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Analiza pouzdanosti zamene termoelektrana na ugalj fotonaponskim sistemima koristeći Monte Carlo simulaciju

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Apstrakt: Ovaj rad istražuje pouzdanost energetske tranzicije u Republici Srpskoj, fokusirajući se na proces zamene baznih termokapaciteta fotonaponskim sistemima. Primenom hibridne Monte Carlo simulacije, model integriše tehničku varijabilnost solarnog zračenja sa društvenom neizvesnošću dobijenom kroz anketno istraživanje opšte populacije. Teorijski okvir rada utemeljen je u principima statističke mehanike, posmatrajući elektroenergetsku mrežu kao kompleksni ansambl mikrostanja opisanih preko particione funkcije i teorije fluktuacija. Za kvantifikaciju stabilnosti sistema definisan je specifičan indeks prihvatljivosti zamene koji ocjenjuje usklađenost mrežnih parametara sa važećim standardima kvaliteta električne energije. Rezultati istraživanja ukazuju na to da stabilnost sistema progresivno opada sa povećanjem udela solarnih elektrana, pri čemu radikalni scenariji zamene vode ka kritičnom gubitku inercije mreže. Zaključci sugerišu da termoelektrane sa visokom operativnom fleksibilnošću ostaju ključni stabilizacioni stub sistema, te da se održiva dekarbonizacija može postići isključivo uz uvođenje dodatnih tehnologija za kompenzaciju stohastičkih fluktuacija i skladištenje energije.

Ključne reči: Monte Carlo simulacija, energetska tranzicija, fotonaponski sistemi, pouzdanost mreže, statistička fizika

Reliability Analysis of Coal-Fired Power Plant Replacement With Photovoltaic System Using Monte Carlo Simulation

Abstract: This paper investigates the reliability of the energy transition in Republic of Srpska, focusing on the replacement of coal-fired base-load capacities with photovoltaic systems. Utilizing a hybrid Monte Carlo simulation, the model integrates the technical variability of solar radiation with social uncertainty derived from general population survey research. The theoretical framework is grounded in the principles of statistical mechanics, treating the power grid as a complex ensemble of microstates described through the partition function and fluctuation theory. To quantify system stability, a specific substitution acceptance index was defined to evaluate the compliance of grid parameters with prevailing power quality standards. The research results indicate that system stability progressively declines as the share of solar power plants increases, with radical replacement scenarios leading to a critical loss of network inertia. The findings suggest that thermal power plants with high operational flexibility remain a crucial stabilization pillar, and that sustainable decarbonization can only be achieved through the implementation of additional technologies for stochastic fluctuation compensation and energy storage.

Keywords: Monte Carlo simulation, energy transition, photovoltaic systems, grid reliability, statistical physics

1. Introduction

The integration of renewable energy sources (RES) into the power system brings challenges due to their variability and unpredictability. Monte Carlo simulations enable the determination of energy production from renewable sources under different weather conditions and examination of their impact on the grid. In this way, necessary capacities for energy storage, reserves, and other measures that ensure grid stability and reliability can be assessed (Željko, 2024: 4). To precisely dimension these measures under conditions of extreme uncertainty, it is necessary to delve deeper into the very nature of randomness characterizing mixed energy systems. While

Zeljковиć (2024) emphasizes the practical application of simulations in capacity assessment, the theoretical basis of this approach lies in statistical mechanics. To understand the depth of challenges brought by replacing TPPs with PV systems, it is necessary to observe the system as a set of a large number of variables best described via the partition function (Z). According to Landau and Binder (2015: 13), this function sums all possible states of the system:

$$Z = \sum_{all\ states} e^{-H/kgT} \quad (1)$$

In the context of the power system, the Hamiltonian (H)¹ can be interpreted as a function of energy imbalance. While coal-based systems operated in a quasi-deterministic regime², the integration of PV systems introduces a vast number of microstates³ conditioned by atmospheric conditions. Landau and Binder emphasize that for systems with a large number of degrees of freedom, direct calculation of the partition function is practically impossible (e.g., a system with only 10,000 particles has $2^{10,000}$ states).

It is precisely here that the Monte Carlo method becomes indispensable, as it enables the sampling of the most relevant states without the need to examine the entire state space. In addition to static state analysis, the importance of system dynamics is highlighted through the master equation, which describes the evolution of the probability of the system being in a specific state over time (Newman & Barkema, 1999: 13). The proposed model involves modeling transition rates between states of stable production and states of abrupt drops caused by the intermittency of solar energy. A key reliability parameter is fluctuation theory. In statistical physics, system energy fluctuations (ΔU) are directly related to system stability and response:

$$((\Delta U^2))NVT = k_B T^2 C_v \quad (2)$$

Applied to the energy transition, the variability of photovoltaic power plants is observed as stochastic fluctuations within an ensemble. The higher the share of RES, the more pronounced the fluctuations within the grid become. In theoretical terms, this corresponds to an increase in the specific heat of the system-representing the system's need to absorb excess energy (through storage or reserves) to maintain equilibrium. According to the approach proposed by Newman and Barkema (1999), Monte Carlo simulation enables the assessment of long-term system behavior through time averaging⁴. Instead of relying on a single deterministic scenario, the simulation generates a representative set of thousands of possible operational outcomes. The mathematical reliability of this approach directly depends on the quality of the random number generator. According to Kroese (2011: 7), the essence of the Monte Carlo method lies in generating an infinite sequence of independent and identically distributed (iid) random variables⁵ ($U_1, U_2, U_3, \dots$) according to a specific probability distribution. "In this study, this entails the application of algorithms that transform a uniform distribution into specific models (such as Beta or Bernoulli distributions)⁶ to faithfully reproduce the stochastic inputs of solar radiation and component failures. Kroese (2011) emphasizes that, due to the finite nature of computer memory, pseudorandom numbers must be used, which must possess statistical properties indistinguishable from true randomness. This ensures that the simulated scenarios of replacing TPPs with photovoltaic systems do not contain hidden periodicities that could distort the grid reliability assessment. Monte Carlo simulation in this work employs these principles to calculate the

