

Revisiting Maximum Magnitude Assumptions Within the Development of Loviisa's Seismic Hazard Assessment

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Abstract: Finland's low-seismicity environment presents substantial challenges for probabilistic seismic hazard analysis (PSHA), as the sparse regional earthquake catalogue leads to significant uncertainty in modelling key parameters. Among these, the maximum magnitude (m_{\max})—the upper bound on physically credible earthquake size—plays a central role in shaping hazard estimates for nuclear facilities.

This paper discusses and applies a Fennoscandia-specific prior distribution for m_{\max} , constructed using analogue stable continental region (SCR) domains selected based on geological age and constrained by an updated earthquake catalogue compiled from the International Seismological Centre Bulletin. The resulting prior systematically favours lower maximum magnitudes than the more global SCR priors commonly employed in Finnish PSHAs.

Consistent with current national practice, the Bayesian posterior distribution was combined with the existing Kijko distribution using equal weighting, and subsequently discretised using a five-point Miller–Rice approximation for implementation in the Loviisa PSHA. Incorporation of the revised m_{\max} distribution leads to a uniform but modest reduction in seismic hazard across frequencies and exceedance levels, reflecting the dominant role of low-to-moderate magnitude earthquakes in Finland's hazard profile.

1. INTRODUCTION

Loviisa Nuclear Power Plant (NPP) consists of two VVER-440 type pressurized water reactor units, each with a net electrical output of 507 MW, located on the southern coast of Finland. Unit 1 began commercial operation in 1977, followed by Unit 2 in 1980. The plant is notable for its unique combination of Soviet reactor technology and Western-designed safety, and its overall operating risk has been significantly reduced over the decades through extensive modifications and updates [1, 2].

In 2023, the Finnish government granted the Loviisa NPP a renewed operating license valid until the end of 2050. This long-term extension drives a broad modernisation programme encompassing multiple investment portfolios and hundreds of individual projects. Probabilistic risk assessment (PRA) plays a central role in prioritizing these projects, guiding the selection of systems and components for upgrades and helping to define appropriate target levels for their improvements.

As the risks from internal events—such as individual equipment failures and human errors—have been substantially mitigated through previous upgrades, external hazards have become relatively more important. Among these, earthquakes constitute a key contributor to the remaining risk. Recent sensitivity studies [3–5] and reviews of Loviisa's seismic hazard assessment [6, 7] demonstrate that small variations in certain model parameters can have profound impacts on the total seismic hazard. Ensuring that these parameters are well justified and based on robust evidence, rather than coarse assumptions, is therefore essential.

This paper discusses the methods and implications associated with defining the maximum earthquake magnitude (m_{\max}) in Loviisa's probabilistic seismic hazard analysis (PSHA), as presented in a 2026

Master's thesis [8]. Additionally, it briefly summarizes broader PSHA developments in Finland during the 2020s. Section 2 describes the PSHA framework for the Loviisa NPP, Section 3 presents the methodology used to assess m_{\max} , Section 4 outlines the hazard calculation approach, and Section 5 presents the results. Finally, Section 6 provides the overall summary and conclusions.

2. PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR THE LOVIISA NPP

PSHA is a methodology developed to quantify the likelihood of different levels of earthquake-induced ground shaking at a specific location over a given time period. Its primary objective is to integrate information on seismic sources, their recurrence behaviour, and applicable ground motion models to estimate the annual frequency of exceedance (AFE) for various ground motion intensities. Unlike deterministic seismic analysis, which focuses on a single bounding earthquake scenario, PSHA accounts for the full distribution of possible future earthquakes and their probabilities. The results are typically expressed through hazard curves, uniform hazard response spectra (UHRS), and peak or spectral acceleration values (PGA and SA) at selected frequencies. [9]

The original design of the Loviisa NPP did not account for earthquakes of any magnitude, reflecting the prevailing design philosophy in low-seismicity regions at the time. As the understanding of nuclear safety and seismic risk evolved, seismic considerations were gradually incorporated into the plant's safety assessments.

The first site-specific PSHA for Loviisa dates back to the early 1990s [10], although earlier regional seismic hazard studies for Southern Finland had already been conducted in the 1970s and 1980s (e.g. [11]). Since the initial plant-specific assessment, the hazard framework has undergone several major updates to incorporate new geological and seismological information. A significant improvement occurred in 2016, when the hazard analysis was re-evaluated using updated ground-motion models and a newly defined seismic source zonation proposed by Korja et al. [12].

Following the 2016 revision, Loviisa's PSHA has been continually refined, with official hazard estimates produced in 2018, 2021, and 2024. Compared with the earliest assessments, these updates have resulted in a notable increase in the estimated seismic hazard. A further revision is planned for 2026, incorporating the findings of the most recent Master's thesis work [8].

