection between strong wind and power grid faults. The approach considers line galloping uncertainty and trajectory complexity, using adaptive simulation strategies to simulate cascading fault scenarios during extreme wind conditions. Omogoye et al. (2021) study hurricane impacts on the electric power system, particularly the distribution network. They suggest reviewing resilience enhancement techniques for the distribution network and proposing a statistical model for predicting line outages during hurricanes to improve short-term operational planning.

Another relevant topic is the oil and gas supply which can be disrupted by EWEs leading to production shutdowns, such as hurricanes in the Gulf of Mexico in 2004 and 2005 (Schaeffer et al., 2012). Shao et al. (2017) present an integrated approach to electricity and natural gas planning aimed at enhancing the power grid's resilience against adverse events. They suggest supporting the OPL with underground natural gas pipelines to achieve improved resilience and cost-effectiveness. Additionally, this integrated solution helps mitigate the considerable damage caused by extreme events on interconnected infrastructures. In 2021, the more recent example of supply disruption includes the natural gas shortage of 31 GW of power production capacity due to freezing in Texas (IEA, 2021; Mann et al., 2021; Shrestha et al., 2023).

Therefore, the infrastructures of transmission and distribution such as the OPL, are greatly affected by EWEs, where the main cause of the infrastructure disruption is the extreme wind resulting from extreme storms such as hurricanes, typhoons, tropical and extratropical cyclones, and snowstorms (with ice deposition). On the other hand, fires caused by high temperatures during heat wave events and drought events, combined with those caused by human error, pose a serious risk to energy transmission and distribution infrastructures, such as overhead power lines, leaving studies lacking about these impacts in this work. As mentioned in the different studies analyzed above (e.g., Gonçalves et al., 2023; Liberato, 2014), these events caused destruction and serious damage to the components of the electrical lines, leading to the interruption of electrical supply to populations for several days.

Thus, Fig. 2 highlights the connections between extreme weather events and the impacts caused by weather variables (precipitation, wind, and temperature) on energy systems and electrical infrastructures that jeopardize the resilience of the electrical grid.

From this review, the wind energy sector is one of the most affected by EWEs, so, an analysis of these impacts on the wind energy systems (WES) is presented in the next section.

Wind energy systems

Wind resource

Wind resource is a renewable, efficient, and clean energy source, offering substantial potential to reduce greenhouse gas emissions. (Ahmed et al., 2020; Davy et al., 2018; Schaeffer et al., 2012). In recent years, wind energy has become increasingly attractive and presents a successful economic development, and it is one of the fastest-growing technologies to produce renewable energy (Khchine et al., 2019; Nogueira et al., 2019). The potential of wind energy relies on near-surface winds, which can be influenced by various factors such as circulation patterns, terrain, and EWEs (Hueging et al., 2013; Pryor & Barthelmie, 2013; Tobin et al., 2016). These factors can lead to fluctuations in wind power generation, resulting in variations in the availability of electric power. Changes in the intensity and frequency of extratropical cyclones, for example, can affect wind patterns, leading to variations in calm and strong wind periods (Catto et al., 2019). Additionally, understanding the impact of climate change on wind resources is crucial for assessing energy availability (Carvalho et al., 2021; Davy et al., 2018; Devis et al., 2018; Fernández-Alvarez et al., 2023; Lledó et al., 2019; Martinez et al., 2023; Nogueira et al., 2019; Tobin et al., 2018), as they are a potentially high risk for

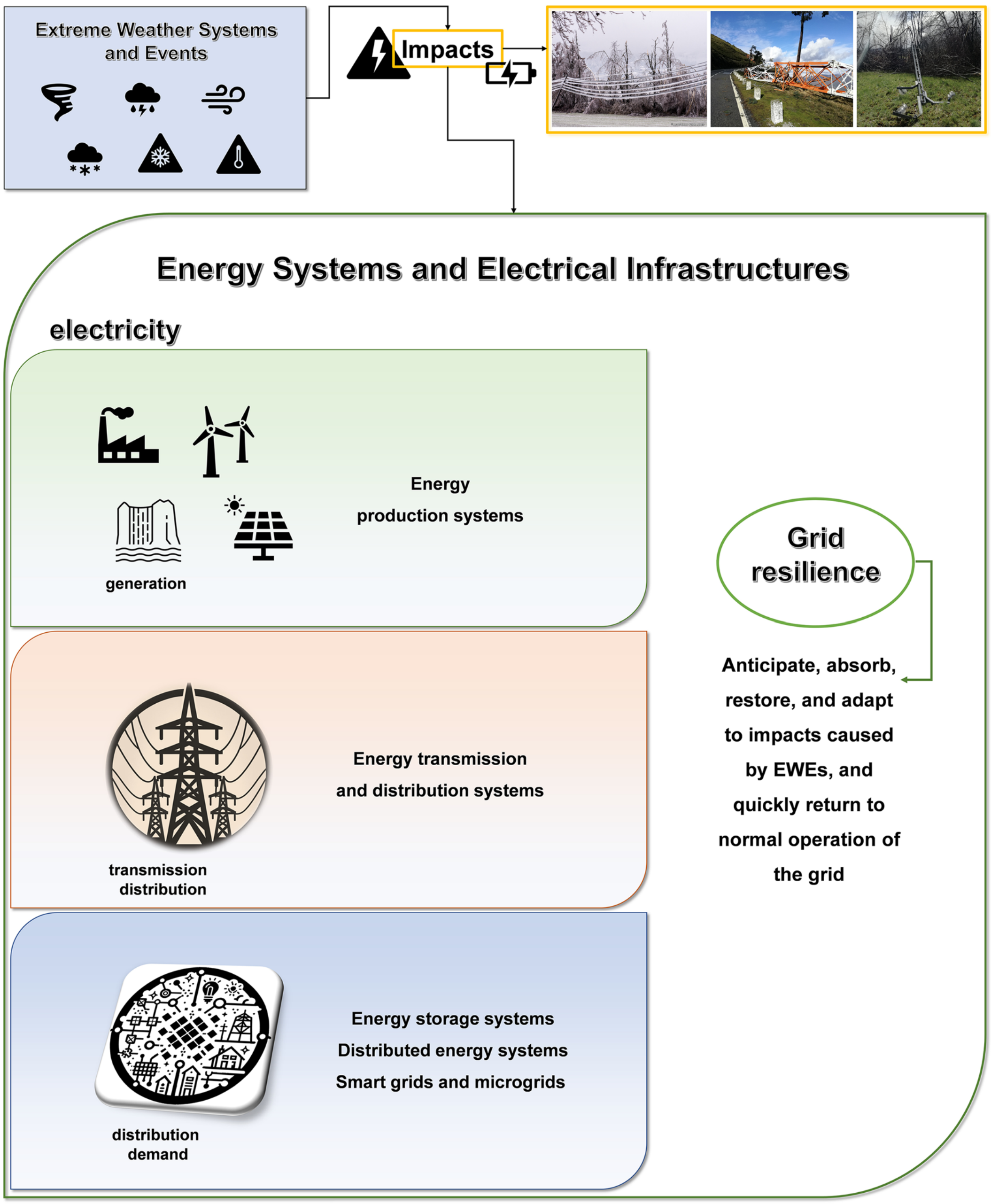

Fig. 2 Impacts of extreme weather events on energy systems and electrical infrastructures, and grid resilience (photographs courtesy of Agostinho Fernandes and Sílvia Loureiro)

investors (Modaberi et al., 2023; Solaun & Cerdá, 2019). Numerous studies have explored the influence of climate change on Europe's electricity sector (e.g., Dowling, 2013; Wenz et al., 2017) and its impact on wind speeds and wind energy potential across the continent (Hueging et al., 2013; Reyers et al., 2016; Tobin et al., 2016). In most of these investigations, results consistently indicate a small increase in wind energy potential annually across northern Europe, while there is a small decrease projected for southern Europe under future climate scenarios (Devis et al., 2018; Liberato et al., 2015; Moemken et al., 2018; Santos et al., 2015; Tobin et al., 2016). These events would entail more pronounced fluctuations in electricity production (Costoya et al., 2022; Moemken et al., 2018; Nogueira et al., 2019; Ravestein et al., 2018; Tobin et al., 2016) which poses challenges to the reliable functioning of wind turbines, especially in Europe, where wind energy plays a significant role in the energy mix due to the substantial installed capacity of onshore and offshore wind, with further expansion expected in the coming years (WindEurope, 2023; Zhang et al., 2019). In the context of the IPCC (2021) report, it suggests a probable decrease in global mean wind speeds. This decline is expected to be most pronounced in regions where prominent wind power facilities are currently installed, such as the western United States, northern Europe, and East Asia. Consequently, alterations in wind patterns might lead to reduced wind energy production, potentially resulting in disruptions to electrical grids. Conversely, along with the predicted decrease in mean wind speeds, there is a projected increase in cyclone intensity. These intensified cyclones could surpass the operational limits of wind farms, temporarily interrupt their operation, and cause physical impact to turbines and associated energy infrastructure (IEA, 2022). However, some studies highlight that the increase in storminess during specific periods may contribute to an increase in wind power generation, as occurred during the December months of 2017 to 2019 in Southwestern Europe (Gonçalves et al., 2021, and references therein). Therefore, it is crucial to implement measures and solutions to adapt WES and minimize the impacts of EWEs on their safe and dependable operation.

Wind technology

Wind farms can be based onshore with turbines that are located on land or more rural areas, as these are usually built in less-populated areas where buildings and obstacles do not interrupt the air; or offshore when turbines are typically installed on the ocean. Offshore systems, in contrast to onshore wind farms, are considered more efficient due to the higher wind speeds, increased consistency, and lack of impediments presented by landmasses or human-made structures (Whittlesey, 2017; Eriksson et al., 2008; Watson et al., 2019; Roga et al., 2022; Kiwi Energy, 2019; National Grid, 2022).

As wind turbines (WTs) continue to grow in both capacity and size, their susceptibility to various factors intensifies. However, there remains a lack of research focusing on elements that impact WTs, such as extreme wind events, gusts, blade icing, sea ice, permafrost, and air density. These variables are influenced by numerous factors that are considerably more difficult to predict but with great influence on WES (Modaberi et al., 2023; Solaun & Cerdá, 2019).

In the following paragraphs, some studies that discussed important aspects related to WES are presented and analyzed.

The study of Couto et al. (2021) uses weather type classification to analyze wind power generation in Portugal, and the results show cyclonic regimes that present high variability, while anticyclonic regimes present more low-generation events. Therefore, these results allow the enhancement of the predictability of wind resources and, so, minimize impacts on the electricity production and systems. In this sense, the work of Zhang et al. (2019) discusses the importance of considering extreme weather and climate change in wind power deployment to improve global sustainability, security, economics, and resilience. The results found that if extreme wind speed increases by 20%, the first capital cost of wind unit installation by the end of the century could increase by 12% due to the higher strength of tropical cyclones. Additionally, rising sea levels due to storm surges and sea ice pose higher risks to inland and offshore wind tower structures and foundations. On the other hand, increasing the hub height and rotor diameter in wind turbine technology leads to an increase in annual energy production and turbine capacity factors, which can limit the use of fossil-based power generation. So, Martin et al. (2020) show that increasing the turbine hub height from 80 to 160 m and the rotor diameter from 90 to 130 m increased the average annual energy production and capacity factors by 19% and 45%, respectively. Advancements in wind turbine technology, specifically in the rotor diameter and hub height, are the main drivers of cost reductions in wind power. Larger rotors decrease specific power, which boosts capacity factors and allows for wind power to be generated in low-wind areas.

