

# Simplified Seismic Risk Assessment of Offshore Wind Turbines: A Case Study in Greece

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## ABSTRACT

Floating offshore wind turbines are emerging as a key technology for renewable energy generation, yet their deployment in seismically active regions remains a challenge. Greece, with its extensive coastline, is a prime candidate for such an assessment. This work presents a simplified seismic risk assessment framework for floating turbines. The case study explores the potential deployment of small tension-leg platform (TLP) systems in Greek offshore regions, having seismic risk as the decision metric. For this, hazard information from the latest European Seismic Hazard Model, ESHM20, is integrated with recently published fragility functions for TLP systems, while water depth is explicitly considered as a key variable influencing seismic response. By combining hazard and fragility data, the framework helps build a view of risk for the studied assets. The study demonstrates how such a simplified approach can support not only engineering-oriented site screening and design considerations, but also the development of a consistent view of seismic risk relevant for offshore wind planning and insurance-related applications.

*Keywords: Seismic risk assessment, Floating offshore wind turbines, Catastrophe management, Insurance*

## INTRODUCTION

Offshore wind energy is expanding rapidly as part of the global transition to renewable-energy solutions. Ambitious targets for offshore renewable energy have been set for the coming decades, with the European Commission calling for offshore wind capacity to grow to at least 60 GW by 2030 and 300 GW by 2050 within the EU. As technological advancements have enabled approaching deeper waters, floating wind technology is expected to play a key role in the next phase of offshore wind development.

At the same time, offshore wind farms are being considered in regions with more complex environmental and geophysical conditions. Among these, seismic hazard - although less frequent than other perils such as wind and wave loading - can have disproportionate consequences for offshore infrastructure. Beyond structural damage, earthquake-induced damage may lead to extended downtime, costly repairs, and significant financial losses, making seismic risk a relevant consideration not only for engineering design but also for risk management, insurance planning, and investment decision-making. For floating wind turbines, seismic loading may affect both the floating platform and critical components such as mooring systems and nacelle equipment, potentially leading to loss of functionality and costly downtime (James et al., 2026).

This issue is especially relevant for Greece and the broader eastern Mediterranean region. Greece has one of the highest seismic hazard levels in Europe, due to its complex tectonic setting (see e.g. Danciu et al., 2024). At the same time, the country's offshore bathymetry is characterized by deep waters close to the coast, which strongly favors floating wind solutions over fixed-

bottom foundations. Recent studies on offshore wind development in Greece have identified several potentially suitable areas - particularly in parts of the Aegean Sea - based on wind resources, water depth, and spatial planning constraints (Chalastani et al., 2025). However, these assessments typically focus on technical feasibility, environmental considerations, and socio-economic factors, while seismic risk is not explicitly addressed in a quantitative and comparable manner. This limits the ability of stakeholders - such as developers, planners, and insurers - to build a consistent view of risk across candidate offshore locations.

From an engineering perspective, in recent years researchers have begun to study the seismic performance of floating wind turbines, including spar, semi-submersible, and tension-leg platform (TLP) systems (Li et al., 2025; James et al., 2026; Kaynia et al., 2023). These studies indicate that TLP-supported turbines may be particularly sensitive to earthquake loading, due to their stiff vertical response and the dynamic behavior of their tendons. They also show that seismic response can vary significantly with key parameters such as turbine capacity (indicative of the dimensions of the turbine) and water depth.

Despite these advances, there remains a gap between detailed structural analyses and practical, transparent tools that can support offshore wind planning at a regional scale. In particular, there is a need for simplified risk-based frameworks that combine seismic hazard and fragility information in a way that allows consistent comparison across many potential offshore sites. Such frameworks are valuable not only for early-stage engineering and site screening, but also for building a view of risk that can inform insurance planning and broader financial decision-making.

In this context, the present study evaluates the seismic risk of small floating offshore wind turbines in Greek waters via a simplified framework. The analysis combines site-specific seismic hazard information derived from the European Seismic Hazard Model (ESHM20) (Danciu et al., 2021) with existing fragility functions for floating offshore wind turbines based on the work of James et al. (2026). A representative small-scale (5 MW) TLP-supported turbine is considered, and nacelle damage is selected as a key performance indicator. The results aim to support risk-informed offshore wind planning in seismically active regions, while also demonstrating how different risk metrics can be used to inform insurance-related applications.