During the 2020s, particular attention has been given to the Gutenberg–Richter (GR) parameters, which were identified as having strong influence on the resulting hazard estimates [5]. The GR relationship,

$$\log_{10}(n(m)) = a - bm,$$

describes the cumulative number of earthquakes $n(m)$ with magnitude $\geq m$ [13]. The parameter a represents the overall activity rate within a seismic source, while the parameter b reflects the relative proportion of small to large earthquakes.

Visakorpi [5] demonstrated that the choice of the method used to estimate these parameters is critical. In the 2021 PSHA, the GR parameters were derived using a least squares (LS) regression approach that fits a linear regression model to the seismic data. However, this method has been criticised for violating the fundamental assumptions of regression analysis that can bias the results [14].

These concerns motivated reconsideration of the maximum likelihood estimation (MLE) method. The MLE approach for estimating the b -value was originally introduced by Aki in 1965 [15] and has since been widely applied in seismicity analyses, with slightly varying formulations. The applicability and robustness of the MLE method in the Finnish low-seismicity context were further supported by the verification work conducted by Heikkilä [16].

The MLE method was incorporated into Loviisa's PSHA following the implementation described in Vehmas' 2024 Master's thesis [17]. In the 2024 hazard model, both LS and MLE parameter sets were

assigned equal weights, as the rationale behind the earlier use of LS in the 2021 assessment was not fully understood. However, in the forthcoming 2026 update, the LS method is expected to be fully replaced by the MLE approach, which is also supported by the independent review of Loviisa's PSHA by the University of Helsinki [7].

Vehmas [17] demonstrated that employing MLE instead of LS regression leads to substantially lower seismic hazard estimates for the Loviisa site. His work further refined the GR parameters using an updated Fennoscandian earthquake catalogue, thereby providing a more current and robust basis for the forthcoming hazard reassessment. In addition, the sensitivity of the results to catalogue completeness was examined, with alternative completeness models explicitly incorporated into the parameter estimation to account for related epistemic uncertainty.

3. ESTIMATION OF THE MAXIMUM MAGNITUDE

Building on prior PSHA developments for the Finnish nuclear sites, Asikainen's 2026 Master's thesis [8] analysed the sensitivity of seismic hazard estimates to both the definition of seismic source zones and the maximum magnitude parameter (m_{\max}), which defines the upper bound on physically possible earthquake size within each source. A portion of the thesis also contributed to the ongoing study by Mäntyniemi et al. [18], which focuses on updating the Bayesian probability distribution of m_{\max} by revising the 2012 Electric Power Research Institute (EPRI) Stable Continental Region (SCR) database (Appendix K.1 of [19]) for analogue domains relevant to Fennoscandia. This section outlines the workflow used to assess m_{\max} for the Fennoscandian region, including the approach for updating the SCR catalogue.

3.1. Methodology

Because no active faults capable of hosting large earthquakes have been identified and characterised in Fennoscandia, deterministic approaches that estimate m_{\max} from fault geometry or slip rates are not feasible [9]. Consequently, probabilistic methods must be applied. Two of the most widely used methods are the Bayesian approach developed by Johnston et al. [20] and the Kijko method introduced by Kijko [21]. The Bayesian method combines observed local seismicity with prior information drawn from globally similar tectonic settings, whereas the Kijko method relies solely on the statistical distribution of regional earthquake magnitudes.