Moreover, as the WTs undergo continuous improvements, it becomes imperative to establish updated standards that include the latest designs, especially for offshore wind conditions. The first offshore wind markets emerged in Europe and there is a need to adapt systems, documents, and standards to suit diverse markets such as Europe, Japan, and the US. This adjustment is crucial as the natural and climatic conditions in Europe do not reflect the extreme conditions, such as typhoons, hurricanes, earthquakes, and icing, prevalent in other global regions (IRENA, 2019).

Thus, EWEs are a necessary consideration for wind energy systems operators because of the vulnerability of these systems. In addition, more studies are needed to support normal operation, stability, and security of electricity demand and to adapt the WES during extreme events (Clarke et al., 2021). Progress in climate research allows the characterization of potential changes in extremes over time. Consequently, taking advantage of this improved predictive capability is imperative when considering changing benchmarks for power disruptions and other effects on ES (Perera et al., 2020). The adoption of cutting-edge technology will thus reinforce safety measures and maintain the stability of WES and distributed energy systems. This emphasis on technological innovation is crucial as wind energy plays a key role in shaping the future landscape of global energy structures.

WTs, onshore or offshore, have built-in mechanisms to lock and feather the blades (reducing the surface area pointing into the wind) when wind speeds exceed 55 miles per hour (25 m s^{-1}) (U.S. Department of Energy, 2018). The National Renewable Energy Laboratory (NREL) and the University of Miami developed WT simulation software (FAST) and a forecast model to optimize WTs for hurricane resiliency and structural efficiency. They use a downwind orientation, allowing the blades to bend without hitting the tower and reducing structural damage during an extreme event (Kim et al., 2016; U.S. Department of Energy, 2018 and references therein). Zhou and Yang (2020) propose a wind turbine with sensors on the turbine itself, on the blades, and on the tower to monitor its operation. So, the inclusion of a wind speed detector improves power generation efficiency by allowing the turbine to predict wind conditions. Additionally, sensors on the wind blades can detect the degree of damage, preventing accidents and minimizing losses for the company and surrounding people due to blade breakage. This is crucial for typhoon scenarios, which can cause offshore wind power ramp events and impact power system stability.

Another issue is analyzed by Wang et al. (2019) which proposed a framework to mitigate the impact of wind power ramping caused by typhoons on offshore wind farms. Their strategy optimizes curtailment, considering generator adjustments, demand response, and grid resilience. This approach efficiently utilizes system adjustments, maintains supply–demand balance, and minimizes costs while ensuring security and stability. WTs need backup power systems during hurricanes. This allows them to adjust their direction and face the wind. The Philippines already uses this technology (Han et al., 2014; Worsnop et al., 2017). In Japan, turbines must withstand strong winds and lightning storms. Thus, investment to expect every possible scenario that affects wind energy is required (Fortune, 2021). Vestas developed the V136-4.2 MW Extreme Climate turbine, optimized for extreme weather and low to medium wind speeds. It withstands up to 53 m s^{-1} winds and 74–78 m s^{-1} gusts. With a full-scale converter, it operates in low-grid capacity areas, increasing winter storm energy production by 56%. This WT model is suitable for onshore/offshore sites, it targets projects in Japan, Asia, the Caribbean, and the UK (Vestas, 2019, 2022). Siemens Gamesa also has a model of WTs suitable for extreme weather conditions and typhoon resistant (Siemens Gamesa, 2022), while Enercon modifies turbine components for performance in extreme climates, without limiting the operation of the turbines (Enercon, 2022). These robust technologies can withstand typhoon winds [over 33 m s^{-1} (119 km h^{-1})] by adjusting blade pitch to support safe spinning while generating sufficient power. A backup system allows the turbine to align with the wind even when the power grid shuts down. MHI Vestas Offshore Wind will deploy over 30 typhoon-strength turbines at the Akita Noshiro Offshore Wind Farm Project in Japan, boosting the growing sector (Spectra, 2020; Vestas, 2020).

A different solution to mitigate EWE impacts offshore is the floating platform with reduced steel usage which is being developed. These platforms use a central counterweight and pulley system to respond to waves, increasing wind generator effectiveness and reducing maintenance costs. The design minimizes wear and tear on turbines, enabling greater energy capture during EWEs (Popular Lin et al., 2019; Science, 2021).

The WindFloat Atlantic project in Viana do Castelo, Portugal, is a significant achievement in offshore wind energy (WindFloat Atlantic, 2023a). It features the largest turbine ever installed on a floating platform, situated 20 km offshore in waters 100 m deep. Using Principle Power's advanced technology, the project enables the installation of floating platforms in deep waters, tapping into abundant wind resources. The project's innovation lies in its design, inspired by the oil and gas industry, to support multi-MW floating wind turbines in deep waters (over 40 m). The semi-submersible floating structure is anchored to the seabed and maintains stability through water entrapment plates and a ballast system. WindFloat Atlantic is versatile, compatible with any offshore floating wind turbine, and can be fully assembled onshore, reducing the need for marine resources. The project's resilience was tested during the record-breaking storm Ciaran in November 2023, withstanding extreme conditions of 20-m-high waves and wind gusts reaching 139 km/h. The storm's wind speeds peaked at 38.8 m per second, surpassing the project's previous records. During the storm, the operations and maintenance teams ensured the infrastructure's safety and continuous energy production (WindFloat Atlantic, 2023a, 2023b). This event highlighted the project's exceptional engineering and its capacity to endure severe weather, reinforcing WindFloat Atlantic's role as a pioneering model in floating offshore wind technology and environmental stewardship. (EDP, 2022; OceanWinds, 2021; WindFloat Atlantic, 2022, 2023a, 2023b).

In the Nordic region, WTs must withstand extreme weather conditions and work with minimal maintenance. The EU-funded Njord project provides durable WES for telecom, surveillance, and residential sectors, capable of operating at high altitudes for up to 25 years (European Commission, 2020). Icewind and the Njord team offer two models, Freya and Njord, of durable vertical-axis WTs for remote locations (Icewind, 2022a). The Freya model provides sustainable energy solutions with reduced operational costs and can survive wind speeds up to 60 m s^{-1} with a rated power of 100W and a max power of 600W (Icewind, 2022b). The Njord model (Njord 100 and Njord 500) serves industries in harsh climates and provides a maintenance-free solution for users, with startup and survival speeds of 2 m s^{-1} and 60 m s^{-1}, respectively. The Njord 100 has a rated power of 100W and a max power of 600W, while the Njord 500 has a rated power of 500W and a max power of 3000W (Icewind, 2022c).

Extreme cold and ice accumulation on wind energy systems is a major concern and an assessment of the climate where a wind farm is to be located includes not just cold, but humidity and wind speed. Strategies to minimize ice impact include adjusting turbine location and arrangement. De-icing or anti-icing products, such as the panels installed directly in the turbine rotors warm up the rotors, keeping them ice-free. Nacelles are equipped with fan heaters to maintain warmth and minimize extreme weather effects on wind farms. Components like gearboxes, wind sensors, and electrical systems have heating elements to prevent freezing. Turbines detect ice on blades and shut down until it melts for safe operation. However, only under very rare circumstances does the cold weather force a turbine to shut down, and when it happens, the turbines are keeping warm to continue protecting their systems and ensure they are ready to go once the blades are safe to spin again. Algorithms are adjusted for winter conditions, considering air density, pressure, and other factors affecting turbine performance (Kollar et al., 2019; MidAmerican Energy Company, 2021; Stoyanov & Nixon, 2020). As it said, an ice sensor integrated with an ice mitigation system is needed to prevent ice formation on wind turbine blades. Madi et al. (2019) review ice sensing and mitigation techniques for wind turbine blades. Integrated ice sensor and mitigation systems have drawbacks and require significant improvement as current technologies are inefficient when combined in integrated systems.

Thus, within the field of wind energy, predictive abilities are crucial to curtail production costs and mitigate the impact of unforeseeable ramp events, which can undermine the reliability of power networks. Additionally, improvements in planning tools are essential to optimize the economic and technical aspects of wind energy. This requires consideration of practical limitations and incorporation of available adaptable solutions. Consequently, the distinct attributes of WES, encompassing intermittency, turbine technology, and protective measures, pose new challenges to the effective integration of wind energy into the economy (Ahmed et al., 2020; Roga et al., 2022). Therefore, the vulnerability of the wind energy systems to weather conditions, as EWEs, needs to be understood and it is crucial to assess the impacts of these events on WES (resource, turbines and infrastructures associated) that have important implications for energy security and power system resilience.

Throughout this analysis, it can be concluded that WES are heavily exposed to extreme weather conditions, characterized mainly by extreme winds and gusts of wind, storms, typhoons and lightning, snowstorms, and ice accumulation on turbine components and the indirect effect of high waves. However, there are already numerous solutions developed to mitigate the effects of these extreme weather conditions on systems, which include:

- Forecasting and defense mechanisms against extreme winds and lightning, through the installation of sensors and more automated control systems.
- Backup mechanisms in situations where the turbine is forced to shut down, to protect the essential components of the turbine.
- Turbines, built with more resistant materials and components adapted to the locations where they will be installed.

These measures reduce installation and maintenance costs and, in turn, wind energy production costs, while increasing energy security and power system resilience, as is summarized in Fig. 3.

Strategies and measures for impact mitigation and adaptation of energy systems

Throughout this work, a comprehensive review is performed on the impacts of extreme weather events (EWEs) on energy systems (ES) and wind energy systems (WES), making evidence of the continuous and constant need for systems to be improved, adapted, and checked, to withstand the effects of the occurrence of EWEs.

Strategies and measures to mitigate the impacts of EWEs on energy systems include a series of proactive approaches aimed at reducing vulnerabilities, increasing resilience, and ensuring the continued operation of energy infrastructure during adverse weather conditions (Bruckner et al., 2014; IPCC, 2014; Panteli & Macarella, 2015). The main objective is to improve adaptability and reinforce energy systems against EWEs impacts, minimizing disruptions and ensuring sustained functionality, reliability, and sustainability of energy infrastructure (Gosh & De, 2022; Jufri et al., 2019).

Thus, to complete this review, the next sections explore these strategies and measures to mitigate the impacts of EWEs on systems and new technological solutions to minimize the impacts associated with EWEs.