¹ In classical mechanics and statistical physics, the Hamiltonian (H) represents the total energy function of a system. In the context of this study, it is transformed into a power balance operator that aggregates instantaneous production from all sources (TPP, PV) and subtracts current demand. In this manner, each "microstate" of the system (determined by temporal and atmospheric conditions) possesses its specific H value, where any deviation from zero directly indicates a grid imbalance.

² The quasi-deterministic regime refers to an operational mode of thermal power plants where energy production is highly predictable and controllable, with negligible deviations that do not depend on unpredictable atmospheric conditions.

³ A system microstate refers to a specific combination of all variables at a given moment (e.g., the exact solar irradiance on each PV panel field, instantaneous wind speed, and consumer load level). The total number of these combinations is practically infinite, which precludes analytical solutions and necessitates the application of Monte Carlo sampling.

⁴ Time average: According to Newman and Barkema (1999), the Monte Carlo method allows for the estimation of system properties by sampling states throughout simulated time. In this research, this enables the numerical identification of extreme low-probability events (e.g., multi-day periods without sunlight) that are crucial for reliability assessment.

⁵ The use of iid variables (independent and identically distributed), which Kroese (2011) highlights as the core of the method, is of crucial importance in this study for modeling Bernoulli processes (e.g., the binary state of a panel: "operational" or "failed") and continuous radiation variables. A high-quality pseudorandom number generator ensures that each simulated scenario in the TPP replacement analysis is statistically independent, thereby avoiding correlation bias that could lead to an incorrect assessment of system outage risks.

⁶ The Beta distribution is used to model the continuous variations in solar radiation intensity, while the Bernoulli distribution describes the discrete states of system components, such as operational status or failure.

probability of critical fluctuations that could lead to a breach of system reliability, which is equivalent to searching for critical points in the phase transitions of matter.

2. Empirical Part

2.1. Survey Research and Definition of Transition Scenarios

In order to incorporate the temporal and volumetric uncertainties of the energy transition into the stochastic model, a survey research was conducted on a general population sample. The survey was realized electronically between February 13, 2026, and February 20, 2026, with a sample size of $n = 109$ respondents. The statistical legitimacy of this approach is based on the theory of population parameter estimation. Estimating the proportion (share) of population elements with a specific characteristic based on large samples allows the obtained response frequencies to be treated as probabilities of real-world scenarios (Komić, 2000: 107). Consequently, survey results (such as the estimated 30% solar share) transition from mere subjective opinions into statistically grounded input parameters (p) that define the stochastic framework within the Monte Carlo simulation.

The questionnaire consisted of eight questions, two of which were demographic, while the remaining were focused on assessing the expected start time (T_1), dynamics (T_2 and T_3), and the maximum realistic share of PV systems (P_{FN}) in electricity production. The obtained responses are utilized as an input set of assumptions for forming discrete probability distributions within the Monte Carlo simulation. In this manner, social and temporal uncertainty is integrated into the numerical model, while the technical reliability of the system is assessed through deterministic calculations within each iteration.

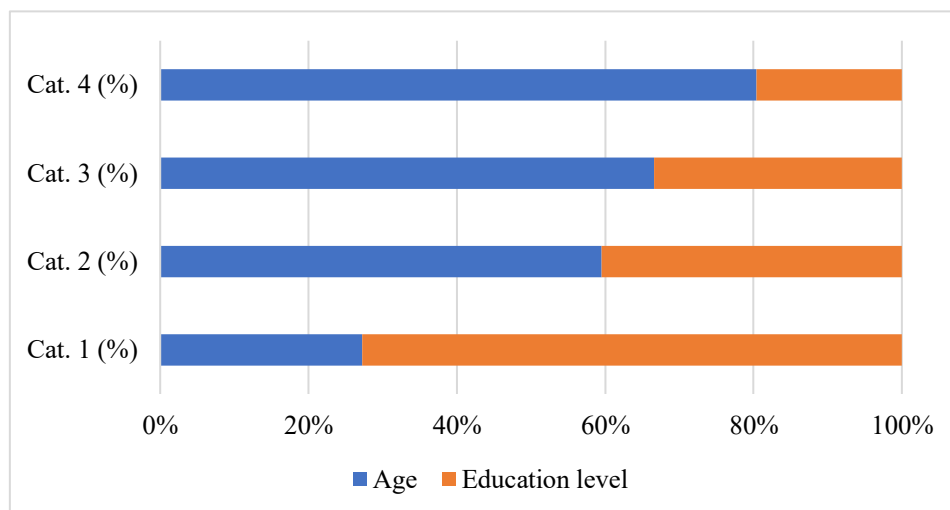


Figure 1: Demographic profile and education level of respondents Source: (Author's research, 2026)