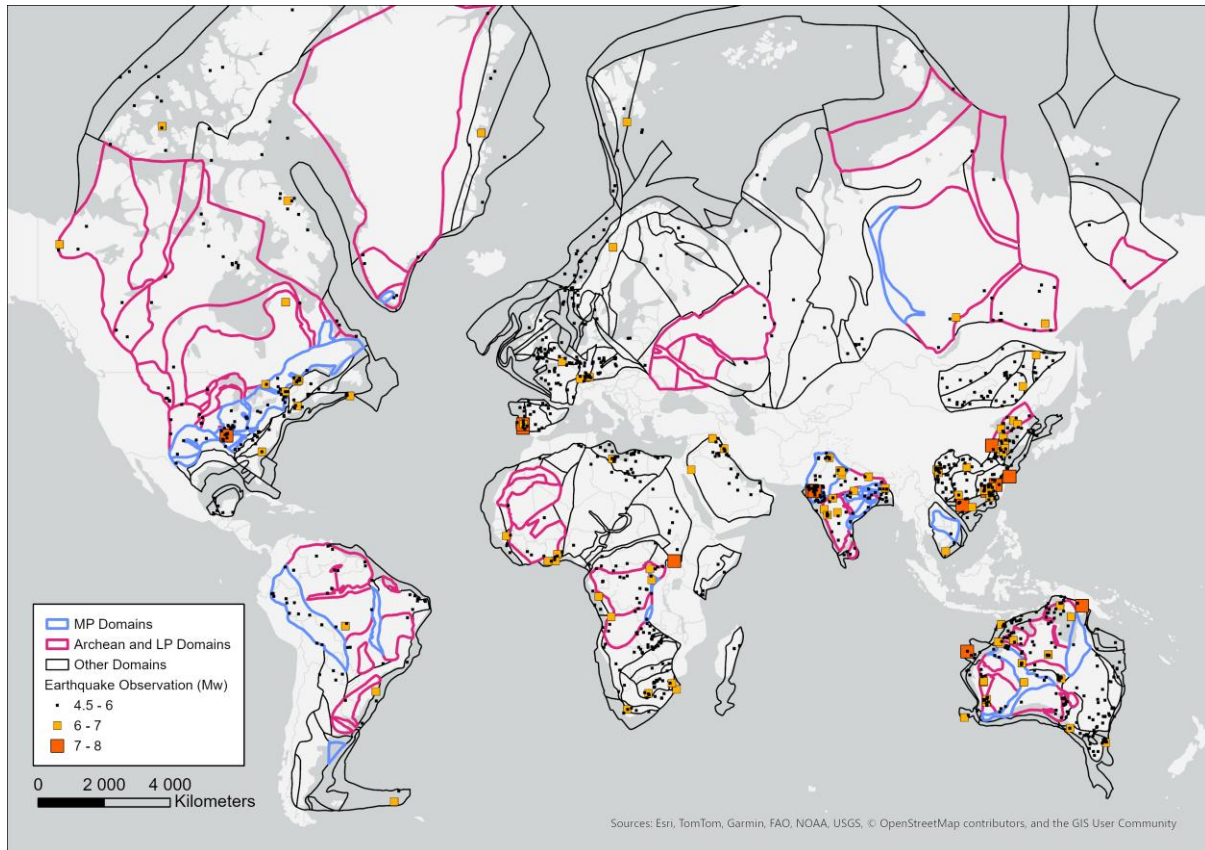
Within the development of Loviisa's PSHA, the Kijko approach has shown limited sensitivity to reasonable variations in regional seismicity parameters, such as those arising from catalogue updates. As a result, the Kijko-based distribution of m_{\max} has remained unchanged since the 2018 PSHA, and subsequent work has focused on refining the Bayesian implementation.

The applicability of the Bayesian method in Fennoscandia is, however, constrained by the absence of large earthquakes in the regional catalogue. Within the relevant study area, only a single event reaches magnitude $M_w = 4.5$, with all others falling below this threshold. Thus, the local catalogue exerts negligible influence on the Bayesian posterior, placing substantial importance on constructing an appropriate prior distribution that accurately reflects the geological properties of the region.

The EPRI studies from 1994 [20] and 2012 [19] demonstrated that geological age is one of the few globally available parameters with some predictive value for maximum earthquake size. Accordingly, the EPRI implementation forms groups of analogue tectonic domains based primarily on crustal age and derives a normal prior distribution for m_{\max} from the observed maximum magnitudes (m_{\max}^{obs}) within each domain. The mean and standard deviation of the prior are computed from these observations, and a bias correction is applied to the mean because m_{\max}^{obs} is inherently a lower-bound estimator of the true m_{\max} .

In Asikainen’s 2026 thesis [8], this framework was adapted to Fennoscandia. Analogue domains were selected based on geological age, using three groups: Archean, Lower Proterozoic (LP), and Middle Proterozoic (MP). The Archean and LP domains were chosen to represent the Fennoscandian Shield, while the MP domains reflect crustal conditions similar to southwestern Sweden and the majority of Norway. These domains were used to construct the Fennoscandian prior, following the EPRI methodology [19, 20] for the remaining computational steps. Figure 1 illustrates these analogue domains, together with the other EPRI domains and earthquakes from the 2012 SCR catalogue.

Figure 1: Analogue domains used for the Fennoscandian prior, shown together with all other domains and the earthquake observations from 495–2008 included in the 2012 EPRI SCR catalogue. Figure adapted from [8].



3.2. Data

To ensure adequate catalogue coverage, the 2012 EPRI SCR database [19] was updated for the analogue domains using the most recent events from the Reviewed Bulletin of the International Seismological Centre (ISC). Seismic events from 1900 through the end of 2023 were retrieved from the ISC using their polygon-based event search interface [22]. The search was automated via a Python script and targeted the selected analogue domains, defined by coordinate vertices. Events were required to have magnitude ≥ 4.5 , depths between 0–50 km, and magnitudes associated with the prime hypocentre.