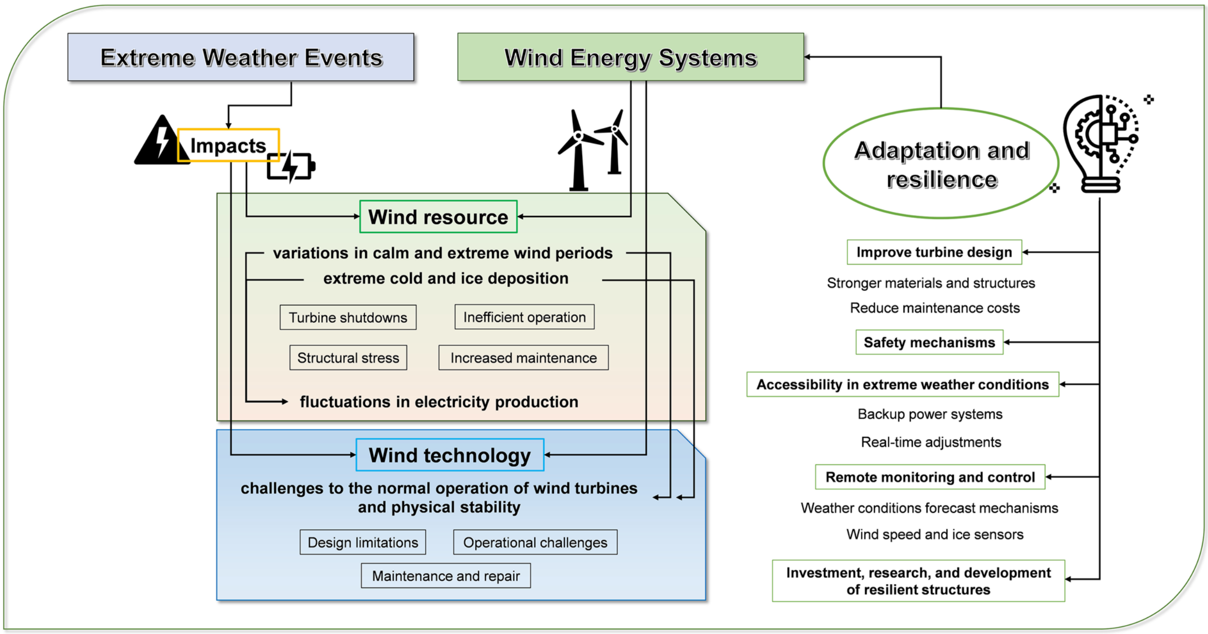

Fig. 3 Extreme weather events and their impacts on wind energy systems, and the adaptation and resilience solutions to minimize them

Mitigation of impacts on energy systems

Strategies and measures for mitigating the impacts of EWEs on ES are identified and some studies are analyzed in this work. The growing frequency and intensity of EWEs represent major risks to energy infrastructure and supply, so all stakeholders need to act to ensure that the systems can predict, adapt, and recover from adverse impacts (IEA, 2022). Table 2 synthetizes mitigation

Table 2 Mitigation strategies and measures (Adapted from: Afzal et al., 2020; Bhusal et al., 2020; Bie et al., 2017; Ghosh & De, 2022; Hossain et al., 2021; Ibrahim et al., 2022; Jufri et al., 2019; Mahzarnia et al., 2020; Panteli & Macarella, 2015; Webster & Jian, 2011)

Mitigation strategies	
Short-term	• Before, during, and after the weather emergency • Corrective actions help effectively manage the disaster as it unfolds
Long-term	• To provide robustness and adaptability to future weather conditions • Preventive control actions and proper operational procedures help to prepare for the forthcoming weather event
Mitigation measures	
Engineering	• To design more robust structures to withstand extreme conditions and weather • To relocate or refit extremely vulnerable existing infrastructure • To improve the reliability of control systems to be more resilient to higher temperatures and humidity
Non-engineering	• To revise operational procedures, policies, and regulations • To improve localized models used to predict storms and/or flood hazards
Systems and power grid	• Vegetation management • Physical revitalization and upgrade • Substation relocation, and line rerouting • Enhance visualization and awareness of situations with sophisticated surveillance and prediction capabilities • To improve planning for emergencies and prevention and precise forecast of the weather event location and intensity • The operation of the system linked to emergency generators and mobile substations • The management of repair parts and restoration teams • The network monitoring system • Updating of standards of regulated projects
Others	• To assess risks • To incorporate climate resilience in energy and climate plans • To identify cost-effective measures and incentivize utilities to act • To implement resilience measures, evaluate and adjust them to continuously improve system resilience

strategies and measures based on several works such as Panteli and Macarella, (2015); Jufri et al. (2019); Webster and Jian (2011); Ibrahim et al., (2022); Hossain et al., (2021); Ghosh and De, (2022); Bie et al., (2017); Afzal et al., (2020); Bhusal et al., (2020); Mahzarnia et al., (2020), which represent a wide range of fundamental aspects.

Moreover, supporting electrical safety in the ES requires new tools and approaches [Adapted from (IEA, 2022)]:

- Improved responsiveness and agility in power generators
- Greater connectivity and adaptability among consumers
- Reinforcement of network infrastructure
- Implementation of digitalization to facilitate dynamic electricity and information flows
- Adjustments to address climate change, weather patterns, and changes in consumer behavior.

It is worth noting that an enhancement strategy that works well in a particular event may have adverse effects on another event. For instance, underground power lines may improve infrastructure resilience against windstorms but may prolong the restoration time during a flood or earthquake due to the challenges in finding faults. Therefore, system planners need to make informed decisions when implementing enhancement measures. Specific characteristics of the systems and the utility grid must be prioritized, to find a balance between diverse types of measures and thus ensure the overall resilience of the system (Afzal et al., 2020).

Energy storage systems (ESS), distributed energy systems (DES), smart grids, and microgrids have been ranked as new technology solutions that enhance grid reliability (Hossain et al., 2021). In the following points, these topics are addressed including the definitions and means of operation of these systems.

Energy storage systems

The storage of energy and the incorporation of storage systems in the energy production systems can be one of the solutions to minimize the impacts of EWEs. ESS include various systems and components used to store diverse forms of energy. Among these, batteries, a key component of ESS, find wide application in providing emergency backup power and black-start services, thereby increasing grid resilience. ESS serve as an energy repository, mitigating the intermittent nature of distributed energy resources (DER) like renewable energy sources (RES), which depend on resource availability and require storage solutions (Hossain et al., 2020, 2021; Huggins, 2016).

Jasiunas et al. (2021) analyzed the impacts of EWEs on the energy sector, considering supply-side factors, demand-side, and energy storage. As RES grow, long-term electrical storage demand rises, and so, ESS balance supply–demand disruptions since batteries can provide emergency power to communication infrastructure (Jasiunas et al., 2021; Widera, 2020). On the other hand, Jing et al. (2021) propose a two-layer modeling framework for urban energy systems (UES) considering the impact of EWEs (such as heatwaves, floods, and typhoons). Applying the framework to Xiamen, China shows that energy storage (pumped hydro and battery) ensures critical demand during typhoons and avoids excessive supply investments. This adds a 2.8% cost over 20 years. Proper EWEs impact consideration in energy planning ensures reliable UES despite fluctuating renewables, offering a flexible and efficient paradigm for UES planning (Jing et al., 2021).

Despite the high initial costs, the use of ESS has multiple benefits (Hossain et al., 2020, 2021; Huggins, 2016), such as:

- The backup power, such as load leveling, frequency and voltage regulation, and power quality improvement
- The supply of backup power during emergencies and black-start services
- The effective planning of battery storage can reduce grid vulnerability
- The use of RES with associated ESS helps the transition to a decentralized and therefore, more reliable electricity grid
- ESS and renewable grids provide superior economic efficiency and increased operational productivity
- To present a vital role in the resilience of the system and grid reliability enhancement.

Distributed energy systems

Distributed energy systems (DES) comprehend small-scale energy generation units located at or near the site of consumption. In these systems, the end-users serve as producers, including individuals, small companies, or local communities. These energy-producing units might operate independently or connect to neighboring units via a network to exchange surplus energy. When interconnected, these form localized distributed energy networks that could further connect with similar networks nearby (Vezzoli et al., 2018 and references therein).

Moreover, ES can be also classified into centralized energy systems—defined as large-scale energy generation units that deliver energy via a vast distribution network, usually far from the point of use; and decentralized energy systems—characterized by small-scale energy generation units that deliver energy to local customers. These units can operate independently or be interconnected to share surplus energy, forming locally decentralized energy networks. These networks might further connect with neighboring similar networks to create a broader energy-sharing system.

Therefore, DES provide energy close to consumers using small-scale technologies. These systems integrate energy production, transmission, conversion, storage, and consumption, linking the different resources. In addition, DES allow the integration of renewable resources, recovery of waste heat, and matching between supply and demand levels. Therefore, these systems lead to economic and environmental advantages in distributed production plants (Soderman & Petterson, 2006; Somma et al., 2015), and improve grid quality, reduce congestion, and enhance flexibility without requiring new transmission lines (Liu et al., 2021; Mancarella, 2014; Mar et al., 2019).

On the other hand, using DES and Distributed Renewable Energy (DRE) are effective ways to enhance the distribution system's resilience. This is because DRE) generation refers to small-scale generation units that use RES like sun, wind, water, biomass, and geothermal energy at or near the point of consumption, where users are also producers. Thus, DRE systems bring about environmental advantages by using renewable resources, low greenhouse gas emissions, and low environmental impact compared to non-renewable centralized energy generation units. From a socioeconomic perspective, these systems offer benefits due to their small-scale nature, requiring modest economic investment, easy installation, and maintenance. This accessibility empowers individuals and local communities to set up and manage these systems, thereby democratizing resource access, enhancing the quality of life, reinforcing local employment, and promoting the dissemination of skills (Vezzoli et al., 2018). In addition, integrating DRE systems with ESS during isolated operations presents utilities with another solution to mitigate the adverse impacts of severe events (Gosh & De, 2022; Li et al., 2017) combined with other key features to improve the network resiliency which includes adaptability, redundancy, flexibility, fast recovery, and automation of the systems.

Smart grids and microgrids

Smart grids are a sophisticated version of electrical grid systems, integrating digital technology to improve the reliability, efficiency, and sustainability of electricity services. Overall, smart grids mark a substantial shift from conventional electrical grids, using advanced technology to create an electricity system that is more efficient, reliable, and environmentally sustainable (Escobar et al., 2021; Hossain et al., 2021).

Microgrids represent an alternative approach to mitigate the effects of EWEs. These microgrids can take the form of smart grids that offer greater stability and effectiveness in device management and security through sophisticated computing technologies and smart meters. This innovation emerged as a flexible structure capable of meeting the diverse requirements of different groups seeking to integrate distributed energy resources (DER) (Hirsch et al., 2018; Hossain et al., 2021).

Therefore, a microgrid offers essential power support in two distinct manners during substantial power outages: (1) operating independently of the main grid, using DER to sustain vital loads. This operation, known as islanding, is crucial for maintaining network reliability; (2) restoring power to critical loads in sections of the distribution system experiencing insufficient power. The microgrid reconnects to the network after isolating faulty areas and assists these sections as an immediate source of essential power supplies (Gosh & De, 2022; Li et al., 2014). So, integrating microgrids to assist in the restoration of critical loads during severe incidents presents an effective solution to increase the resilience of the distribution system (Gosh & De, 2022).

The use of microgrids offers several benefits as it improves available power generation, supplying greater energy to a wider region. Being situated in proximity to loads produces two effects: reduced losses and the potential to act as an alternative to network resources by minimizing power flows in transmission and distribution circuits. Under standard operating conditions, microgrids operate autonomously, without exchanging power with the primary grid or other microgrids. During emergencies, a failed microgrid receives power from other microgrids, preventing its failure and ensuring continued supply to customers during the repair period, on which they depend (Li et al., 2017; Mar et al., 2019). Smart grids and microgrids have reduced susceptibility to the effects of extreme weather events (EWEs) and can respond quickly and effectively to their impact. Specifically, defensively isolated microgrids have the potential to facilitate optimal grid restoration while allowing for the maximization of grid capacity. Additionally, DER and microgrid systems play a key role in minimizing the repercussions of failures in power transmission and distribution infrastructure by generating, storing, and regulating electricity locally (Hossain et al., 2021; Panteli et al., 2016; Xu et al., 2016).