## **METHODOLOGY**

The risk assessment framework adopted in this study is based on the explicit definition of exposure, hazard, and fragility components. The exposure input defines the assets at risk, their geolocation, and their relevant characteristics. The hazard component describes the intensity and frequency of the expected hazard at the site of interest. The fragility model describes the probability of damage conditional on the hazard level. The definition of these three components constitutes the core of the risk calculation, as discussed in the following.

### **Exposure**

The study area is comprised of 1807 sites located in the southeastern Aegean Sea, Greece, shown in Figure 1a in cyan. This area was selected to capture a representative range of offshore conditions relevant to earthquake risk assessment of wind turbines. In particular, the region exhibits significant spatial variability in both seismic hazard and bathymetry, while it also overlaps with areas identified in the literature as technically suitable for offshore wind development (see e.g. Chalastani et al., 2025). The case study explores challenges for small-size (5 MW capacity) TLP floating wind turbines (Figure 1b) that could be deployed in this region, with particular emphasis on nacelle damage. TLPs represent an increasingly attractive solution for offshore wind deployment due to their adaptability to varying environmental conditions and water depths, while their nacelle is a critical component governing system functionality and operational performance (James et al., 2026).

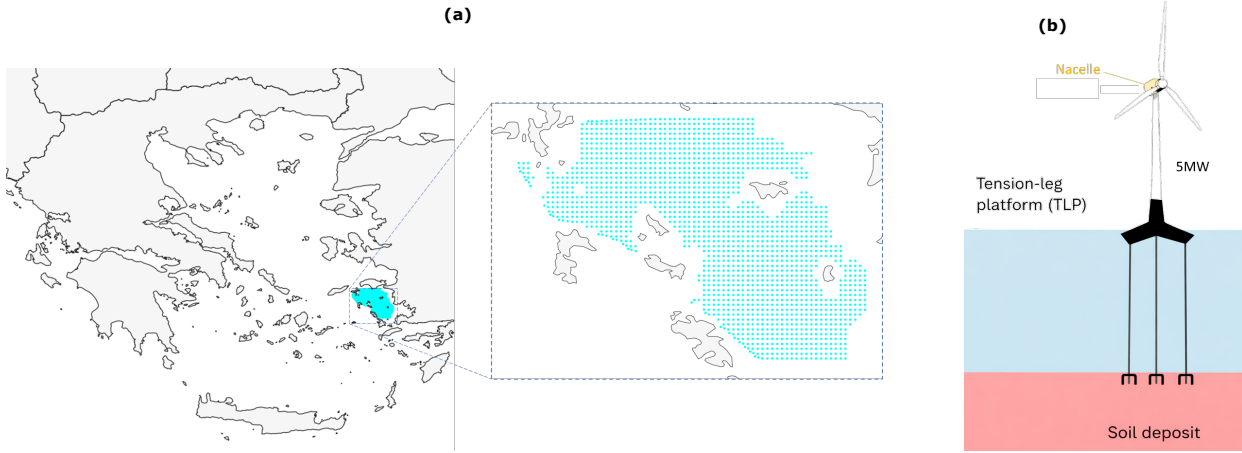


**Figure 1.** Location of the case study (a), and illustration of the considered turbine type (b).

## Hazard

Seismic hazard information was obtained from the latest European Seismic Hazard Model, the ESHM20 version (Danciu et al., 2021), and is expressed in terms of peak ground acceleration, PGA, at rock. The hazard data in ESHM20 is given in terms of accelerations for various probabilities of exceedance in 50 years,  $P_{50}$ . In order to refer to annual values, these probabilities are converted into mean annual frequency of exceedance, MAF, as follows (Eads et al., 2013; Silva et al., 2016):