Because the ISC reports multiple magnitude types, preprocessing was required to ensure consistency with the EPRI catalogue, which uses moment magnitude. The initial query returned 826 events. Of these, 50 were discarded because they were flagged by ISC as known or suspected anthropogenic events, predominantly nuclear test explosions in Russia and North Korea. A further 174 events were excluded due to magnitude types lacking global conversion formulas. This yielded 602 retained events, consisting of two with directly reported Mw values and the remainder reported in short-period body-

wave magnitude (mb) or surface-wave magnitude (MS). These were converted to Mw using the empirical relationships of Giacomo et al. [23].

Because the EPRI and ISC catalogues overlap chronologically, some earthquakes may appear in both datasets. To prevent double counting, potential duplicates were identified using a three-criterion matching scheme: (1) the events originated from different catalogues, (2) they shared the same calendar date, and (3) they occurred within the same domain. Earlier trials involving epicentral distance thresholds and magnitude-difference limits were tested but ultimately discarded due to negligible effect on the resulting maximum magnitude distribution.

When duplicate events were identified, they were merged on an event-by-event basis, assuming that each catalogue contains only unique recordings. Within each domain and date, the catalogue with more events determined the number of merged entries. Each merged entry was produced by pairing an event from the larger catalogue with matching entries from the smaller one, and the magnitude and epicentral coordinates were taken as the arithmetic mean of the contributing records.

The complete merged catalogue is publicly available on GitHub [24]. Table 1 summarises key parameters for those analogue domains in the final SCR catalogue that contain data.

Table 1: Number of selected domains in each region that contain data in the final SCR catalogue (# DNs), together with the mean domain-level values of area, maximum observed magnitude (m_{\max}^{obs}), raw number of catalogue events (N), completeness corrected event count (N^{corr}), and the regional b -value assigned following [20].

Region	# DNs	Mean Value of				
		Area (km ²)	m_{\max}^{obs} (Mw)	N	N^{corr}	b
Africa	6	931 274	5.810	9.00	12.45	0.982
Australia	9	649 707	5.946	20.33	30.53	0.896
China	2	344 881	5.875	13.00	17.28	1.029
Europe	3	736 476	5.367	2.33	2.44	1.156
India	8	336 721	5.930	20.75	43.78	0.966
North America	12	1 062 113	5.685	13.42	20.99	0.728
Russia	4	881 556	5.888	11.50	14.91	1.160
South America	5	1 724 008	5.588	30.40	43.62	1.212

4. HAZARD CALCULATIONS

To evaluate the hazard implications of the updated m_{\max} distribution, it is necessary to implement it within the broader PSHA computational framework. The goal of the calculation is to determine the annual frequency of exceeding a ground motion level c , obtained by integrating over all relevant magnitudes and source-to-site distances. This is expressed as

$$v(C > c) = n_{\min} \int_{m_{\min}}^{m_{\max}} \int_{r_{\min}}^{r_{\max}} P(C > c | m, r) f_M(m) f_R(r) dr dm, \quad (1)$$

where n_{\min} is the recurrence rate of earthquakes with magnitude greater than m_{\min} , $f_M(m)$ and $f_R(r)$ are the probability density functions for magnitude and source-to-site distance, respectively, and $P(C > c | m, r)$ is the conditional probability that the ground-motion parameter exceeds level c during an earthquake of magnitude m at distance r . The parameter m_{\min} represents the lowest magnitude considered capable of producing ground motions that could affect the NPP; for Loviisa's PSHA this value is set to Mw = 4.5.

In practice, Equation (1) is evaluated numerically by discretising the magnitude and distance ranges. When multiple seismic sources contribute to site hazard, the total AFE is obtained by summing the

exceedance rates from all sources. By computing $v(C > c)$ for a range of intensity values, a seismic hazard curve is obtained. Repeating the calculation across a set of frequencies allows the construction of mean hazard curves from which UHRS are derived for selected exceedance levels.

The seismic hazard estimate for the Loviisa NPP is produced using a modified version of the HAZ45 program originally developed by Norman Abrahamson [25]. The modified implementation includes updated ground-motion prediction equations based on the NGA-East GMPE suite [26] and allows for magnitude-dependent b -values, whereby different b -values are applied at higher magnitude ranges rather than assuming a single constant value. Both modifications have been assessed as appropriate for Finnish conditions.

To evaluate the sensitivity of the hazard estimates to the choice of m_{\max} , Asikainen [8] performed a direct comparison with the earlier work of Vehmas [17]. Except for the updated m_{\max} distribution, all modelling choices were kept as consistent as possible with Vehmas' methodology to isolate the influence of the revised value.