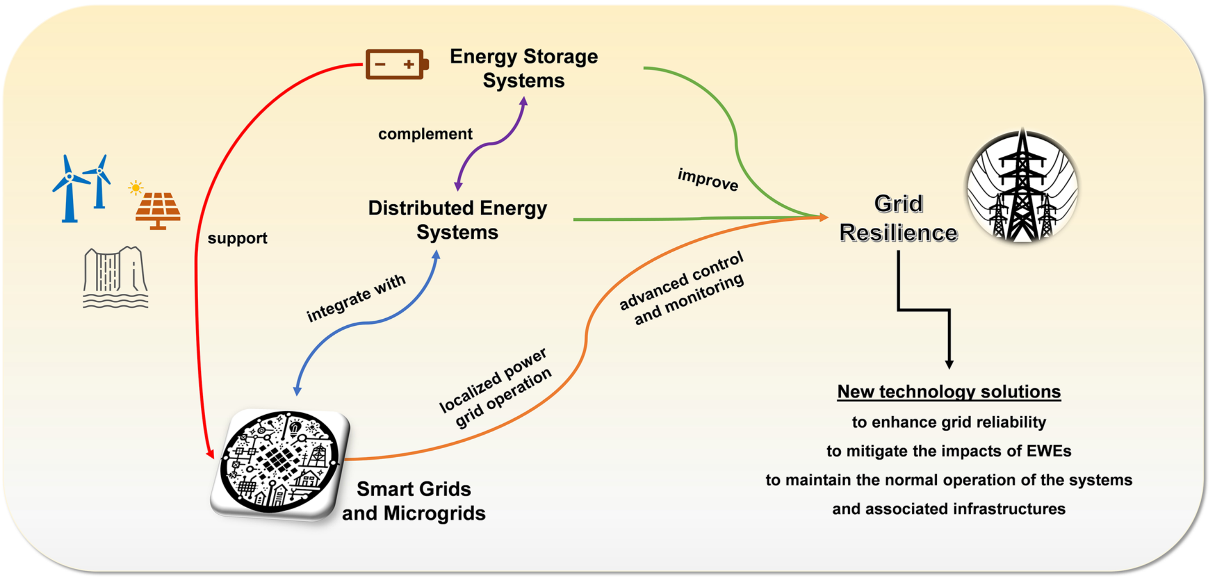

Fig. 4 Solutions to improve grid resilience based on energy storage systems, distributed energy systems, and smart grids and microgrids

These new technology solutions—energy storage systems (ESS), distributed energy systems (DES), smart grids, and microgrids—and the relationship between the concepts are represented in Fig. 4.

Therefore, microgrids and their several activities are emphasized as being one of the most efficient strategies to improve power distribution system resilience (Gao et al., 2015; Gosh & De, 2022; Mahzarnia et al., 2020). However, existing regulations around the world for power exchange between multiple microgrids are insufficient, necessitating immediate review and adjustment to meet the growing needs of interconnected microgrids, such as integrating more DER, implementing islanding, and enhancing energy storage within each microgrid (Afzal et al., 2020).

Forecast studies on extreme weather conditions and impacts on WES

In recent years, the relationship between forecasting an extreme weather event and its impact on energy systems has become a key area of study. For the power grid to become more resilient to these types of events, power utilities need to prepare and stage repair crews, which is only possible if they can accurately anticipate the impacts that extreme weather can have on their systems (Perera et al., 2020; Watson et al., 2022).

With the rise in renewable energy, such as wind power, the need to accurately predict EWEs has intensified, and so, numerous forecasting and prediction studies have investigated the impact of EWEs on resource availability and energy systems, aiming to improve planning, efficiency, and resilience (Mohamed et al., 2019; Panteli & Macarella, 2015; Perera et al., 2020; Watson et al., 2022). Furthermore, the ability to predict EWEs, particularly wind speed patterns—wind speed prediction and the prediction of operation probability for wind turbines—is essential for the efficient operation of wind turbines, as it directly impacts their performance (Arora et al., 2018; Bazionis & Georgilakis, 2021; Ghorbani et al., 2016; Jiang et al., 2021; Karaman, 2023; Liu et al., 2022; Xinxin et al., 2023).

Lei et al. (2009) divided the forecasting methods into four categories: *physical models* which use a lot of physical considerations to reach the best prediction precision; *conventional statistical models*, such ARMA model, which aim at finding the relationship of the online measured power data; *spatial correlation models* which consider the spatial relationship of the wind speed in different wind speed measurement stations. The wind speed time series of the predicted points and its neighboring observation points are employed to predict the wind speed*; new methods based on artificial intelligence*, such as artificial neural networks (ANN), fuzzy logic models, support vector regression machines (SVR), and hybrid models are advanced ones and have less error than others (Lei et al., 2009; Shi et al., 2012; Hu et al., 2016 and references therein; Arora et al., 2018; Jiang et al., 2021; Gupta et al., 2022; Farahbod et al., 2022 and references therein; Karaman, 2023).

Physical methods have advantages in long-term prediction while the statistical method does well in short-term prediction. Both physical and statistical models are utilized simultaneously in typical forecasting methods. To train the system on the local conditions, numerical weather prediction (NWP) results are regarded as input variables together with historical data and statistical theories. Statistical models are the autoregressive model (AR), moving average model (MA), autoregressive moving average model (ARMA), and autoregressive integrated moving average model (ARIMA) (Lei et al., 2009; Shi et al., 2012; Hu et al., 2016 and references therein; Jiang et al., 2021; Daniel et al., 2020; Bazionis & Georgilakis, 2021; Liu et al., 2022).

Several studies explored various modeling approaches, including GARCH (Generalized Autoregressive Conditional Heteroskedasticity) and machine learning models, to forecast wind speeds for better understanding and optimizing wind turbine operations (Chen et al., 2013; Liu et al., 2011, 2013; Zhou et al., 2010). In the study of Zhou et al. (2010), GARCH was used to model wind speed, effectively capturing variations in time series. By correlating the power curve and wind speed, the wind power estimate was easily derived from the predicted speeds. Validating its prediction model with an example, GARCH demonstrated its advantage in improving prediction accuracy over ARIMA. Numerical calculations using sequences with diverse volatility clusters highlighted GARCH as having better forecasting performance, particularly with sequences that highly fluctuate. Liu et al. (2011) evaluate ARMA–GARCH methodologies for wind speed modeling, employing 10 different model structures with various GARCH approaches on seven years of hourly wind speed data from Colorado, USA. Various evaluation methods confirm the effectiveness in capturing the changing trend of the mean and volatility of wind speed. These models display time-varying nonlinear and asymmetric characteristics in wind speed volatility, consistently improving sufficiency. However, as height increases, the explanatory power of the ARMA–GARCH(-M) model decreases slightly. No single model structure universally outperforms others at all heights, emphasizing the need to evaluate potential models for optimal sufficiency in wind speed datasets. In the study of Liu et al. (2013), the real wind speed and power data were used to apply a methodology that employs ARMA-GARCH-M to predict wind speed and calculate the operation probability and the expected power output of the wind turbine. The results affirm its effectiveness, and reliability in wind speed estimation, and accuracy in forecasting turbine operations and power output. Chen et al. (2013) introduce GARCH in mean-type models for wind power forecasting, incorporating volatility and intermittency impacts into the forecasting equation. The GARCH in the mean effect curve highlights volatility's negative influence on wind power. The parameters are estimated using Conditional Maximum Likelihood Estimation, applied to historical coastal wind power data from East China. Comparatively, the proposed GARCH in mean type model proves effective, outperforming classical wind power forecasting models like ARMA and GARCH, showcasing their superiority in accuracy. Chen et al. (2019) showcase GARCH-type models' effectiveness in capturing the time-varying volatility of wind power series, highlighting asymmetry through parameter estimation. Enhanced News Impact Curve analysis emphasizes volatility responses to shock magnitude and sign. Consistent results across multiple model specifications validate the effectiveness of the asymmetric effect of volatility models in improving wind power forecasting.

The integration of GARCH models and machine learning techniques provides a robust framework for predicting wind speeds, subsequently improving the operational assessment and management of wind turbines in renewable energy systems (Chen et al., 2019; Liu et al., 2022). So, this holistic approach allows energy systems to adapt and optimize their operations in response to changing weather dynamics, thereby maximizing energy generation while ensuring reliability and profitability (Xinxin et al., 2023). These models have been utilized due to their ability to capture time-varying characteristics and volatility in wind speed data, and to increase the accuracy of weather predictions, directly influencing the operational probability of wind turbines (Karaman, 2023; Xinxin et al., 2023).

Machine learning methods such as neural networks, random forests, and support vector machines have effectively predicted wind speed using diverse data to improve accuracy over varying time frames (Bazionis & Georgilakis, 2021; Farahbod et al., 2022). These models predict various EWEs (such as storms, extreme temperature fluctuations, and extreme windstorms), assisting in energy planning for proactive risk management and resource optimization (Liu et al., 2022; Xinxin et al., 2023).

Therefore, the interaction between GARCH models and machine learning algorithms offers a powerful solution for predicting extreme weather and its impact on energy systems, particularly wind speeds predicting for efficient operation of wind turbines (Chen et al., 2019; Liu et al., 2022).

Figure 5 synthesizes the main categories of wind speed forecast models covered in this section.

Continued advancement in predictive analytics has immense potential to optimize renewable energy integration, improve network management, and reinforce the reliability of energy systems in the face of increasingly

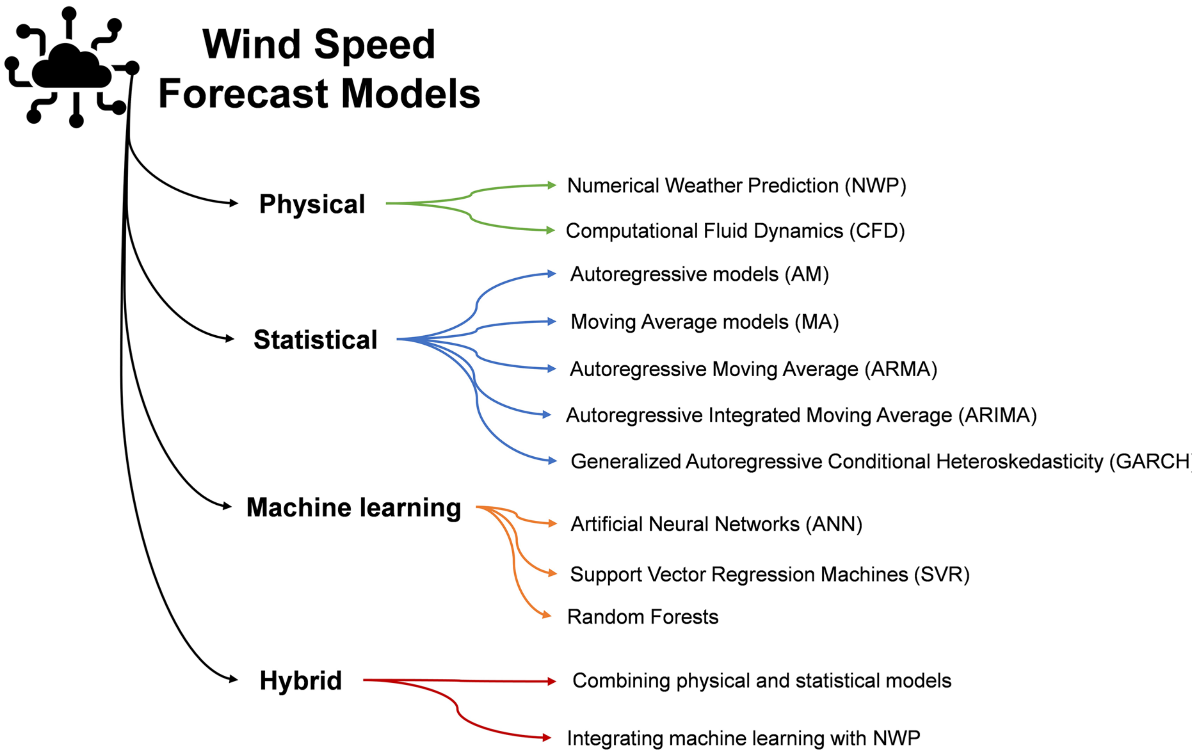

Fig. 5 Wind speed forecast models main categories

unpredictable and extreme weather patterns (Karaman, 2023; Liu et al., 2022).