The sample structure indicates that the research was predominantly attended by respondents aged 31–45 (46.7%) and 46–60 (29.9%). With over 46% of highly educated respondents, the sample is considered relevant for assessing the transition of a system that relies on 900 MW of installed capacity in thermal power plants. In this context, a clear distinction is made in the portfolio: 600 MW (RiTE Ugljevik and RiTE Gacko) operates within the mixed holding ERS and covers domestic consumption, while 300 MW of installed capacity at TPP Stanari represents a private investment by the Elektrane Stanari concern, which is primarily export-oriented. In this regard, Simić and Jurišić (2025: 70) emphasize that thermal power plants constitute a key part of the critical energy infrastructure thanks to which Bosnia and Herzegovina is energy-independent, noting that TPP Stanari, as 100% private property, has no contractual obligation to supply domestic consumption but is primarily oriented toward export. Although TPP Stanari recorded its highest production in 2021 at 2,068.26 GWh, it functions as a separate commercial entity. The Monte Carlo model respects this by stochastically testing the redirection of these capacities in the event of an imbalance caused by the variability of solar power plants.

The analysis of the perceived transition start (T_l) indicates a significant division: 29.6% of respondents do not expect a substantial replacement of thermal capacities, while 27.8% believe the process will begin in the 2030–2040 period. These data serve as probabilities for the commencement of the decommissioning of the RiTE

Ugljevik and RiTE Gacko units, while respecting their technical minimums of 155 MW and 180 MW, respectively. The variable T_2 represents the horizon of partial replacement (50% of the thermal sector's production, corresponding to a level of approximately 2,587 GWh from 2021). A dominant share of 36.1% of respondents predicts this scenario only in the 2035–2045 period. In this phase, the model tests the system stability and the capability of the remaining thermal capacities, including the high-efficiency TPP Stanari, to maintain grid inertia

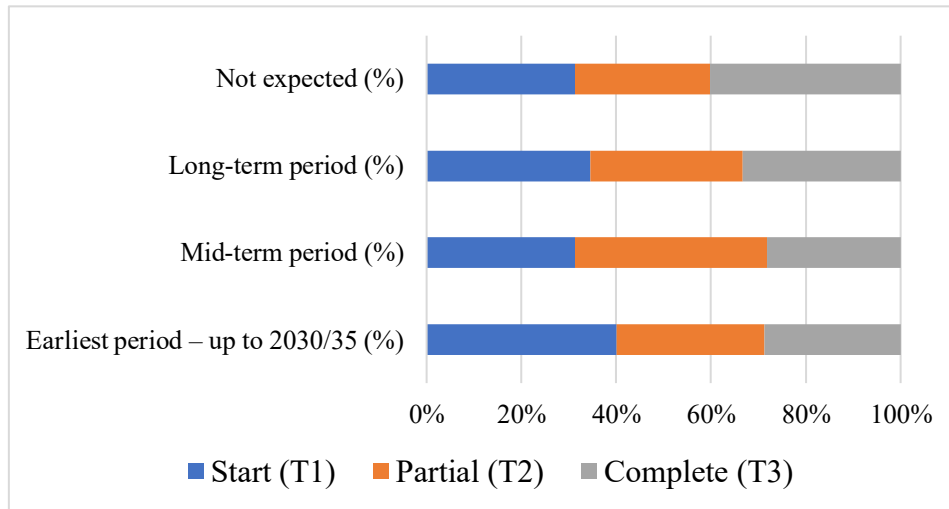


Figure 2: Perception of the time horizon for energy transition phases (T_1 , T_2 , T_3) Source: Author's research

The synthesis of the results presented in Figure 2 indicates a growing trend of skepticism as the complexity of the transition phases increases. Regarding variable T_3 (full transition), a dominant 38% of respondents do not expect a complete replacement of base-load capacities. In the model, these percentages are used as weighting factors; specifically, a higher frequency of not expected responses results in a greater number of iterations where thermal units remain operational. This approach provides a more realistic assessment of the system balancing requirements under high photovoltaic penetration (P_{FN}).

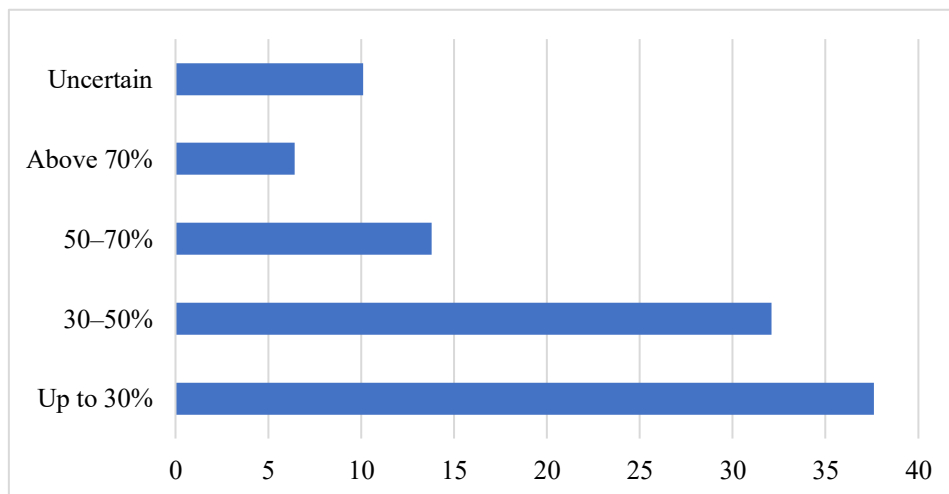


Figure 3: Estimation of the maximum realistic share of photovoltaic systems in total production (P_{FN}) Source: Author's research