In Vehmas' thesis and earlier PSHAs, two separate m_{\max} distributions were used: one based on the Kijko method and one based on the Bayesian method. The Kijko distribution was developed for the 2018 PSHA update, while the Bayesian distribution was updated in the 2021 PSHA using a prior derived from the original 1994 EPRI study [20]. These continuous cumulative distribution functions (CDFs) were discretised by dividing them into finite intervals, and the resulting discrete sets of Table 2 were implemented as independent logic-tree branches with equal branch weights of 0.5.

Table 2: Discrete m_{\max} distributions used in Loviisa's 2021 and 2024 PSHAs.

Kijko m_{\max} Distribution (Mw) [weight]	Bayesian m_{\max} Distribution (Mw) [weight]
5.5 [0.726]	5.25 [0.01]
6.0 [0.201]	5.75 [0.08]
6.5 [0.057]	6.25 [0.23]
7.0 [0.016]	6.75 [0.36]
	7.00 [0.32]

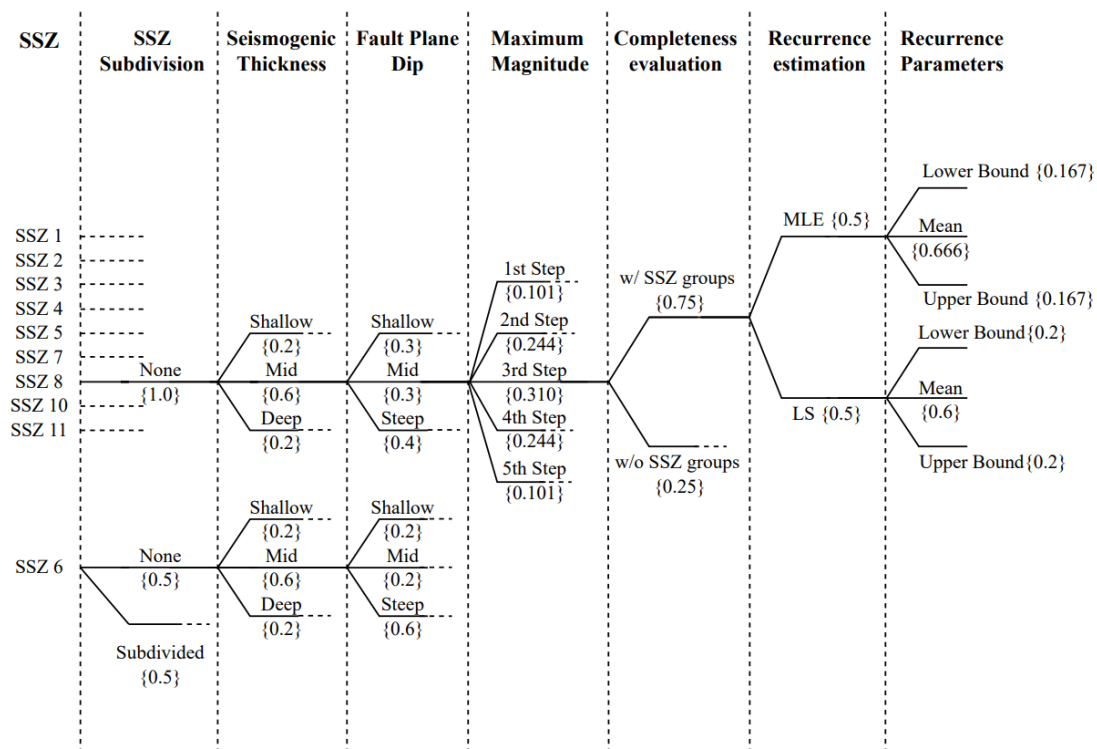
Asikainen [8] adopted a different approach. Rather than incorporating the Kijko and Bayesian distributions separately in the logic tree, he first combined their continuous forms with equal weighting to create a single composite distribution, truncated to the magnitude range [5.00, 8.25], which was judged to represent plausible bounds for the true m_{\max} . This distribution was then discretised using the five-point approximation proposed by Miller and Rice [27], which aims to preserve the statistical moments (e.g., mean and standard deviation) of the underlying distribution. In this method, the discretisation points correspond to the values of m_{\max} for which the composite CDF attains prescribed cumulative probabilities. Each point is then assigned a weight according to Table 3.

Table 3: Miller and Rice five-point discrete approximation to a continuous probability distribution [27] and the rounded weights used in PSHA calculations.

Cumulative Probability of a Continuous Distribution	Miller and Rice Probability Weight	Modified Weight for PSHA
0.034893	0.10108	0.101
0.211702	0.24429	0.244
0.500000	0.30926	0.310
0.788298	0.24429	0.244
0.965107	0.10108	0.101

The resulting m_{\max} logic tree is illustrated in Figure 2, together with the other epistemic uncertainty branches associated with the seismic source zones defined for the Loviisa site [12]. The HAZ45 program computes the mean hazard by summing the hazard contributions from all logic-tree branches, weighted by their corresponding probabilities. Exceedance rates were calculated for 18 acceleration levels between 10^{-5} g and 5 g, and for 21 frequencies between 0.1 Hz and 100 Hz.