$$\text{MAF} = -\frac{\ln(1 - P_T)}{T} = -\frac{\ln(1 - P_{50})}{50} \quad (1)$$

The data was further interpolated linearly in log-log space to build the hazard curves shown in Figure 2a, which provides the median (50th percentile) PGAs with corresponding MAFs across all sites. The curves are colored by the relative (percentile) ranking of site depth, with the colorbar labeled in meters using the corresponding depth values. It is noticed that there are overlaps across the depth range (i.e. sites with similar bathymetry exhibit different hazard levels). In Figure 2b, the spatial distribution of the 475-year PGA,  $\text{PGA}_{475}$ , over the study area is presented for benchmarking of the seismicity, together with a histogram to summarize its distribution.

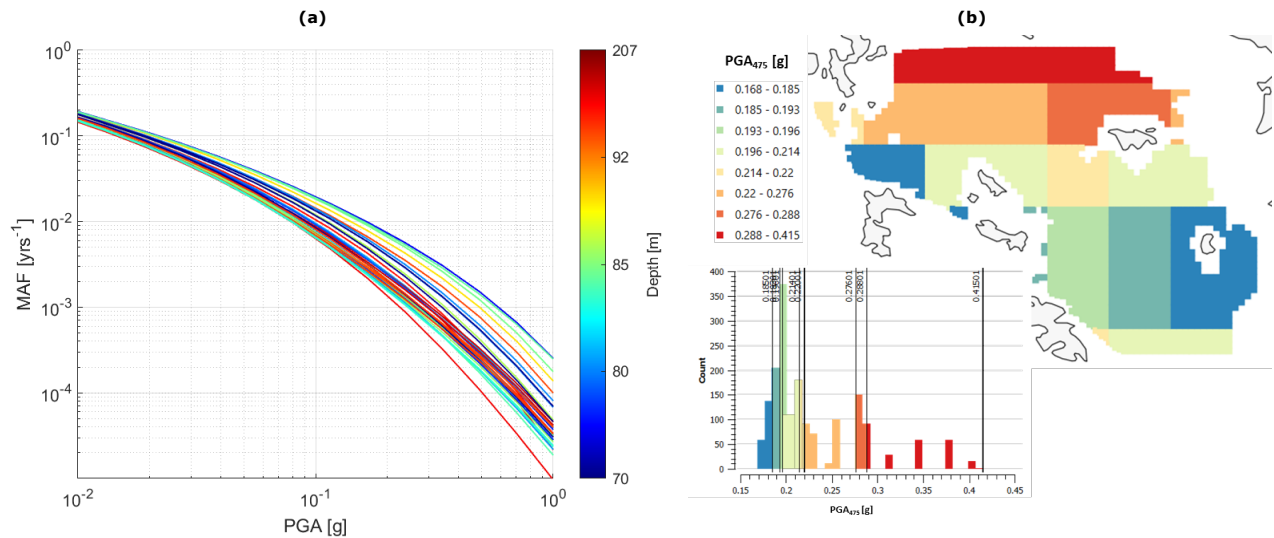


**Figure 2.** Seismic hazard of the studied region: (a) hazard curves, and (b) 475-year PGA.

## Fragility

In this study, water depth is treated as a fragility characteristic, considering it influences the structural response and damage mechanisms for a given level of shaking. For this reason, bathymetry information is collected from the General Bathymetric Chart of the Oceans (GEBCO,

2025) and presented in Figure 3, showing a map with the spatial variation of water depth as well as a histogram of its distribution across the assessed sites.