Therefore, governments and energy companies must act to enhance the resilience of energy systems to EWEs. Since, the implementation of mitigation strategies and measures to improve the energy systems seeks to answer three questions—the reduction in the magnitude of the immediate impact caused by EWEs, maintenance, and the re-establishing of the operation of the systems and network as quickly as possible after the occurrence of such events (Gonçalves et al., 2023; Jufri et al., 2019; Watson et al., 2022). Figure 6 summarizes the points covered throughout this work. The interconnection between EWEs and energy systems, in particular wind energy systems, and the mitigation of the impacts of EWEs caused on ES. Mitigation of impacts therefore includes strategies and measures (as detailed in Table 2) that involve the implementation of technologies such as energy storage systems, distributed energy systems, smart grids, and microgrids. Concerning wind energy systems, implementing advanced forecasting systems and prediction models using artificial intelligence is crucial to accurately predict wind speed, and energy produced by wind turbines, and prevent extreme wind or low-speed events.

Concluding remarks

Extreme weather events (EWEs) are associated with numerous socioeconomic impacts on the energy sector, namely on energy systems (ES) and all associated infrastructures, and more specifically on wind energy systems (WES), which are comprehensively reviewed in this paper.

Concerning WES, there is a constant challenge wherein scientists and engineers must implement systems capable of initiating power generation at lower wind speeds while withstanding extreme wind conditions. In this way, wind farms may help mitigate some of the harmful effects of EWEs, when new technologies with resistant components allow them to take advantage of the full potential of wind systems, with a lot of energy available or very low wind speeds, during snowstorms or extreme winds. Moreover, the funding of wind energy projects heavily depends on the accurate projection of future wind resources at specific locations. Therefore, wind technology must remain adaptable to innovative solutions and be flexible to accommodate changes in physical and climatic parameters that continually affect it (Caltech, 2022; Gonçalves et al., 2022; Rajabzadeh & Kalantar, 2022).

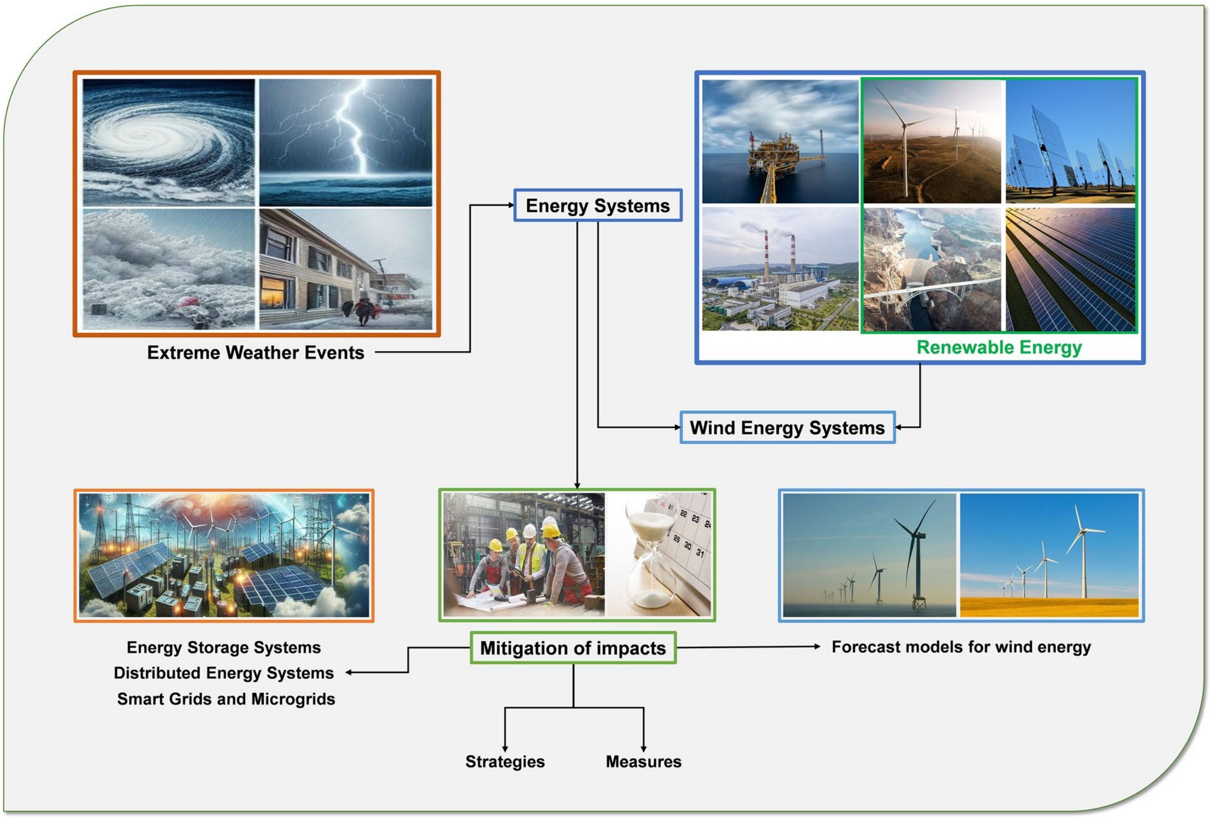

Fig. 6 The interrelations between extreme weather events, energy systems, and the mitigation of the impacts of EWEs on ES, technology, and tools

Therefore, the main highlights and conclusions of this review study may be summarized in the following points:

- Providing climate and weather data can help energy planners and suppliers better understand the potential risks and impacts of the EWEs. This knowledge aids in more effective risk assessment and the development of mitigation and adaptation strategies and measures.
- Evidence of the need to modify and upgrade engineering standards, operations, and maintenance standards due to increased EWEs severity.
- Need for significant investments in resilience strategies for improved system and grid capability.
- Implementing measures such as flood protection, relocation of substations, and stronger wind power plants.
- Upgrade electrical grids with underground lines and robust infrastructure to reduce damage.
- Integration of microgrid components (RES, DER, ESS) to improve energy management and grid resilience.
- Use smart technologies to monitor and control the grid, making the transition to a smarter grid.
- Accurate prediction of EWEs, especially wind speed patterns, is vital for optimizing wind turbine performance. The use of machine learning methods, such as neural networks and random forests, improves wind speed predictions on different time scales, aiding operation efficiency.
- Energy management plays a significant role in system operation and control, improving system efficiency.
- Resilient energy systems present high redundancy, functional diversity, adaptability, and modularity.
- Risks associated with inadequate maintenance and supervision lead to potential economic losses, so it is important to select strategies based on cost/benefit analysis.

Therefore, this interdisciplinary study contributes as a call of attention and action to the need to perform new interdisciplinary studies on the impacts of EWEs in the energy sector. Furthermore, it highlights the need to adapt systems to make them more resilient and prepared to face EWEs with minimal impacts.

With this review paper, it is possible to conclude that there is much published scientific work on this theme and that there are already good solutions and innovative strategies proposed to face the EWEs. However, this review also highlights that it is necessary to intensify the implementation and adaptation of the systems and, of course, to further foster research to develop new solutions that follow the evolution of technology and society, to mitigate the EWEs' impacts in the energy sector.

Abbreviations

ES	Energy systems
EWEs	Extreme weather events
WES	Wind energy systems
ESS	Energy storage systems
DES	Distributed energy systems
PV	Photovoltaic
RES	Renewable energy sources
OPL	Overhead power lines
DPSN	Distribution power system network
WTs	Wind turbines
DER	Distributed energy resources
UES	Urban energy systems
DRE	Distributed renewable energy

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Declarations

Competing interests
The authors declare that they have no competing interests.

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5 Summary and Conclusions

The main objective of this thesis is to study the variability of recent extreme weather events (EWEs), such as high-impact storms and extratropical cyclones (ECs), and their impact on renewable energy sources (RES), particularly wind energy, in the Iberian Peninsula (IP) region. First, the physical mechanisms and weather events associated with the ECs that affected the IP were identified and analysed. Then, the impact of these events on the availability of RES (in particular for wind speed) and renewable electricity production (wind energy) in southern Europe and the Iberian Peninsula was assessed. In addition, the need to adapt energy systems (ES) to maintain their physical integrity and operation, ensuring electricity production and grid stability during EWEs, was assessed. For this, an analysis was conducted to assess the risk of disruption to overhead power lines (OPL) in Portugal caused by EWEs. Furthermore, the evaluation of the adverse impacts of the EWEs on the ES recognizes them as a major cause of widespread electrical disturbances on a global scale. These weather-related power disruptions are known to have significant and long-lasting impacts, resulting in extensive damage to transmission and distribution infrastructure.

5.1. Main conclusions

The main findings of this thesis are presented below, in the same order as the articles presented in Chapter 4:

1. **Synoptic and dynamical characteristics of high-impact storms affecting the Iberian Peninsula during the extended winters of 2018-2021**

During 2018–2021 extended winters, high-impact storms with strong winds and heavy rainfall had a significant impact on the IP region, causing adverse socio-economic impacts. The synoptic and dynamic characteristics of these events were analysed, and the following key findings emerged from the research:

- Since 2017, 28 high-impact storms, selected by the SW Group's meteorological organizations, have had an impact on the IP. In 10 of these cases, the development was explosive.
- The high-impact storms studied with explosive development lasted from two to four days, with a wide range of values for the minimum pressure reached at the instant of maximum intensity, between 955 hPa and 985 hPa. January was the month with the highest frequency of events.
- The analysis of the trajectories of the events and their classification into groups allowed to observe that the North (967.31 hPa) and Hybrid (976 hPa) groups had lower minimum pressure values compared to the results of Karremann *et al*. (2016).
- The analysis of the concurrent extreme events showed that on the storm days, the values of precipitation and wind speed were extreme on the days of the storms. The northwest region of the IP was the most affected, with daily accumulated precipitation exceeding the 98th percentile on 34.1% of the storm days, while instantaneous wind gusts at 10 meters were greater on 45.7% of the storm days, and wind speeds at 10 meters surpassed the 98th percentile on 46.8% of the storm days.
- The composite anomaly analysis (period 1991–2020) indicates lower values of MSLP (less than - 21.6 hPa), higher values of IVT (up to more than 327.6 kg $m^{-1}s^{-1}$), and higher values of wind speed at 250 hPa up to more 29.6 m s^{-1} than the mean values of the respective climatology. In addition, there were higher values of θe at 850 hPa (up to more than 19.1 ºC), and heat fluxes with values of Q_E (less than - 150 W m^{-2}), Q_H (less than - 40 W m^{-2}) and Q_N (less than - 160 W m^{-2}) lower than the average values of the respective climatology.
- The heat flux analysis (Q_E, Q_H, and Q_N) and the SST anomalies (more than - 1ºC) show an ocean cooling with the storm passage, and the ocean-atmosphere heat exchange shows its influence on the storm formation.
- The extreme wind and humidity values associated with the high-impact storms -especially those with explosive development- can be used to explain the

significant and widespread effects that followed their passage over the continents.