Figure 2: Logic tree to account for the m_{\max} modification with the branch weights in braces. The five magnitude steps refer to the five points of the Miller and Rice approximation in Table 3. Figure adapted from [8].



5. RESULTS

5.1. Maximum Magnitude Distribution

The updated SCR catalogue constructed for the analogue domains yields a mean observed maximum magnitude of $m_{\max}^{\text{obs}} = 5.78$ Mw with a standard deviation of 0.60. After the bias correction is applied, the mean increases to 6.04 Mw. This corrected mean forms the basis of the Bayesian prior distribution shown in Figure 3.

A sensitivity test was performed by excluding the Middle Proterozoic analogue domains, which primarily represent crustal regions in Norway. This exclusion increases the bias-corrected mean only slightly, to 6.09 Mw. Because this difference is small and does not materially influence the resulting hazard estimates, the complete analogue-domain set was retained for the construction of the Fennoscandian prior.

The resulting prior distribution lies distinctly below the SCR priors commonly used in earlier studies. This reflects the empirical observation that regions with geological characteristics similar to the Fennoscandian Shield tend to have lower maximum magnitudes than the global SCR average. For context, earlier PSHAs for Loviisa employed the non-extended crust prior proposed by Johnston et al. [20], while the SENSEI project [3] used the EPRI NMESE (non-Mesozoic and younger extension) prior [19]. Figure 3 compares the updated Fennoscandian prior with these more global alternatives.

The Bayesian posterior is effectively identical to the prior due to the limited regional earthquake data. It was subsequently combined with Fortum’s Kijko-based m_{\max} distribution from the 2018 PSHA, with each distribution assigned an equal weight of 0.5. As illustrated in Figure 4, the resulting combined distribution inherits higher probabilities of smaller magnitudes from the Kijko contribution, while the upper-tail behaviour is governed primarily by the Bayesian posterior.

Figure 3: The Fennoscandian m_{\max} prior distribution derived from the updated SCR catalogue compared with the more global priors suggested in the literature [19, 20]. All distributions are truncated and normalised to the interval [5.00, 8.25]. Figure adapted from [8].