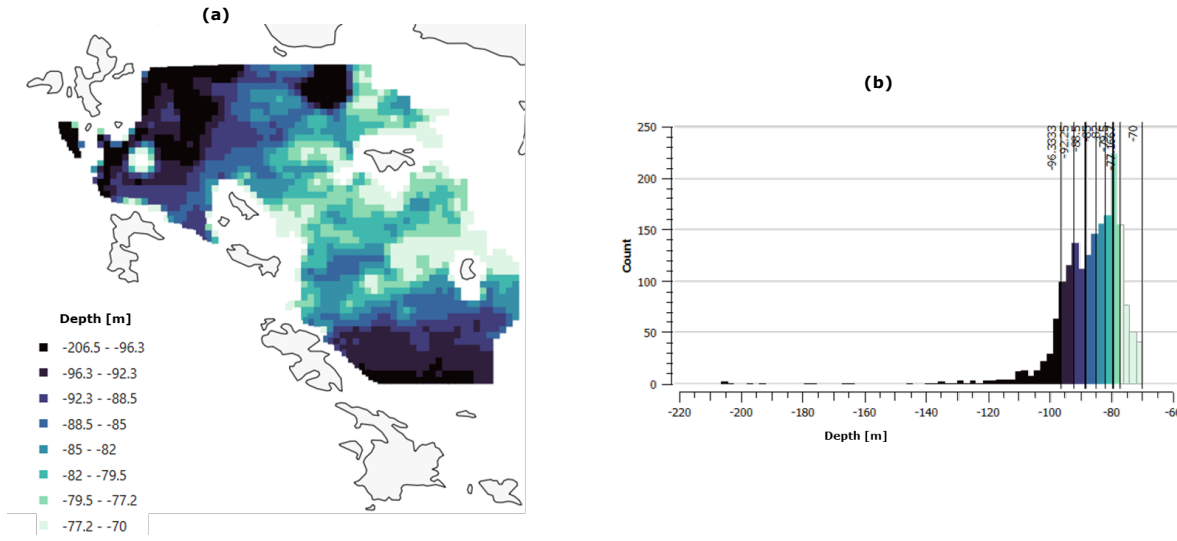


**Figure 3.** Bathymetry data for the region: (a) spatial variation, (b) summarizing histogram.

Next, for fragility assessment, a connection needs to be established between seismicity, water depth, and the probability of damage exceedance. A recently published article (James et al., 2026) presents seismic fragility curves for offshore floating wind turbines. As concluded in that article, nacelle acceleration is the most critical factor affecting the TLP wind turbines under seismic shaking. For this, the focus herein is on nacelle damage for a 5 MW TLP-supported wind turbine, using the published fragility curves reported for three discrete water depths: 70 m, 100 m, and 150 m. James et al. (2026) show that with increasing depth, the fragility is decreased, and for nacelle acceleration the median of their developed fragility curves increases from 0.22 g (70 m) to 0.35 g (100 m) and 0.43 g (150 m). The fragility functions in that work implicitly account for hydrodynamic effects through the underlying numerical simulations used in their derivation. However, in the present simplified framework, hydrodynamic loading is not independently modeled or varied, and its influence is therefore embedded within the fragility relationships rather than explicitly treated.

To consider herein a broader range of depths, the median,  $\theta$ , and standard deviation,  $\beta$ , of a lognormal distribution that approximates the published fragility curves are first defined and then extrapolated as continuous functions of depth, as shown in Figure 6a. It is noted that the dispersion is considered constant herein, taken as the average of the available data, i.e.  $\beta=0.54$ , to avoid unrealistic crossovers of the curves. Figure 6b shows the resulting fragility curves for the various locations, colored according to the local water depth (using the color ramp discussed in Figure 2a) to illustrate the depth-dependent fragility behavior. As depth increases the fragility curve shifts to the right, showing a less fragile system.

It should be highlighted that the reference fragility study of James et al. (2026) provides results for only three discrete water depths, while the bathymetry of the examined region varies continuously. To apply the methodology consistently across all sites, the fragility parameters are expressed herein as depth-dependent continuous functions obtained through interpolation of the available data and extrapolation where required. The dispersion parameter is assumed constant, taken as the average of the reported values, to avoid unrealistic crossover among fragility curves. This simplified approach allows fragility curves to be assigned across all sites, but it also introduces additional uncertainty. In addition, the focus herein is on the effects of hazard and depth variation on the seismic risk. Soil conditions are assumed to be uniform across all sites, consistent with the reference fragility study and future work may incorporate the effects of spatial variability in soil stratigraphy.