2. Wind Energy Assessment during High-Impact Winter Storms in Southwest Europe

An initial study was performed to evaluate available wind resources and wind energy potential (WEP) for the December months of 2017, 2018, and 2019. The study also aimed to determine the impact of high-impact storms on electricity production using wind energy technology in southwestern Europe. The main conclusions of this study are:

- The use of two equations (Prandtl's logarithmic law –LogL– and Power law –PL) for vertical wind extrapolation at turbine height, followed by the computation of WEP, highlights the sensitivity of WEP to the changes in wind conditions.
- With differences of up to 80%, the LogL equation allows higher WEP values in offshore regions (5 to 25 $MWh.day^{-1}$), while the PL equation permits higher WEP values in onshore regions (15 to 40 $MWh.day^{-1}$).
- Over the three months of the study, the WEP calculation, with the different roughness and friction coefficients applied to each equation (LogL (z_0) and PL(α)), demonstrated that the coefficient depreciates as its value increases, causing the WEP to rise in onshore regions and decrease in offshore locations.
- The results of theoretical values in this work follow the values of the official reports (statistics of the EU-28 countries) of the power output from wind energy, indicating an increase in the production in December 2017 and 2019, and a decline in December 2018.
- The 8 December 2018 event studied was considered a record day for wind energy production in Europe (onshore with almost 90 GW.day, and offshore with almost 100 GW.day). Nevertheless, even with strong wind gusts reaching 20 $m\ s^{-1}$, affecting many regions of Europe (the northern region of Europe - British Isles, France, Germany, the Netherlands, and the entire North Sea region), wind turbines continued to produce electricity.
- As evidenced by the high WEP values on storm days, the high-impact storms that affected Europe with severe winds during these December months have become a beneficial factor in renewable power production.

Advances in wind energy technology have led to more resilient and efficient turbines, enabling safe and effective operation even in extreme weather conditions such as with extreme winds. Therefore, these improvements mean that wind turbines no longer need to be turned off these conditions, allowing continuous energy production even in periods of strong winds. By proving the growing capacity of RES, such as wind energy, to meet changing environmental and energy needs, this progress represents an important step toward a more consistent and reliable future energy supply.

3. Disruption risk analysis of the overhead power lines (OPL) in Portugal

The numerous high-impact storms that hit mainland Portugal in four consecutive winters (2017/2018 to 2020/2021) are unusual. The devastation of the OPL during these winters, and the fact that there is still no analysis of them, was the motivation for this pioneer study. Methodologies, adaption strategies, and suggestions for risk management related to high-impact storms were proposed to assess the risk of OPL disruption resulting from extreme events that impacted Portugal during the four extended winters of 2018–2021. The main findings obtained from this study are:

- The cause-effect diagram and the risk matrix were the methods used to link several factors (hazards that potentiated a risk situation of the disruption of OPL), clearly explain the impacts (effects or consequences), and quickly establish precise conclusions.
- The cause-effect diagram allows us to quickly analyse risks in a qualitative method and to manage them by identifying strategies and mitigating actions. The schematic representation makes it possible to understand the issue, the causes, and the consequences of the presence of a problem on the line by a verification of the impacts on the environment and the structure.
- Of the 29 events identified as having a significant effect on mainland Portugal, 9 events (31%) disrupted the OPL.
- Of these 9 storms causing OPL disruption, one storm was a snowstorm, and 8 storms as windstorms. Six of these windstorms were considered compound events with both precipitation and wind associated; the other two windstorms were characterized by wind only.

- The OPL disruption was mainly caused by strong winds that reached values exceeding 105.1 km h^{-1} (29.22 m s^{-1}), or level 11 on the Beaufort Wind Force Scale. This damage was also largely caused by the compound events of wind and rain.
- The nine extreme storms that disrupted the OPL have a “Medium Risk” degree, but the types of effects are different. This is because these events can have impacts with lasting consequences on the environment, substantial economic injuries that disrupt essential services to communities, and require financial support.
- The storms Elsa and Fabien posed the greatest risk, with a risk score of 10 to 14 (on a risk matrix scale of 0 to 25), which is classified as a “Medium Risk” level.
- Storm Emma has a “low” probability of occurrence, however, it has numerous “accentuated” impacts affecting millions of people during its formation and passage, so is therefore classified as “Medium Risk” level.
- The various improvement measures discussed focus on strengthening the resilience of the physical network and operational capabilities. The aim is to mitigate the severity of the effects, thereby improving operational efficiency and accelerating network restoration.
- The main strategic measures are vegetation control, preparation of repair teams, network monitoring, partial line burial, line improvement, and replacement.
- This work reveals the cause-effect relationship between the EWEs associated with high-impact storms and the OPL's disruption in Portugal. This is particularly important as populated regions are expected to be affected by stronger and more frequent EWEs in the near future.
- Weather conditions, OPL constituent materials, all electrical infrastructures, and design and operation strategic management must be considered preventive measures to minimize the effects of EWEs.
- To enhance the resilience of power systems and infrastructures in the face of the growing threat of EWEs induced by climate change, it is vital to tailor strategies and adopt new management approaches for specific contexts, as is the case of Portugal. Additionally, it is essential to confirm whether the measures defined and implemented are more suitable for the given circumstances.
- Implementing strategies to improve network capability resilience requires large investments, however, a fragile network can turn into a huge economic loss due

to failures in network operation. Therefore, an optimal selection of improvement strategies based on cost-benefit analysis is required.

- The development of these types of studies is essential for companies in the Energy and infrastructure sectors because it enables them to adjust projects to the worst-case scenarios, including strong winds that affect the OPL, and the highest limits that these can support.

4. Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures

An evaluation of the severe impacts of EWEs on energy systems (ES) and their related infrastructures, as well as an analysis of the real impact of these events on the ES (in particular the wind energy systems (WES)), was conducted through a comprehensive review of existing studies and publications on the subject.

Additionally, a set of strategies, measures, and new technological solutions were proposed to mitigate the adverse impacts on ES and improve their resilience to maintain electricity production and grid stability in the face of EWEs.

The most important conclusions of this research are as follows:

- Access to climate and weather data is crucial for energy planners and suppliers to effectively assess and mitigate risks associated with EWEs. This information is essential for developing appropriate risk management and adaptation strategies.
- Current design and technical standards, as well as the operation and maintenance procedures, need to be updated due to the increasing severity of the EWEs. In addition, energy management is important for system control and operation and improves the effectiveness of ES operation by keeping the whole system under control.
- Significant investment in resilience strategies is required to improve the capability and reliability of systems and networks.
- The risks of inadequate maintenance and supervision, which can lead to significant economic losses, highlight the importance of choosing strategies based on a thorough cost-benefit analysis.
- The ability of a resilient system to cope with unavoidable impacts and reduce the severity and/or duration of damage is based on its ability to bend rather than break.

In this sense, it is crucial to project resilient ES with high functional diversity, redundancy, flexibility, and modularity.

- It is imperative to implement defensive measures like flood safeguards, relocation of substations, and reinforcement of wind power plants. In addition, networks need to be upgraded with underground cabling and robust infrastructure to minimize damage by EWEs.
- Incorporating new engineering technologies, such as energy storage systems (ESS), distributed energy systems (DES), and microgrids, improves overall grid resilience and reliability through better energy management of all operating systems. These technologies can respond more quickly and effectively to the effects of severe weather and can even enable full grid restoration.
- The use of smart technologies for network monitoring and control is crucial for a more intelligent system.
- The challenge for WES is to design systems that can generate energy at low wind speeds and withstand extremely high winds. Wind farms can potentially mitigate the negative effects of EWEs by operating in adverse conditions, such as icy weather in cold regions.
- Accurate prediction of EWEs, particularly wind speed patterns, is essential to optimize the efficiency of wind turbines. Employing machine learning techniques such as neural networks and random forests, increases the accuracy of wind speed forecasts over various periods, thereby improving operational efficiency. Thus, continued research is needed to harness the full potential of wind systems during EWEs or low wind conditions.
- EWEs are already a major challenge for ES researchers and engineers. Continued investments and creative solutions are therefore required to evaluate the vulnerability and resilience of ES and to adapt the systems to changing weather patterns.
- This study highlights the need for new research on the severe impacts of EWEs on the energy sector and the need to adapt systems to minimize their impact. Existing strategies are effective, but intensifying implementation and finding new solutions is crucial.

Governments and Energy companies must act to strengthen energy systems' resilience against EWEs. This involves the implementation of mitigation strategies and measures with three key objectives: to reduce the intensity of the immediate impact of EWEs, to maintain the system operation, and to rapidly restore systems and network operation after such events. Therefore, more rigorous implementation of these strategies and continuous research are needed to develop new solutions that keep pace with technological and societal advances, to mitigate the impacts of EWEs on the energy sector.

5.2. Concluding Remarks and Future Work

The main objective of the thesis was to analyse the variability of EWEs and their influence on RES (in particular wind energy), focusing on the North Atlantic European region, particularly in the IP. Although very broad in its scope, it focuses particularly on the EWEs associated with extratropical cyclones and high-impact storms, which had repercussions on wind energy production, but also negative effects on the IP during the extended winters of 2018-2021. Thus, a first characterization of these extreme events for the IP region is presented. The storms studied here were those named by the Southwest European (SW) group. As these events continue to affect the IP region with significant socioeconomic impacts due to the associated strong winds and heavy precipitation, it is crucial to continue and update this study in the future.

Concerning the assessment of the effects of the storms on the wind resources availability and the consequent production of wind energy in southwest Europe and the IP, this study suggests that storms with strong winds can benefit the renewable energy industry by increasing wind resources availability and consequent wind energy production on storm days. Moreover, modern wind energy technology has advanced to the point where storms and extreme wind occurrences can increase the potential for harnessing wind power, as wind turbines do not need to be turned off and can continue to produce energy during these periods.

Through the analysis of the risk of OPL disruption and, consequently, of all the associated infrastructures, this work emphasizes the impact of weather conditions on the energy systems, with wind being the main cause of OPL disruption. Despite the “medium” level of risk associated with these occurrences, some effects have long-term consequences and major socioeconomic effects (significant losses and need for financial assistance). This is especially crucial given that Portugal is one of the countries highly susceptible to climate change damage and it is expected that future EWEs associated with ECs to be more frequent and extreme. In addition, the energy sector is one of the most impacted by climate change and the resulting increase in EWEs, therefore it is essential to consider this type of research to understand the strong impact of these events on ES and infrastructure. Furthermore, it is important to make an appropriate choice of improvement strategies based on a specific cost-benefit analysis for each case (OPL, in this case), as well as to adapt and review the measures implemented and the strategic management of operations during these events. In addition, the implementation of risk analysis and assessment techniques can be extended to different types of case studies and electrical energy infrastructures, including effects on hydro and wind power generation. Thus, this study highlights the need to improve the resilience of the systems and infrastructure in the face of the growing threat of EWEs induced by climate change, and it is, therefore, essential that energy companies improve their design and systems to support the most severe scenarios and define new management methods for specific contexts.