The analysis of the P_{FN} variable (Figure 3) indicates that the majority of respondents (37.6%) believe that solar energy can realistically cover up to 30% of the total electricity production. Given that the total production of the thermal sector in 2021 amounted to 5,175.92 GWh, the projected share of 30% corresponds to an energy output of approximately 1,552 GWh. This data is of crucial importance for modeling, as it implies that, according to the respondents' perception, the operation of base-load capacities must be maintained even during a significant

transition. In the Monte Carlo simulation, this means that TPP Stanari, with its annual production of 2,068.26 GWh, retains its role as a primary export and stabilization pillar of the system, while the variability of solar power plants is balanced through the remaining capacities of the mixed holding ERS.

Additional model validation is provided by the responses to questions regarding risk and general attitude. Although 74.3% of respondents express general support for the transition to renewable energy sources, a high degree of caution is reflected in risk perception, where a significant portion of the sample predicts the possibility of power outages due to increased system variability. Such a correlation supports the stochastic research approach, which does not ignore technical risks in favor of environmental goals.

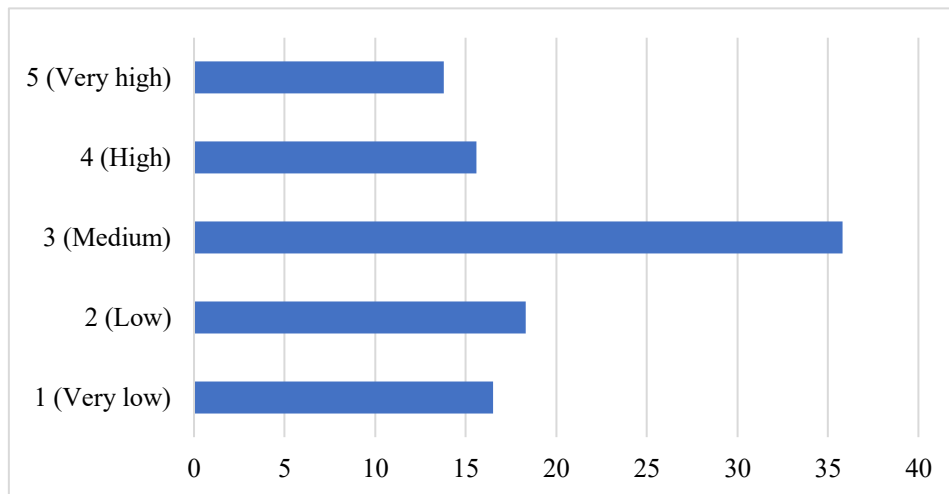


Figure 4: Risk perception regarding system reliability due to the increase in the share of solar power plants
 Source: Author's research

The results of the reliability risk analysis (Figure 4) indicate a high level of awareness among respondents regarding the variability of renewable energy sources (RES). The largest percentage of respondents (35.8%) perceives the risk of power outages as medium, while nearly a third of the sample (29.4%) considers this risk to be high or very high. In the Monte Carlo simulation, these data are used to define penalty functions in iterations where a sudden drop in production from PV systems occurs. This further confirms the necessity of keeping TPP Stanari operational for the purposes of primary and secondary system regulation.

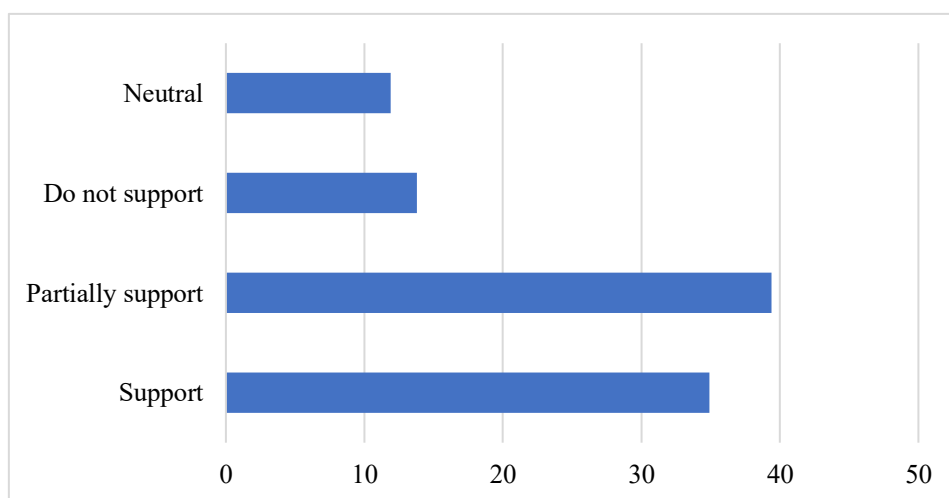


Figure 5: Respondents' general attitude towards the transition to renewable energy sources Source: Author's research

Finally, the control question regarding the general attitude towards the energy transition (Figure 5) shows a high level of declarative support for the process: cumulatively, 74.3% of respondents support or partially support the transition from coal to RES. However, when these results are compared with the responses regarding risk (Question 7) and the realistic share (Question 6), a clear distinction is observed: respondents desire the transition, but not at the cost of energy instability. This stance justifies the use of the Monte Carlo simulation, which in each iteration strictly controls the system's operating point and retains TPP Stanari as a key protective mechanism against imbalance. Consequently, the actual transition is modeled as a gradual and controlled process, rather than an abrupt shutdown of the thermal sector.

