D3.1. Definition of risk indicators for preventive and corrective actions

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1. Purpose within the project

This paper introduces the first risk-based objective layer of the project. The previous SOPF framework minimizes expected operating cost while enforcing chance constraints for operational reliability. This paper modifies the objective function so that cost related risk is optimized explicitly. The model uses Value-at-Risk as a moment-based risk term, while chance constraints continue to manage operational risk such as voltage or branch limit violations. The contribution is the decoupled treatment of economic risk and reliability risk in the PCE-based SOPF setting.

The paper should be understood as a proof of concept for risk aware operation under continuous non-Gaussian uncertainty. It does not yet include N-1 security or balancing coordination. Instead, it shows how the cost distribution itself can be shaped by the optimization. This is important for the project because expected cost minimization alone can hide high cost outcomes. A system operator may accept a higher expected cost if doing so reduces the spread of the operational cost distribution and avoids large unexpected costs.

Aspect	Summary
Main method	PCE-based chance-constrained SOPF with a VaR-weighted objective.
Risk parameter	Risk appetite beta balances expected cost and VaR-based cost deviation.
Operational test system	Modified 5-bus AC/DC grid with Gaussian load uncertainty and Beta RES forecast uncertainty.
Main result	Increasing beta narrows operational cost PDFs, introduces RES curtailment as a risk management action, and produces efficient frontiers for different financial confidence levels.

2. Methodological contribution

The proposed objective combines the expected cost and a VaR-based deviation term. When beta equals zero, the model is risk-neutral and minimizes only the expected value. As beta increases, the model places greater weight on the risk term and becomes more risk-averse. The VaR term can be computed from the second moment already available from the PCE coefficients, so risk aversion can be introduced without scenario generation and without post-processing sampled cost distributions.

This integration is computationally attractive because it uses the same coefficient space as the chance constraints. The model therefore keeps a consistent uncertainty representation for both operational reliability and economic risk. Operational risk is handled through chance constraints, while cost risk is handled through the objective. This separation is a useful project result because it allows a decision-maker to tighten reliability constraints and choose financial risk appetite independently, rather than mixing both effects in a single heuristic margin.

3. Numerical results

The numerical illustration uses a modified 5-bus AC/DC test system with five AC buses, five generators, seven AC branches, three DC buses, converters, and three HVDC branches. All loads are stochastic and Gaussian. RES injections at all buses follow Beta distributions fitted from Belgian TSO wind forecast error data from 2020 to 2023. The RES penetration level is 75%, and the operational risk confidence level for branch limits is 95%. The four panels in Figure 1 summarize the complete set of reported numerical outputs: operational cost distributions, RES curtailment distributions, efficient frontiers, and the mapping from risk target to beta values.