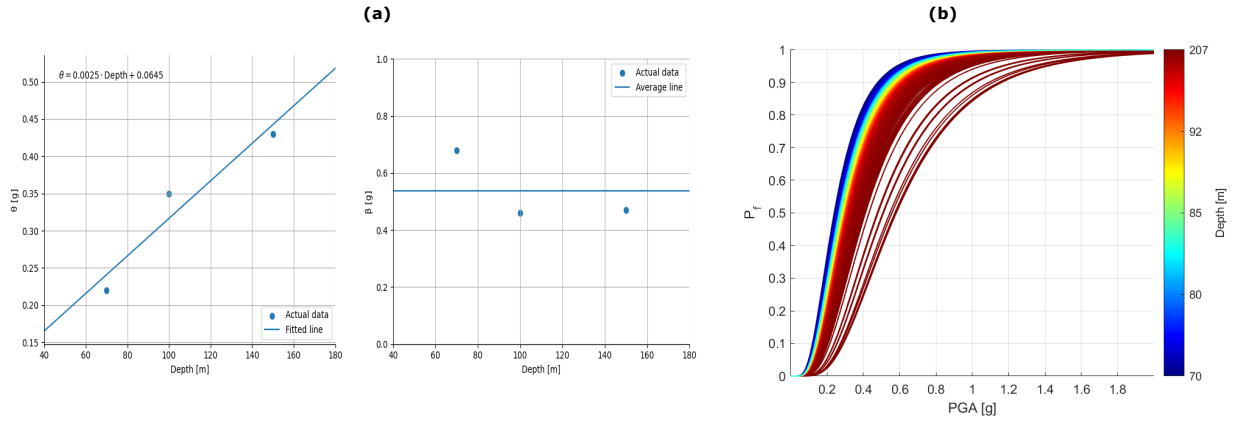


**Figure 4.** Fragility curves for varying PGA and water depths: (a) considered relationship of depth vs fragility parameters, and (b) resulting curves for all sites.

## Risk

As discussed in Figure 2, PGA and depth do not follow the same distribution across the studied region, and thus there can be areas with higher PGAs which increase fragility, but having also deeper waters which in opposite reduces the fragility. This highlights the need for risk-based metrics that consider the interaction of hazard and fragility to rank the regions according to the corresponding risk level.

A 'damage-based' risk metric,  $\lambda_c$ , is utilized herein which gives the mean annual frequency (MAF) of having damage at the nacelle. Analytically, risk can be evaluated by convolution of the fragility curve of the nacelle failure, showing the probability of reaching or exceeding different intensity measure (IM) levels,  $P_f(IM)$ , and the hazard curve of the assessed location,  $H(IM)$ , which provides the MAF of exceeding that IM levels, according to the following equation (e.g. Kennedy, 2011):

$$\lambda_c = \int P_f(IM) \cdot |dH(IM)| \quad (2)$$

where  $|dH(IM)|$  denotes the absolute value of  $dH(IM)$ , with  $d$  being the differential operator.

Additionally, risk curves can be generated expressing the MAF of reaching a  $P_f$ , similar to the loss exceedance curves that are used in the insurance industry (see Figure 3 in Gkimprxis et al., 2021). Essentially, the area below such curves equals to  $\lambda_c$ .

## RESULTS

Following the methodology and input data described in the previous section, the hazard curves and depth-dependent fragility functions were combined to derive risk curves for each site. Figure 5 shows the resulting risk curves expressing the MAF of exceeding different probabilities of having failure at the nacelle. The left plot presents the curves colored according to water depth, while the right panel shows the same curves colored according to the site-specific  $PGA_{475}$ . The two coloring representations highlight different drivers of seismic risk.

In general, higher risk levels for the nacelle are associated with combinations of high seismic hazard and shallow water depth, whereas the lowest risk levels correspond to sites characterized by low seismicity and deep waters. It is interesting to notice however, that the ordering of the risk curves when looking independently at the water depth or the  $PGA_{475}$  is not clear (similar to the comment for the hazard curves). Sites with greater water depths may experience lower fragility but can still be associated with relatively high risk if subjected to high hazard levels. Conversely, shallow-water sites with lower seismic hazard may exhibit comparable or lower risk.