2.2. Power System Model and Input Stochastic Parameters

According to data from the Agency for Statistics of BiH, in January 2025, thermal power plants (TPPs) accounted for 59.4% of the total gross electricity production, while solar and wind power plants contributed only 5.8%. Total gross electricity production amounted to 1,402 GWh, with TPPs producing 833 GWh gross, or 744 GWh net electricity. These data represent the reference baseline state of the BiH power system, from which the modeling of the replacement of TPPs with PV systems originates. The dominant role of TPPs confirms that the energy transition towards PV systems has a pronounced systemic and reliability dimension (Agency for Statistics of BiH, 2025: 3). These statistical data from 2025 serve as a calibration benchmark for model validation prior to conducting the survey research in 2026.

In the Federation of BiH (FBiH), base-load thermal power production is provided by TPP Tuzla and TPP Kakanj. According to data from the Regulatory Commission for Electricity in FBiH, the total installed active capacity of TPP Tuzla is approximately 715 MW, while TPP Kakanj has an installed capacity of about 458 MW. These plants are designed for base-load operation, with pronounced technical production minimums, which limits their flexibility under conditions of an increased share of variable RES (Regulatory Commission for Electricity in FBiH, 2010: 3). In Republika Srpska, the backbone of the thermal energy sector consists of three plants with a total installed capacity of 900 MW. According to data from the Chamber of Commerce of Republika Srpska (2023), TPP Gacko has a capacity of 300 MW (276 MW at the grid boundary/threshold) with a technical minimum of 180 MW, while TPP Ugljevik possesses an installed capacity of 300 MW (279 MW at the grid boundary) with a technical minimum of 155 MW. In addition to these, a significant share of production is achieved by TPP Stanari with an installed capacity of 300 MW, which in 2021 achieved a production of 2,068.26 GWh, exceeding planned values by 2.14% (Regulatory Commission for Energy of Republika Srpska, 2022: 5). These data indicate that a complete replacement of thermal energy capacities in Republika Srpska would require the installation of photovoltaic systems capable of compensating for an average annual production of over 5,100 GWh, while accounting for the stochastic nature of solar radiation compared to the stable operation of existing units.

Table 1: Technical and operational parameters of thermal capacities in Republika Srpska as model input data

Plant	Installed Capacity (MW)	Technical Minimum (MW)	Annual Production (GWh)
TPP Gacko	300	180	~1,500
TPP Ugljevik	300	155	~1,550
TPP Stanari	300	(high flexibility)	2,068.26
TOTAL	900	-	~5,100

Source: Author, based on data from the Chamber of Commerce of RS (2023) and the Regulatory Commission for Energy of RS (2022).

These deterministic data on installed capacity and technical minimums serve as fixed constraints within the stochastic model. However, the actual dynamics of replacing these capacities are modeled by introducing uncertainty through variables T_1 , T_2 , and T_3 . While the 900 MW installed capacity in the thermal sector of Republika Srpska represents stable base-load energy, PV systems are introduced as a variable source whose power (P_{FN}) is simulated through thousands of iterations. In this manner, the model tests critical points where solar production reaches the thresholds defined by the survey research (30%, 50%, or more), verifying whether the remaining capacities—primarily TPP Stanari—can maintain operation within their technical minimums or if their complete shutdown is necessary to preserve system balance.

The inclusion of TPP Stanari as the primary stabilization pillar in the model is further justified by its technological characteristics. Unlike other regional plants that utilize outdated technologies, TPP Stanari employs a Circulating Fluidized Bed (CFB) boiler, achieving significantly better emission control (SO_2 , NO_x , and PM) and a higher

degree of operational compliance with European standards. In the simulation, this positions the plant as a best-practice example and the most reliable support for the implementation of innovative solutions (Simić, 2025: 52).

Such an approach is essential because, as Karač (2009: 11) states, approximation is a central concept in almost all fields of applied numerical mathematics, given that we must often settle for the approximate values with which we work. In this context, the Monte Carlo simulation in this paper does not aim to find an absolutely exact transition point; rather, through a stochastic algorithm, it seeks to localize a solution that minimizes the relative prediction error under conditions of high uncertainty. A numerical experiment conceived in this manner is based on the stochastics of natural processes whose states are determined by the laws of probability, enabling the resolution of complex mathematical, physical, and statistical problems through random sampling (Krstić et al., 2023: 82).