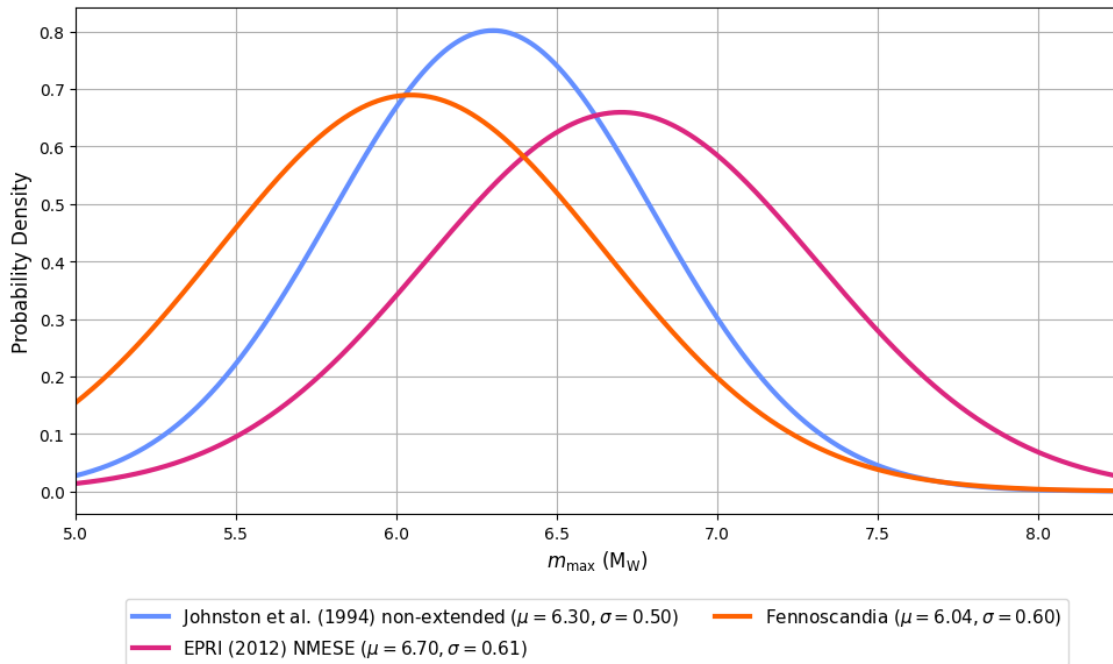
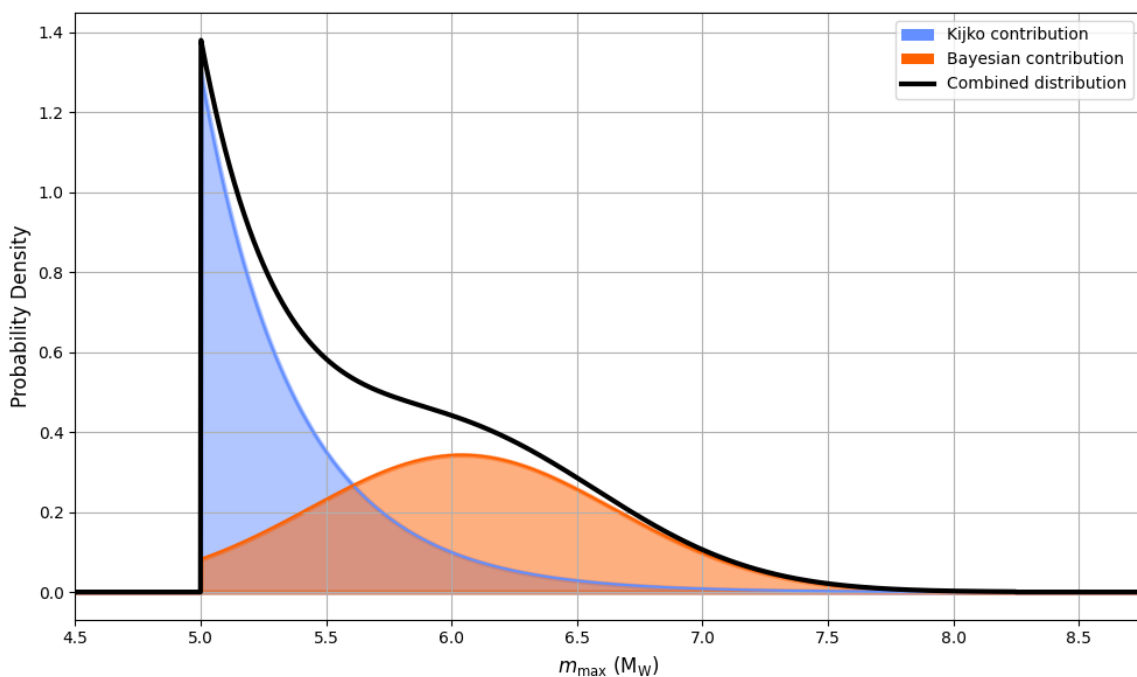


Figure 4: The combined Fennoscandian m_{\max} distribution obtained by weighting the Bayesian posterior and the Kijko distribution equally. The distribution is truncated and normalised to the interval [5.00, 8.25]. Figure adapted from [8].



Applying the Miller–Rice five-point discretisation to the combined continuous distribution produces the discrete m_{\max} values and associated weights listed in Table 4. The weighted mean of the discrete values is 5.74 Mw, which is notably lower than the 6.15 Mw used by Vehmas [17]. This reduction directly reflects the lower mean of the Fennoscandian prior relative to the global priors used in earlier analyses.