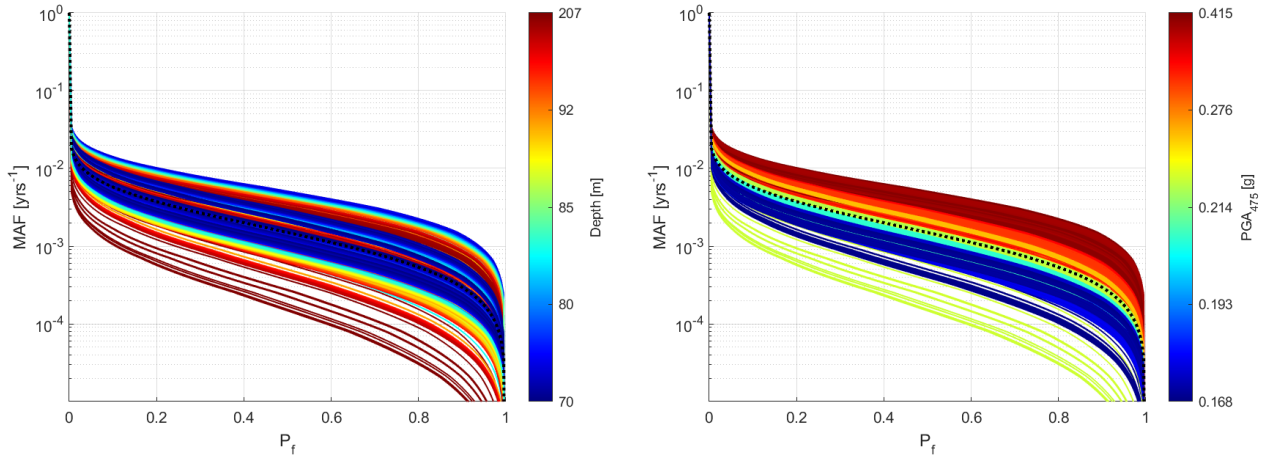


**Figure 5.** Risk curves of the studied locations, colored: (a) by depth, and (b) by  $PGA_{475}$ .

Next, the MAF of nacelle failure for each site is calculated, using Equation 2 (or calculating the area under each risk curve). The resulting  $\lambda_c$  values are shown in Figure 6, providing insights into the combined effects of seismicity and water depth on seismic risk. The results again highlight the systematic increase in risk for shallower sites within comparable hazard levels. As noted above, the highest risk levels are generally associated with combinations of high seismic hazard and shallow water depths, while the lowest risk levels correspond to low hazard and greater depths. Panels (b) and (c) demonstrate clearly the fact that seismic risk depends not only on hazard intensity but also on depth-dependent structural response, whereas the grouping of panel (a) helps to view the effect of depth in regions of comparable hazard conditions.