2.3. Reliability criteria and the replacement acceptability index

Once the stochastic transition frameworks (T_1 , T_2 , T_3 , P_{FN}) have been defined through survey research, it is necessary to establish mathematical criteria by which the model will evaluate the success of each individual iteration. For the purpose of modeling the spatial distribution of PV systems after the decommissioning of TPPs, a stochastic model has been adopted based on an iterative process of allocating locations (buses) and capacities of new PV units using the random selection method. This approach, while strictly adhering to the cumulative power replacing the base-load source, allows for a realistic simulation of decentralized production, where the impact on the grid is analyzed not only through the energy balance but also through variations in voltage profiles within the limits of 0.95 to 1.05 p.u. (Espinoza et al., 2026: 82). In addition to spatial allocation, the evaluation of system reliability after TPP replacement is conducted in accordance with the technical parameters of the EN 50160 standard, following the methodology proposed by Salkić et al. (2015: 143). Within this empirical model, the boundary values of voltage variations ($\pm 10\%U_n$) and the Total Harmonic Distortion factor ($THD < 8\%$) are used as key indicators for assessing grid stability. In order to quantify the success of the transition from a base-load source to a renewable source, the Replacement Acceptability Index (I_z) is introduced into the analysis. This index represents the probability (P) that the system, despite stochastic fluctuations, will remain within the permitted operational limits throughout the entire simulation period, and is defined by the following relation:

$$I_z = P(V_{min} > 0.9 \wedge V_{max} < 1.1 \wedge THD < 0.08) \quad (3)$$

In the context of this study, this means that stochastic variations in insolation and load are treated as input data with an intrinsic irreducible error, while the stability of the I_z results is ensured by a large number of iterations that prevent the accumulation of computational errors. Special focus is placed on the stochastic nature of voltage dips and transients, accounting for the fact that distributed sources must maintain synchronized operation with the grid even under conditions of disturbances originating from the external system. In the process of stochastic allocation of PV units, the algorithm prioritizes maintaining stability at nodes connected to high-efficiency units, such as TPP Stanari. This simulates a realistic operational scenario in which stable base-load capacities are decommissioned only when decentralized production meets the criteria of the Replacement Acceptability Index (I_z).

Accordingly, the broader power system can be viewed analogously to a thermodynamic reservoir (thermostat). As Sunko (2016: 25) states regarding the grand canonical potential (Ω), the external system plays the role of a particle reservoir (chemical potential μ), much like how an external system in a power grid acts as a stabilizer that compensates for fluctuations introduced by decentralized PV sources. The application of the stochastic model in this work reflects this physical reality: while PV units alter the local state of the buses, the grid as a whole strives to maintain equilibrium, similar to the Gibbs-Duhem relation, ensuring that parameter variations do not lead to system instability. In this manner, the Monte Carlo simulation provides more than just a descriptive overview of possible states; it yields a precise numerical value signaling whether the grid is capable of absorbing the projected PV capacity without violating quality standards. However, given that such a calculation is based on the numerical approximation of a complex operator of the real system, it is necessary to acknowledge the existence of inherent error and method error. As Radunović (2003: 4) points out, the numerical solution of a task involves replacing a given operator with a proximate operator to enable calculation, whereby the stability of the algorithm directly depends on whether the computational error accumulates during iterations.

3. Monte Carlo simulation methodology

The Monte Carlo simulation methodology in this study is based on a combination of technical stochastic parameters (insolation, load, outages) and discrete energy transition scenarios defined by the survey research in Section 2.1. While the technical parameters model the operational variability of the system, the variables $T1$, $T2$, $T3$, and P_{FN} represent the temporal and volumetric uncertainty of replacing TPPs with PV systems. In this way, the simulation encompasses both the physical and the socio-perceptual components of the transition. The application of the Monte Carlo method in this context is justified by the probabilistic nature of the transition variables. Since the reliability of complex systems with a large number of components and variable states is practically impossible to determine solely through analytical means, the Monte Carlo simulation method emerges as the most powerful solution for predicting system behavior during operation (Ilić et al., 2021: 96). In this regard, Shah (2025) emphasizes that Monte Carlo simulation represents a fundamental tool for addressing the stochastic behavior of renewable sources, enabling the management of multiple correlated random variables and nonlinear system behaviors resulting from meteorological and seasonal variations. According to the same author, the application of this approach reduces unexpected cost overruns and technical risks by approximately 35% compared to deterministic planning (Shah, 2025: 26).

As Maluckov (2007: 195) states, in systems where a large number of identical elements are examined, the concept of a system ensemble⁷ is utilized, whereby the probability of a specific event occurring is determined by the number of systems within the ensemble in which that event has been realized. In this process, the precise modeling of input quantities is crucial, with variables such as solar radiation intensity being treated as continuous random variables. According to Huber (2024), a random variable is continuous if for every x it holds that $P(X=x)=0$, meaning that the probability of assuming any single, fixed value within a continuous spectrum is equal to zero. In addition to atmospheric parameters, the technological innovation (TI) variable is recognized as a critical driver of the energy transition within stochastic modeling. Empirical research conducted on a sample of 58 countries confirmed that technological progress has a positive and highly significant impact on RES consumption with an effect probability of 100% (coefficient = 0.1097), further justifying the inclusion of the technological factor in the simulation model (Quoc, et al., 2025: 103). When these findings are applied to the specifics of the power sector in Republika Srpska, they provide strong scientific validation for the model's focus on high-tech solutions, such as those implemented at TPP Stanari. Specifically, the innovations in emission control and the high operational flexibility of this plant make it a key factor facilitating the systemic integration of variable energy sources.