In this sense, Europe is facing a fundamental challenge: the modernization of its electrical networks, which will require a substantial investment of 650 billion euros by the year 2030. This investment is crucial due to the ageing of existing infrastructures and the significant increase in the use of renewable energies. Therefore, making considerable investments is imperative, with emphasis on the transport and distribution of electricity on very high-voltage electrical lines. At the same time, it is essential to make advances in the digitalization of electrical networks to efficiently manage the volatility inherent in renewable energies (Jornal Económico, 2024).

Thus, these findings demonstrate the entire scope of the study, highlighting the importance of this topic and its real impact on our day-to-day lives.

Moreover, it is important to highlight that in the winters following those considered in this study, up to the present (February 2024), high-impact storms and ECs have continued to affect the IP region, and subsequently the rest of Europe, with extreme precipitation and strong winds, causing severe socioeconomic impacts in different countries. An example of this is the events that occurred during December 2022, associated with extreme precipitation, which caused numerous damages such as floods in the Lisbon region (IPMA, 2022; Público, 2022a; Meteored, 2022) and in other regions of Portugal and Spain (AeMet, 2022; Expresso, 2022; Público, 2022b; RTP, 2022;). In the winter of 2023/2024, several storms left a trail of destruction in the IP and Europe, such as storm Aline (AeMet, 2023c; SicNotícias, 2023a), Babet (Met Office, 2023b), Ciaran (CNN, 2023; Met Office, 2023c), Domingos (AeMet, 2023d), Gerrit (Euronews, 2023; Met Office, 2023d; SicNotícias, 2023b) and other storms in early January 2024 (Copernicus, 2024a; Copernicus, 2024b; Euronews, 2024), such as storm Henk (Severe Weather Europe, 2023; Jornal de Notícias, 2024; SicNotícias, 2024). With the passage of these events, records for precipitation and wind values were broken, showing the severity and intensity of these storms.

In this way, these events cause several socioeconomic impacts, such as damage to the population and essential infrastructure for society and loss of human life (Stojanovic *et al*., 2021; Gonçalves *et al*., 2023b); impacts on the energy sector (as production, transmission, and distribution of energy (Gonçalves *et al*., 2023a; Gonçalves *et al*., 2024)); and impacts on ecosystems (in particular on forests (Ribeiro *et al*., 2022)).

On the one hand, these events have a destructive impact, but on the other hand, they contribute to very positive and important socioeconomic and environmental factors in some regions. For example, in certain regions under drought or severe drought conditions (such as southern Portugal and Spain), precipitation only occurs when associated with these types of events (Hawcroft *et al*., 2012; Ramos *et al*., 2015; Stojanovic *et al*., 2021). Thus, these events can help to minimize the effects of drought. In terms of wind, these strong storms contribute to a significant increase in the production of renewable electricity in Portugal (APREN, 2023; Expresso, 2023; Jornal de Negócios, 2023; REN, 2023a; Expresso, 2024; REN, 2024a; REN, 2024b). In the case of wind energy, records for wind production were broken in January 2024, January 2023 (storms Gerard and Fien), and October 2023 (storm Aline) (Eco.Sapo, 2023; REN, 2023b; Expresso, 2024; REN, 2024b). The situation is similar in Spain, which presents high values of renewable production in the winter months, with maximum values on stormy days, observed for the years 2022 and 2023. The historical maximum of renewable production in Spain was recorded on 26 January 2023 (REE, 2024).

The high level of wind energy production values achieved at present can be justified by the high installed capacity of wind turbines, but also by the fact that the systems can withstand extreme winds and harness the full potential of the wind to produce energy (Gonçalves *et al*., 2021; Gonçalves *et al*., 2024). This was demonstrated at the *WindFloat Atlantic* wind farm in December 2020, with storm Dora (Eco.Sapo, 2021) and storm Ciaran, in late October and early November 2023 (WindFloat Atlantic, 2023).

The entities responsible for each sector directly affected by these events (whether positive or negative) must define strategies and adopt and implement measures, in the sense that the population must be alert and properly prepared for the occurrence of these events. Companies in the energy sector, including systems and infrastructures, must also adapt systems and make them more resistant and resilient to minimize or maximize the varied types of impact.

Future works

This study must be continued and updated as high-impact storms have serious socioeconomic impacts on the IP region. So, continued research into this type of event is therefore necessary to fully understand the formation, severity, and frequency of these atmospheric systems that impact the mid-latitudes and are accompanied by higher levels of precipitation and wind speed values. Therefore, to raise public awareness of this type of natural hazard and allow for adequate prevention actions, it is crucial to improve knowledge about the processes involved in the genesis of ECs. In addition, in future work, it is considered to realize a storm-centred composite analysis, which allows the development of a distinct study perspective and a more focused analysis (Catto *et al*., 2010; Dacre *et al*., 2012; Calvo-Sancho *et al*., 2022).

Although there are already regional and global studies that indicate that these events will become more frequent and more extreme under climate change (Catto *et al*., 2019; Sinclair *et al*., 2020; Priestley and Catto, 2022; Ridder *et al*., 2022; Little *et al*., 2023; IPCC, 2023), a more localized analysis can be carried out (IP region and southwestern Europe) to understand their characteristics in the near future.

A complementary analysis will also be carried out to assess wind potential under climate change. Indeed, previous studies exist for Europe and the IP on wind production (Pryor *et al*., 2020; Carvalho *et al*., 2021; Russo *et al*., 2022; Costoya *et al*., 2022; Claro *et al*., 2023; Fernandez-Alvarez *et al*., 2023), but it is important to know how extreme wind events projected in the future may affect wind production to assess the availability of wind resources under the new extreme events. In addition, it is important to have available data from wind energy farms and companies to confirm whether severe storms have resulted in wind turbine shutdowns due to the extreme wind speeds and variable gust directions, or whether the wind turbines can use the full wind potential at the peaks of the storms.

The risk analysis of the OPL disruption study intends to draw attention to the need for new theoretical research for developing techniques and/or adding new materials to OPL infrastructures to increase the resilience of the ES to EWEs in Portugal. Based on the current bibliographic study, there are no studies or data in Portugal, Spain, or France that would allow us to compare these results and the methods used. Due to the lack of data, in this work, it was only possible to confirm the number of storms that resulted in OPL disruptions and power cuts to consumers, which is an important barrier that should be considered for future works. Since the Portuguese electricity network is very heterogeneous, it would be interesting to carry out a more localized study to estimate the probability of risk of OPL disruption in values per kilometre year (km.year) and per region/locality. However, these data are confidential and difficult to access, making a more detailed analysis difficult. Although this study was carried out with a short period of data, an environmental risk analysis is expected to continue the study.

There is also a need to accelerate the implementation and adaptation of systems and to further promote research. This research should focus on the development of new technological engineering solutions that keep pace with technological and societal advances to minimize the adverse impacts of EWEs on the energy sector.

A Supplementary Material

This section contains the supplementary material associated with each article, which constitutes the main part of this thesis. All materials related to the published articles can be accessed online through the respective journals.

Synoptic and Dynamical Characteristics of High-Impact Storms Affecting the Iberian Peninsula during the 2018–2021 Extended Winters

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To identify the events with explosive development, the deepening rates of the core pressure for 24 h were analyzed for each storm and then geostrophically adjusted to the reference latitude of 60°N (see equation 1) and classified according to Sanders [77] (equation 2). Furthermore, a definition modified by Zhang et al. [78] was also used to analyze and classify the ECs. The results are presented in Table S1.

Table S1. High-impact storms with explosive development.

	Sanders and Gyakum [75]			Sanders [77]	Zhang et al. [78]	
High-impact storm with explosive development	**Core pressure deepening rate (hPa/24h)**	**Geostrophic adjustment to reference latitude 60 ºN (hPa/24h)**	**1 bergeron = (24 hPa/24 h) x sin60º/sin φ**	**Classification**	**Deepening rate (DR in Bergeron)**	**Classification**
2017-2018						
Ana	29	33.8	1.17	Weak	1.74	Strong
Emma	34	43.17	1.15	Weak	0.78	Weak
Hugo	37	42.46	1.00	Weak	2.28	Strong
2018-2019						
Gabriel	28	33.16	1.18	Weak	1.43	Moderate
2019-2020						
Elsa	30	32.97	1.06	Weak	1.01	Weak
Fabien	23	27.69	1.15	Weak	1.59	Moderate
Jorge	32	33.83	1.04	Weak	1.38	Moderate
2020-2021						
Alex	38	43.6	1.15	Weak	2.16	Strong
Dora	30	32.97	1.10	Weak	1.46	Moderate
Gaetan	30	31.33	1.02	Weak	1.07	Weak

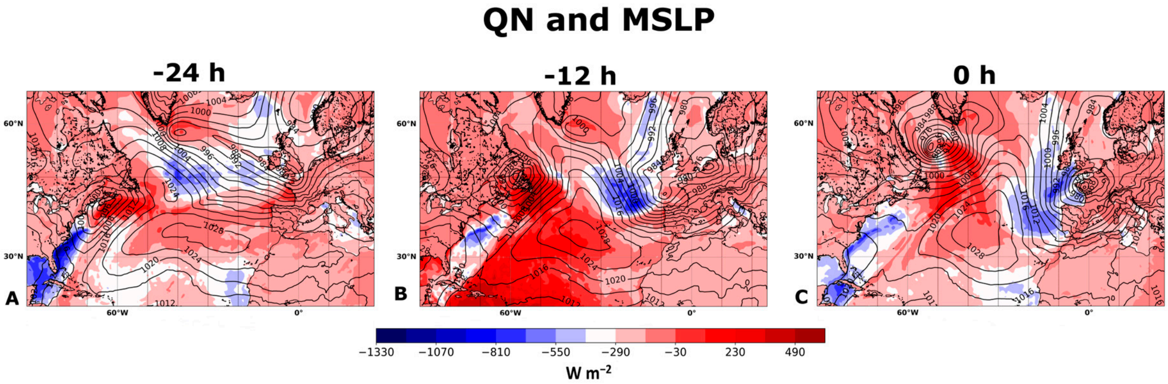

Figure S1. Analysis of the Net surface heat flux (Q_N) (W m^{-2}) for storm Ana at 24 hours **(A)** and 12 hours **(B)** before the instant of maximum intensity (0 h) **(C).** MSLP (black contours at intervals of 4 hPa) is plotted in all figures.