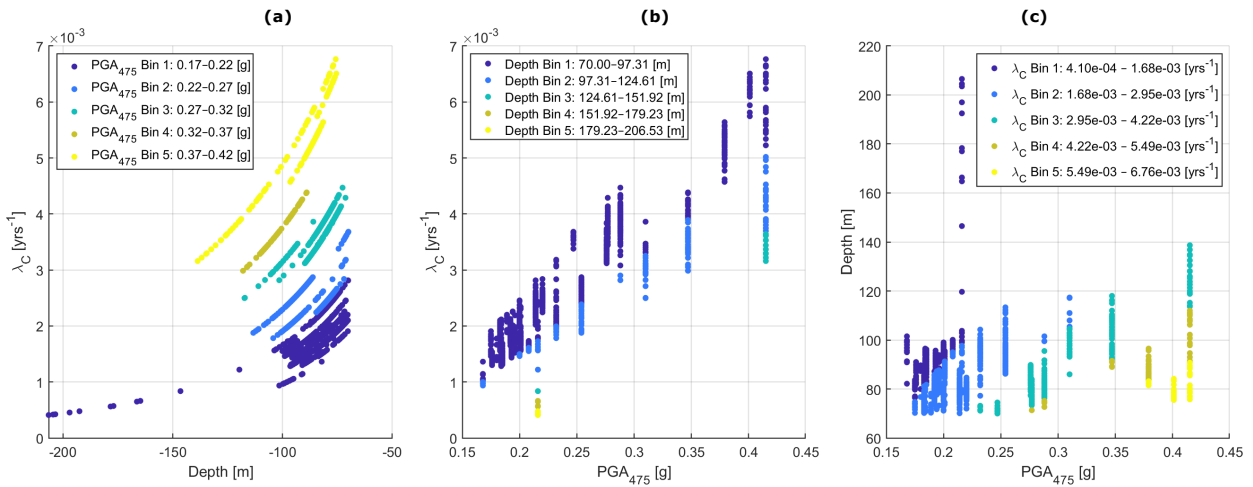


**Figure 6.** Risk results for all locations in relation to location depth and  $PGA_{475}$  data.

The spatial distribution of these values is shown in Figure 7, providing the risk map together with the corresponding histogram. Comparing this map with the inputs in Figure 2 and Figure 3 highlights that the spatial pattern of  $\lambda_c$  can help understand the interaction of spatially variable hazard and depth-conditioned fragility. As discussed, the highest  $\lambda_c$  values emerge in locations where higher seismic hazard coincides with shallow-water conditions and conversely, lower  $\lambda_c$  values are generally associated with areas of lower hazard and greater water depths.

From a practical perspective, the absolute magnitude of the reported risk values provides an indication of the annual frequency scale at which nacelle damage may be expected. Nevertheless, under the present simplified assumptions, these values should be interpreted mainly as comparative metrics for regional screening and prioritization of candidate sites, rather than as definitive thresholds for design or investment decisions. The risk map provides guidance for decision-making, allowing the direct identification of locations that are more or less suitable for the deployment of TLP-supported wind turbines, based on the defined criterion (i.e. damage to nacelle due to earthquake excitation). By synthesizing hazard and vulnerability information into a risk profile, the map enables rapid screening of candidate sites for planning and site

selection, as well as prioritization of mitigation measures and insurance pricing, depending on the priorities of the involved stakeholders.