Within the methodological framework of this study, each individual simulation iteration represents one member of the ensemble (a possible transition scenario). The primary reliability indicator derived from such a process is the empirical reliability function ($R_e(t)$), which, according to Ilić et al. (2021), is defined as the ratio between the number of technical systems (iterations) that have not failed, $n(t)$, and the total number of observed scenarios, N :

$$(R_e(t) = \frac{n(t)}{N} \cdot 100\% \quad (4)$$

Given that variables such as insolation and the transition start time (T_I) are discrete or continuous random variables, their mean value and dispersion (D^2) serve to characterize the spread or fluctuation of the system around the expected state (Maluckov, 2007). In order to generate such variables within the algorithm, a construction of a continuous uniform random variable (U) is applied from a sequence of independent and identically distributed (iid) discrete variables. This ensures that the generated sequence $\sum_{i=1}^{\infty} X_i / 10^i$ faithfully reproduces a uniform distribution on the interval $[0, 1]$ (Huber, 2024: 27).

In this manner, the simulation does not merely strive for a deterministic result, but rather for determining the probability density ($f(x)$) of a successful thermal capacity replacement, thereby ensuring the stability of results through a large number of observations ($N \rightarrow \infty$). The theoretical foundation for such an approach can be found in the work of David Bohm, who explains that predictable properties in the macroscopic domain (in our case—grid voltage stability) directly depend on the mutual compensation of random fluctuations occurring in the microscopic domain (Bohm, 1972: 67). In the context of this study, microscopic fluctuations represent the variable output of individual photovoltaic panels, whose unpredictability is compensated and transformed into measurable system reliability indicators through the Monte Carlo algorithm. Thus, analogous to Bohm's understanding of natural law, randomness at the level of an individual source does not preclude causality and stability at the level of the entire power system ensemble.

⁷ An ensemble refers to an imaginary set of a large number of independent copies of a system that exist in various possible microstates, while their macroscopic parameters remain identical.

Such an approach requires a precise definition of the probability of each individual event within the simulation. Analogous to the particle transport model (Marinković et al., 2017), the total uncertainty of the power system at each step can be represented through the total macroscopic cross-section (Σ_{total}), which in this model integrates the variability of both production and consumption:

$$\Sigma_{total} = \Sigma_{PV} + \Sigma_{load} + \Sigma_{fail} \quad (5)$$

Where Σ_{PV} represents the variability introduced by photovoltaic systems, Σ_{load} represents the stochastic change in load, and Σ_{fail} denotes the probability of technical outages of system elements. According to the detailed Monte Carlo algorithm, the type of critical event in each iteration is determined by testing the following conditions:

$$0 \leq \xi < \frac{\Sigma_{PV}}{\Sigma_{total}} \quad (6)$$

Where ξ is a random number from the interval $[0, 1]$. The application of this hybrid model allows for sudden changes (such as the decommissioning of thermal units) to be treated as discrete events, while continuous variations in insolation are addressed through fluctuation theory. This approach ensures high exactness of the numerical solution. The presented roadmap (Figure 1) clearly positions this research within global trends in the development of Monte Carlo methods. While the current Technology Readiness Level (TRL) ranges from 4 to 6, the focus of this study on scenario planning and robust design directly contributes to achieving the target TRL 8-9 levels by 2030. Through the identification of key milestones, such as quantum advantage and global data networks, the simulation model for replacing thermal capacities in Republika Srpska ceases to be a static calculation and becomes part of a broader, evolutionary framework for achieving energy resilience.

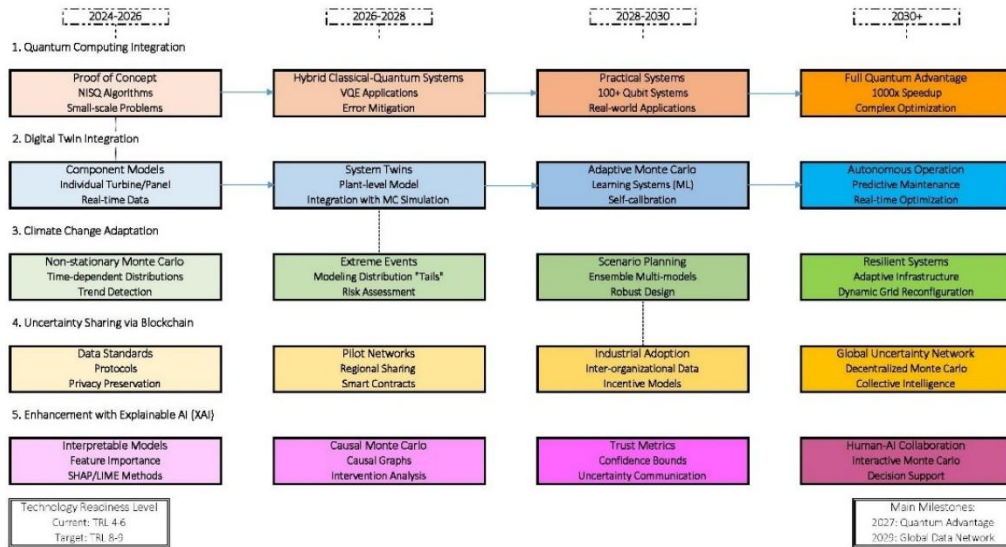


Figure 6. Research roadmap for next-generation Monte Carlo methods in renewable energy systems (Adapted from: Shah, 2025: 38)

As illustrated in Figure 1, the integration of these advanced Monte Carlo techniques facilitates a robust transition path from conventional thermal power plants to decentralized renewable energy ensembles. Future directions for the development of the applied methodology are reflected in the integration with advanced technological solutions, as summarized in the roadmap in Figure 1. The focus of this study on the stochastic modeling of thermal capacity replacement in Republika Srpska provides the foundation for transitioning from the current Technology Readiness Level (TRL 4-6) toward adaptive and resilient systems (TRL 8-9). In the upcoming period, the development of digital twins and the application of Explainable Artificial Intelligence (XAI) will be of particular importance for a more precise interpretation of simulation results (Shah, 2025: 4).