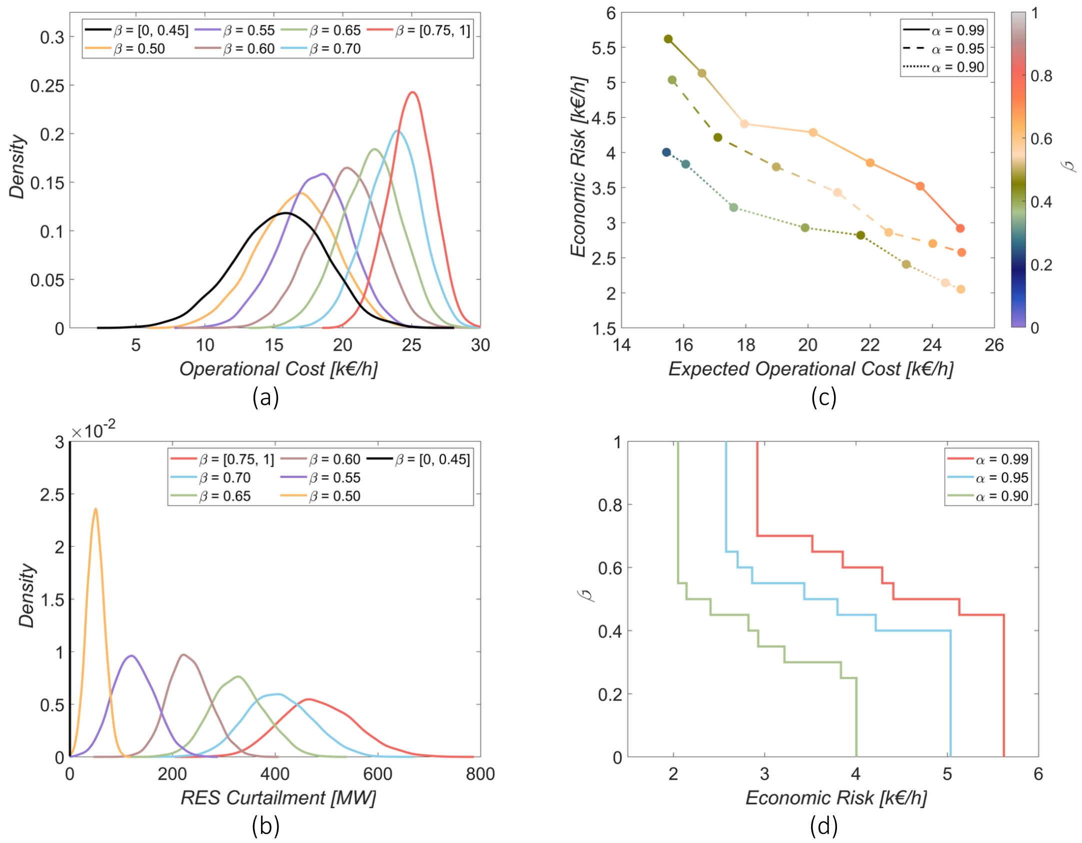

Figure 1: Operational cost PDFs (a), RES curtailment PDFs(b), efficient frontiers (c), and beta values (d) for different VaR confidence levels

The operational cost PDFs show the main effect of risk aversion. For beta values from 0 to 0.45, the cost distributions are grouped together and remain relatively broad. In this range, the optimization remains close to risk-neutral behavior. When beta increases beyond 0.5, the distributions become narrower and shift toward higher expected values. This indicates that the model intentionally pays more on average in order to reduce cost variability and avoid high unexpected costs. For beta values from 0.75 to 1, the distributions again cluster together, suggesting that after a certain risk aversion level, additional weighting of the VaR term produces limited additional risk reduction. This result is useful because it indicates that the risk appetite parameter should not be chosen blindly. There is an efficient range where the risk-cost trade-off changes meaningfully, and regions where the same operating policy is effectively obtained.

The RES curtailment PDFs explain how the model physically implements cost risk reduction. For beta values between 0 and 0.45, there is no RES curtailment. The model uses the available RES as much as possible and accepts the resulting cost variability. When beta increases from 0.5 to 1, RES curtailment appears and its distribution widens with higher expected values. Curtailment therefore becomes a risk management mechanism. By curtailing some RES, the model changes the conventional generator set-points and reduces exposure to unfavorable high cost outcomes. This result is important for the project because it shows that RES curtailment as a decision variable is not only relevant for feasibility. It is also necessary for controlling economic risk.

The efficient frontiers show the optimal trade-off between expected operational cost and the VaR based risk metric at financial confidence levels of 90%, 95%, and 99%. The 99% frontier lies above the 95% and 90% frontiers, which means that a stricter financial confidence level requires higher expected cost for a given degree of risk mitigation. The area above each frontier is inefficient, because a point there would either pay too much for the achieved risk reduction or accept too much risk for the cost paid. The beta mapping panel shows that the range of beta values needed to span the frontier depends on the confidence level. Consequently, beta is not an absolute operational preference; its interpretation depends on the selected financial confidence level.

4. Expanded interpretation of the complete result set

The results demonstrate how the risk-aversion parameter reshapes the cost and curtailment distributions. For small beta values, the optimization behaves as a risk-neutral expected-cost minimization problem. The cost distribution is relatively broad because the model accepts a larger range of possible outcomes in exchange for lower expected cost. As beta increases, the objective assigns more weight to the VaR-based deviation term. The operational cost distribution narrows, which means that the model reduces exposure to high-cost outcomes. This comes with an expected-cost penalty, visible in the rightward shift of the distribution. The clustering of solutions below beta equal to approximately 0.45 and above beta equal to approximately 0.75 indicates that only an intermediate range of beta values produces materially different operating points.

The RES curtailment distributions explain how the model achieves this reduction in financial risk. For beta values between 0 and 0.45, the model does not curtail RES because the expected-cost objective strongly favors using zero-marginal-cost renewable generation. Once beta reaches approximately 0.5, curtailment begins to appear. As beta approaches 1, curtailment distributions become wider and their expected values increase. This does not mean that curtailment is preferred for its own sake. Rather, curtailment changes the conventional generator dispatch distribution and thereby reduces the probability of unfavorable cost outcomes. In other words, the model uses RES curtailment as a controllable risk-management instrument.

The efficient frontier figures provide the most useful decision-support interpretation. Each curve represents the minimum expected cost achievable for a given level of financial risk at a selected confidence level. The frontier for 0.99 confidence lies above the frontiers for 0.95 and 0.90 because protecting against more extreme cost outcomes requires more conservative and therefore more expensive operating decisions. Points above the frontier are inefficient: they either spend too much for a given risk level or fail to deliver enough risk reduction for their cost. This transforms the optimization result from a single dispatch solution into a portfolio of operational strategies. A system operator can therefore select a beta value and confidence level according to risk appetite, budget constraints, and the operational importance of avoiding unexpected high costs.

For the broader project, the paper is a transition from reliability-oriented chance constraints to economic risk management. The chance constraints continue to control operational risk by limiting probabilities of grid limit violations. The VaR term in the objective separately controls cost-related risk. This separation is important because a grid can be physically secure while still exposing the operator to unacceptable cost variability. The paper therefore establishes a methodological bridge toward the later CVaR-based balancing-aware framework, where economic risk is connected explicitly to balancing activation rather than only to total operating cost.