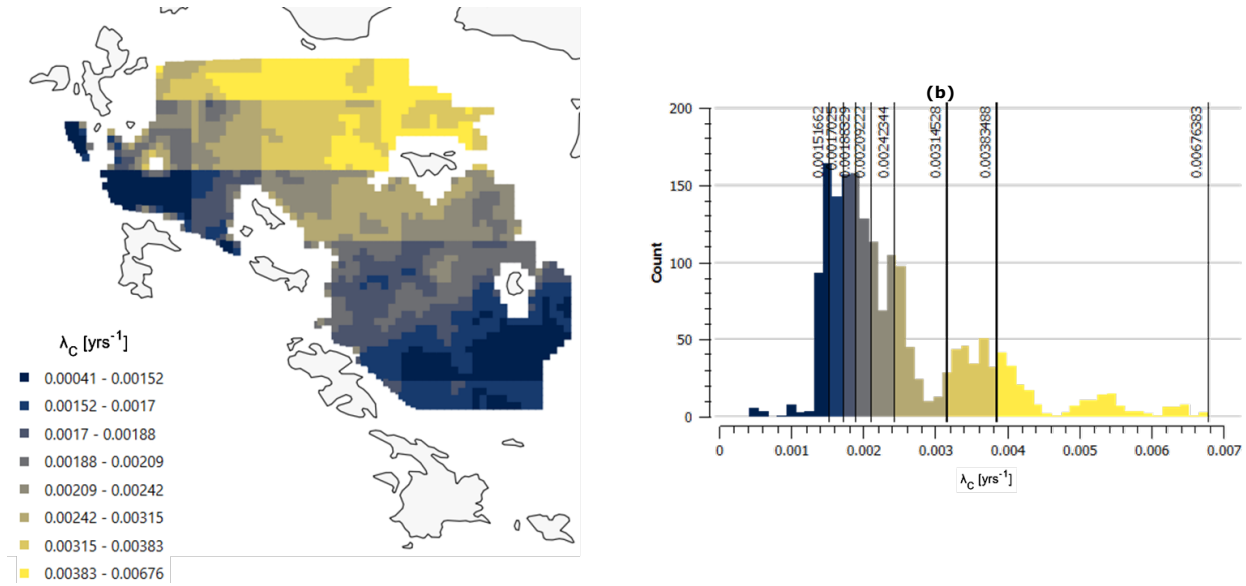


**Figure 7.** Risk distribution across the studied area.

## CONCLUSIONS

This study presented an analytical framework for seismic risk assessment of offshore wind turbines, with particular emphasis on nacelle damage at small (5 MW) TLP-supported turbines. By combining site-specific seismic hazard with depth-dependent fragility functions, the framework enables the derivation of risk curves and mean annual frequencies of damage, allowing direct comparison across different sites.

The application to the southeastern Aegean Sea highlights that seismic risk cannot be inferred from hazard intensity or water depth alone, as risk emerges from the interaction between spatially variable seismicity and depth-conditioned structural response. The resulting risk curves and maps provide practical tools for early-stage site screening and comparative assessment of deployment alternatives, supporting risk-informed decision-making in regions characterized by varying water depths and elevated seismic hazard.

Limitations of the present work point toward important directions for future research. First, the analysis is conducted using PGA as the sole IM. Future extensions of this framework could explore alternative IMs (e.g. spectral acceleration at selected periods or energy-based measures) and assess their influence on fragility and risk estimates. For example, previous research (Gkimprxis, 2024) has implemented the framework presented herein and investigated the effect of alternative IM choices on seismic risk estimates.

Second, the focus of the present study is limited to damage at the nacelle. Although the nacelle is a critical component, offshore wind turbines are complex systems comprising multiple interacting assets, including blades, tower, floating foundation, mooring lines, and export and inter-array cables. Moreover, while nacelle response is influenced by the overall dynamic behavior of the coupled TLP system, including tendon and foundation conditions, it should not be interpreted as a proxy for explicit tendon- or foundation-related failure modes. A more detailed system-level risk assessment would require the consideration of multiple damage states across these components, as well as their potential interdependencies. In addition, alternative foundation systems, whether floating (e.g. spar, semisubmersible) or fixed-bottom (e.g. monopile, jacket, gravity-based), exhibit different dynamic behavior, and future research could investigate the resulting seismic risk sensitivity.

Extending the framework from damage-based metrics to loss-based metrics would further enhance its relevance for stakeholders. In this context, approaches commonly used in the insurance industry - such as loss exceedance probability curves and expected annual loss - could be adopted, moving beyond failure probabilities toward quantification of economic

consequences. Unit costs and repair characteristics play a central role in this. Damage of some assets may not necessarily dominate risk if their replacement or repair costs are relatively low, whereas less fragile but high-value components may control overall losses. Moreover, offshore-specific factors such as repair duration, accessibility, weather windows, mobilization and demobilization costs, and business interruption can significantly influence total losses and should be explicitly accounted for in future studies.

Another important assumption concerns seabed conditions. In the present work, soil conditions are implicitly assumed to be uniform across all sites. Although this assumption helps highlight the effects of hazard and water depth, spatial variability in soil properties and stratigraphy can also significantly influence the resulting fragility and risk estimates. Incorporating site-specific geotechnical information would therefore be a natural extension of the framework.

Finally, this study focuses on seismic risk. In practice, offshore wind turbines are exposed to multiple hazards, including wind, waves, and potentially combined or sequential loading effects. A comprehensive risk-informed planning framework would require the integration of seismic risk with other relevant perils, as well as non-structural decision constraints such as environmental protection zones, maritime traffic, regulatory and political considerations, and spatial planning restrictions (e.g. UNESCO-protected areas).

Concluding, the proposed framework demonstrates how hazard and damage information can be combined to provide transparent, quantitative, and scalable risk metrics for floating offshore wind turbines. By highlighting both its capabilities and limitations, this work lays the foundation for more comprehensive multi-asset, multi-hazard, and loss-oriented risk assessments to support resilient offshore wind deployment in seismically active regions.

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