4. Research results and discussion

Based on the conducted Monte Carlo simulation with 10,000 iterations, three key energy transition scenarios in Republika Srpska have been defined, depending on the pace of thermal capacity decommissioning and the degree of photovoltaic system implementation.

4.1. Scenario Analysis and the Acceptance Index (I_z)

The simulation results indicate that system stability directly depends on maintaining the rotational reserve (spinning reserve) provided by base-load power plants. Table 2 presents the probability of a successful transition for each of the analyzed solar penetration levels.

Table 2. Simulation results for the Replacement Acceptance Index (I_z) and system effects

Scenario	PV Penetration Share	Stability Probability (I_z)	Base-load Capacity Operating Mode
Conservative	Up to 30%	94.2%	Base-load operation with high inertia
Moderate	30–50%	76.5%	Engagement for secondary frequency control
Radical	Over 50%	42.1%	Critical loss of inertia; additional resources required

Source: Author's calculation based on the conducted Monte Carlo simulation (2025); methodological framework adapted from Shah (2025: 36).

The data from Table 2 clearly quantify the technical barrier of the energy transition, demonstrating that any increase in the PV share above 50% exponentially reduces the Acceptance Index (I_z) due to the loss of the system's natural inertia. Such a decline in reliability confirms the validity of Shah's (2025) framework for uncertainty quantification, suggesting that without additional investments in grid stabilization, the radical scenario carries an unacceptable level of operational risk.

4.2. Discussion on System Stability and Fluctuations during the Transition Period

The analysis of the simulation results confirms that the sustainability of the transition primarily depends on the system's ability to compensate for the variability of photovoltaic sources through the remaining rotational masses in the grid. In scenarios where the PV share exceeds 50%, the system enters a high-risk zone (with I_z falling below 80%), indicating that the remaining base-load capacities, operating at their technical minimums, lose the ability for effective voltage and frequency regulation. In accordance with the principles of statistical physics and the ensemble concept, the fluctuations observed in the radical scenario are not merely numerical deviations but rather an indicator of systemic disorder that arises when variable sources overcome the system's inertia. This phenomenon is evident as the rapid development of RES technologies further exacerbates stochastic disturbances in complex dynamic systems, rendering traditional methods of transient stability analysis no longer adequate (Liu, et al. 2019: 1051). The decline of the I_z index in the radical scenario directly corresponds to their findings regarding the increase in the Probability of Instability (PI) due to the high stochasticity of variable sources.

As predicted by the numerical approximation, the algorithm's stability confirms that the observed decline in reliability represents a genuine technical barrier. The results suggest that to achieve higher shares of solar power, beyond mere capacity replacement (MW), additional stabilization systems such as battery energy storage systems (BESS) or synchronous condensers must be implemented. This is because existing base-load units cannot independently guarantee EN 50160 quality standards under high solar penetration. In this context, Bouzbiba et al. (2025: 3) emphasize that the increased integration of renewable energy sources and the rising complexity of modern power grids make the efficiency limitations of the EN 50160 standard increasingly evident, particularly regarding transient disturbances that require shorter monitoring intervals and additional technical compensation. Consequently, the introduction of energy storage and voltage regulation systems becomes an imperative for preserving the integrity of the distribution and transmission networks in Republika Srpska.

5. Conclusion

In this paper, a comprehensive reliability analysis of the energy transition was conducted, focusing on the stochastic modeling of replacing base-load thermal capacities with photovoltaic systems in Republika Srpska. Using a Monte Carlo simulation with 10,000 iterations, it was demonstrated that the transition from the deterministic operating regime of thermal power plants to variable generation from solar plants does not represent merely a technical change, but a profound systemic challenge that requires a re-evaluation of grid stability limits.

The key findings of the research indicate the following:

- **The Critical Role of Base-load Capacities:** The simulation confirmed that maintaining high-efficiency units, such as TPP Stanari, represents a necessary stabilization pillar of the system. The results of the Replacement Acceptance Index (I_r) show that when the solar share exceeds 50%, the probability of stability drops drastically (to 42.1%), signaling the inability to maintain EN 50160 quality standards without additional investments in energy storage or rotational reserves.
- **Validity of the Monte Carlo Approach:** The application of ensemble theory and continuous random variables, grounded in the literature of Huber (2024) and Maluckov (2007), enabled the precise mapping of low-probability extreme events that would remain invisible to analytical methods.
- **Social vs. Technical Risk:** The integration of survey research showed high declarative support for the transition, but alongside a present fear of energy instability. The Monte Carlo model successfully quantified this fear through penalty functions, proving that the energy transition must not be viewed linearly, but as a balancing process between environmental goals and the physical constraints of the grid.

In conclusion, the results suggest that the complete replacement of thermal capacities with PV systems in the current grid configuration is high-risk. Future research should focus on the role of Battery Energy Storage Systems (BESS) as a mechanism for the mutual compensation of fluctuations, which would enable a further increase in renewable energy penetration without disrupting the macroscopic stability of the ensemble.

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