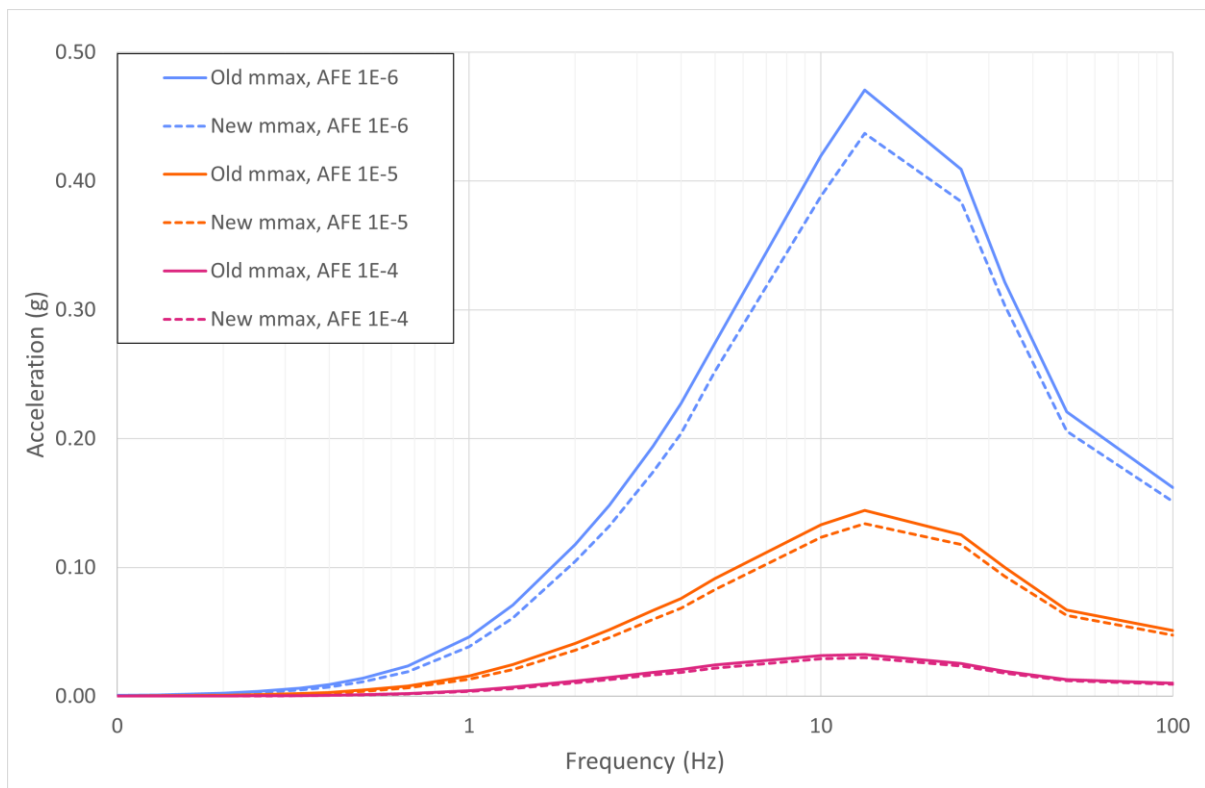
Table 4: Discrete m_{\max} values and their corresponding weights used in the hazard calculations.

m_{\max} (Mw)	Weight
5.03	0.101
5.19	0.244
5.61	0.310
6.25	0.244
6.98	0.101

5.2. Loviisa Seismic Hazard Estimate Sensitivity

Figure 5 compares the mean UHRS values obtained using the updated m_{\max} distribution with those reported by Vehmas [17]. Across all frequencies and AFEs, the updated distribution produces systematically lower hazard estimates. The reduction becomes more pronounced at higher acceleration levels, while remaining largely independent of spectral frequency. Consequently, the overall shape of the UHRS curves remains effectively unchanged.

Figure 5: Loviisa mean UHRS at different AFEs using the updated m_{\max} distribution. The UHRS curves labelled “old m_{\max} ” have been obtained with the m_{\max} distributions of Table 2. Figure adapted from [8].



This behaviour reflects the structure of the updated m_{\max} distribution: the combined Fennoscandian distribution allocates less probability to large magnitudes relative to the earlier Kijko and Bayesian discretisations shown in Table 2. The reduction in the hazard estimate thus arises directly from the reduced contribution of rare, very large earthquakes in the updated model.

6. CONCLUSION

This paper summarised the motivation, methodology, and effects of updating the m_{\max} model for Fennoscandia as part of the ongoing refinement of the PSHA framework for the Loviisa NPP. The work presented here is based entirely on the findings of Asikainen's 2026 Master's thesis [8], and no new methodological developments have been introduced beyond that thesis. Because the regional earthquake catalogue is too sparse to meaningfully constrain the upper tail of the magnitude distribution, the thesis developed a Fennoscandia-specific Bayesian prior by selecting analogue SCR domains according to geological age. This prior has a notably lower mean than the global SCR priors adopted in earlier Finnish hazard assessments, and its combination with the existing Kijko distribution results in correspondingly smaller discretised estimates of m_{\max} .

A fully Bayesian update was not adopted, as the sparse local seismicity provides no meaningful constraint on large magnitudes and therefore renders the posterior effectively identical to the prior, undermining the purpose of Bayesian inference. At the same time, relying solely on the Kijko approach is not ideal either, given its limited empirical support in regions with very low seismicity [19, 21]. For this reason, and in line with recent Finnish PSHAs, the Bayesian and Kijko distributions were combined with equal weights, ensuring that neither method dominates and that both available lines of evidence contribute to the final estimate.

The resulting changes to the hazard estimate of the Loviisa site are moderate. This behaviour is consistent with the broader understanding that, for Finland, hazard levels at practically relevant AFEs are shaped predominantly by the frequency of small and moderate earthquakes rather than by very rare large events. Consequently, the hazard estimates remain relatively stable under reasonable adjustments to m_{\max} . Even so, using a maximum magnitude distribution tailored to the geological characteristics of Fennoscandia reduces unnecessary conservatism and yields a representation of the seismic environment that is better aligned with regional observations. More broadly, the approach presented here may also be applicable to other low-seismicity stable continental regions facing similar data limitations, provided that the analogue selection and weighting choices are carefully justified for the regional tectonic context.

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