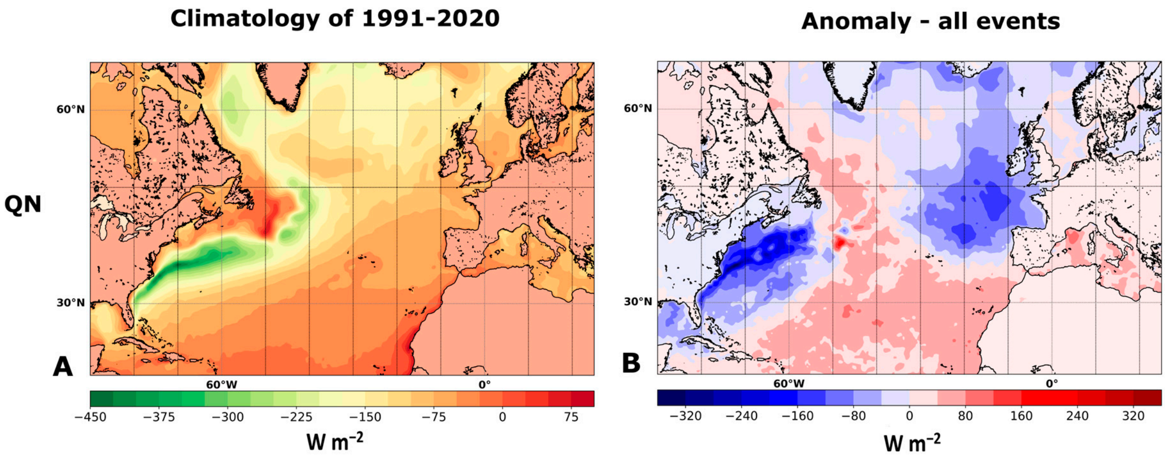

Figure S2. Climatology for extended winter months (ONDJFMA) of 1991-2020: **(A)** Net surface heat flux (Q_N) (W m^{-2}). Anomaly for the composite of 2017-2021 extended winter storms (28 events): **(B)** Q_N (W m^{-2}).

Wind energy assessment during high impact winter storms in Southwestern Europe

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In this way, we then proceed to the WEP calculations using the various values z_0 (Table S1) in equation 1 (LogL) and α (Table S2) in equation 2 (PL), according to the tabulated values [32] and the results are shown in Figures S1 and S2, respectively, of the supplementary material.

Table S1. Roughness coefficient (z_0). Adapted from [32].

Description	Roughness Length z_0 (m)
Water surface	0.0002
Open areas with a few windbreaks	0.03
Farm land with some windbreaks more than 1 km apart	0.1
Urban districts and farm land with many windbreaks	0.4
Dense urban or forest	1.6

Table S2. Friction coefficient (α). Adapted from [32].

Terrain Characteristics	Friction Coefficient (α)
Smooth hard ground, calm water	0.10
Tall grass on level ground	0.15
High crops, hedges, and shrubs	0.20
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.30
Large city with tall buildings	0.40

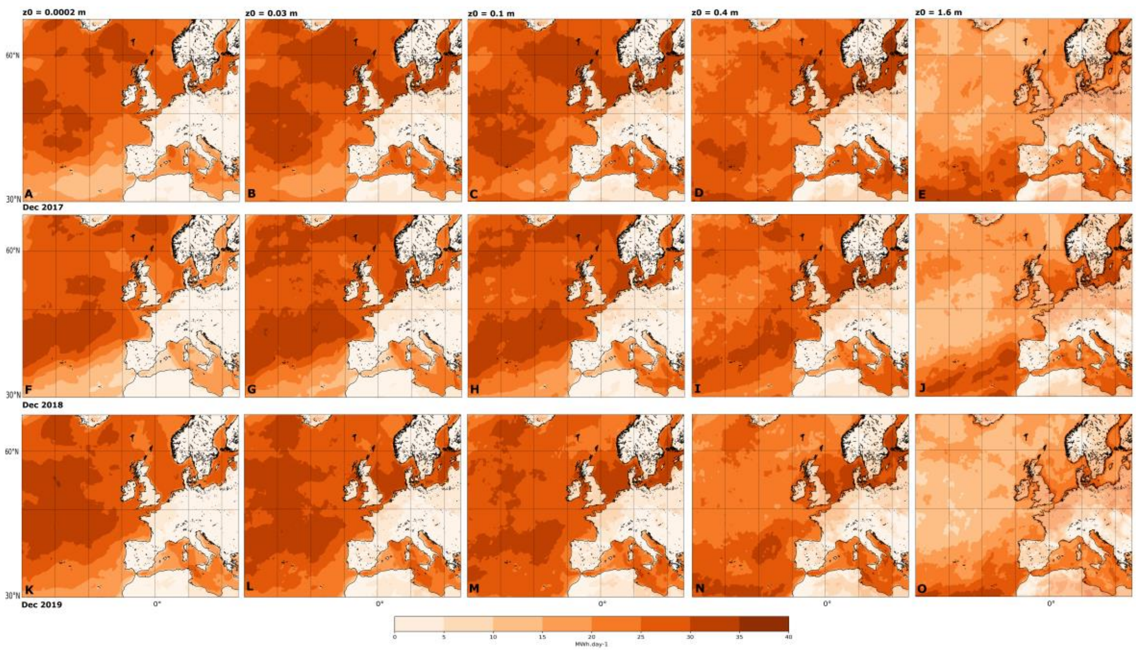

Figure S1. Wind Energy Potential (WEP) (MWh.day^{-1}): December 2017 (A), (B), (C), (D) and (E); December 2018 (F), (G), (H), (I) and (J); December 2019 (K), (L), (M), (N) and (O); Calculations made using equation 1 (LogL); (A), (F) and (K) calculations made using 0.0002m as z_0 coefficient; (B), (G) and (L) calculations made using 0.003 m as z_0 coefficient; (C), (H) and (M) calculations made using 0.1 m as z_0 coefficient; (D), (I) and (N) calculations made using 0.4 m as z_0 coefficient; (E), (J) and (O) calculations made using 1.6 m as z_0 coefficient, for the respective months of each year.

In relation to Figure S1, we see that the first column (Fig.S1 A, F, K) refers to a value of z_0 for offshore regions and the remaining columns correspond to values of z_0 for onshore conditions. This analysis was repeated for the three months of December (2017, 2018 and 2019) under study.

In general, it is notable that when we increase the value of z_0, the roughness of the land is devalued allowing the increase of WEP in the onshore regions. This pattern is similar for the 3 months under study. The second column (Figures S1. B, G, L) with the value of $z_0 = 0.03$ m is the reference for comparison between the different figures (columns), considering that it was the value of z_0 used in the entire study.

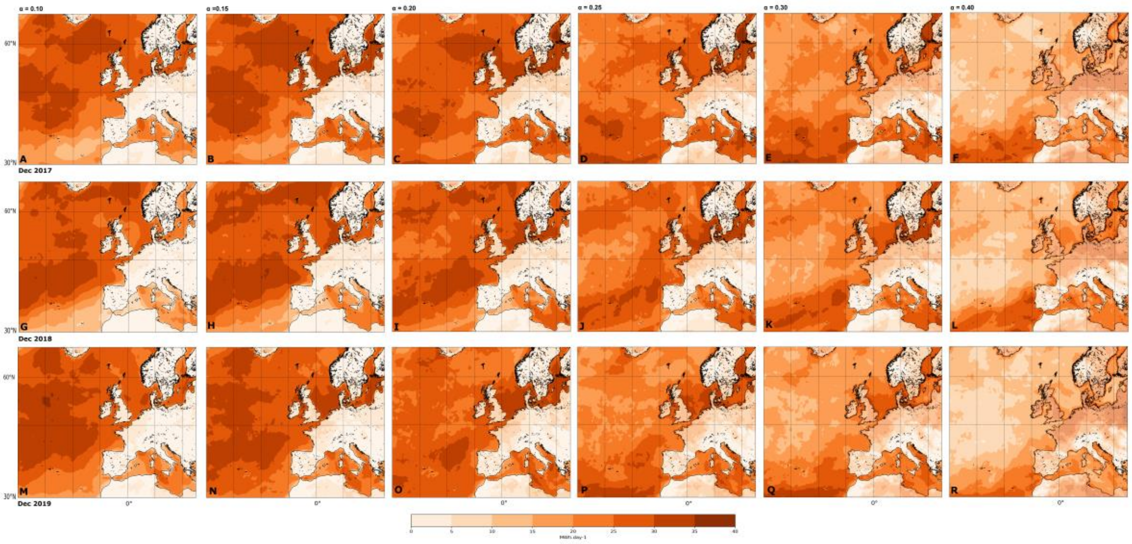

Figure S2. Wind Energy Potential (WEP) (MWh.day^{-1}): December 2017 (A), (B), (C), (D), (E) and (F); December 2018 (G), (H), (I), (J), (K) and (L); December 2019 (M), (N), (O), (P), (Q) and (R); Calculations made using equation 2 (PL); (A), (G) and (M) calculations made using 0.10 as α coefficient; (B), (H) and (N) calculations made using 0.15 as α coefficient; (C), (I) and (O) calculations made using 0.20 as α coefficient; (D), (J) and (P) calculations made using 0.25 m as α coefficient; (E), (K) and (Q) calculations made using 0.30 m as α coefficient; (F), (L) and (R) calculations made using 0.40 m as α coefficient, for the respective months of each year.

In relation to Figure S2, the first column (Fig. S2 A, G, M) corresponds to the α value for offshore conditions (α = 0.10) and the remaining columns (figures) correspond to α values for onshore conditions. As the α value increases, the WEP values increase in the onshore regions, and there is a decrease in the offshore regions. This means that when we increase the value of the friction coefficient of the terrain, the influence of this parameter in the extrapolation of the wind speed is neglected, thus allowing to obtain higher values of WEP in the onshore regions. The third column (Fig. S2 C, I, O) with the value of α = 0.20 is the reference for comparison between the different figures (columns), since it was the value used in the entire study.

In Figures S1 and S2, the low WEP values in the mountainous regions of the Pyrenees and Alps should be highlighted, with this pattern being maintained in all figures.

Disruption risk analysis of the overhead power lines in Portugal

Ana Gonçalves, Margarida Correia Marques, Sílvia Loureiro, Raquel Nieto, Margarida L.R. Liberato

Energy

Supplementary material

Table A1. Level of probability. (Adapted: [16,79,80,82,90-94]).

Probability/Level	***Description***
High (5)	It is expected to occur in almost all circumstances. High level of recorded incidents. Strong evidence. Strong probability of occurrence of the event. Strong reasons to occur. It can occur once a year or more.
Medium-high (4)	It will likely occur under almost all circumstances. There are regular records of incidents and strong reasons for their occurrence. It can occur once every five years. It can occur once in periods of 5-10 years.
Medium (3)	It might happen at some point. It can occur with an uncertain periodicity, randomness, and/or with weak reasons to occur. It can occur once every 20 years. It can occur once in periods of 20-50 years.
Medium-low (2)	It's not likely to happen. There are no records or reasons that lead to the estimate that they occur. It can occur once every 100 years.
Low (1)	It may only occur in exceptional circumstances. It can occur once every 500 years or more.

Table A2. Level of severity (consequence). (Adapted: [16,79,80,82,90-94]).

Severity/Level	***Impact***	***Description***
Residual (1)	Environment	No impact.
	Socioeconomics	Absence or reduced level of constraints in the community. No financial loss.
Reduced (2)	Environment	Small impact on the environment, no lasting effects.
	Socioeconomics	Disruption (less than 24 hours). Some financial loss.
Moderate (3)	Environment	Small impact on the environment, no lasting effects.
	Socioeconomics	Some disruption in the community (less than 24 hours). Some financial loss.
Accentuated (4)	Environment	Some impacts with long-term effects. Partial community functioning with some services unavailable.
	Socioeconomics	Significant loss and necessary financial assistance.
Critical (5)	Environment	Significant environmental impact and/or permanent damage.
	Socioeconomics	The community fails to function without significant support.

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