Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume 26, July 2026

Role of External Grid Representations in Frequency Stability Studies of Power Systems with High Non-Synchronous Generation

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Abstract. The transition toward power systems with high shares of non-synchronous generation has made the quality of dynamic system modeling increasingly important for credible stability assessment. Particular sensitivity arises at the boundaries of the study area, where the external grid is commonly represented by reduced or equivalent models rather than by a full dynamic description of the interconnected system. This manuscript addresses the role of external grid representations in frequency stability studies, with emphasis on the physical meaning of the equivalent, its parameters, and the consequences of parameter uncertainty. The discussion is centered on frequency stability, while its relation to other calculation types and stability classes is also clarified. A critical review of literature is used to show that the influence of external grid representation is recognized, but still insufficiently structured for present-day low-inertia systems. A simulation-supported case study based on a Hungarian islanded microgrid model and the IEEE 9-bus system is then used to illustrate how external-grid inertia assumptions affect the frequency nadir. The manuscript shows that the external grid can no longer be treated as a purely technical closure of the model. In low-inertia conditions, it becomes an active determinant of the computed dynamic behavior, and its parameterization must therefore be treated as a modeling problem of first-order importance.

Key words. Frequency stability, external grid equivalent, non-synchronous generation, low-inertia power systems

1. Introduction

The large-scale integration of wind and photovoltaic generation has transformed the physical basis of frequency stability. In conventional power systems, the early response to an active-power imbalance was shaped primarily by the aggregate kinetic energy of synchronous machines and by the electromechanical coupling of strongly interconnected transmission networks. In contrast, present-day systems contain an increasing share of converter-interfaced generation whose contribution to inertial response is either absent or explicitly synthesized by control. As a result, the rate of change of frequency, the depth of the frequency nadir, and the interaction between local and inter-area dynamics have become substantially more sensitive to modeling assumptions than in earlier synchronous-machine-dominated systems [1], [2].

This sensitivity is particularly important in weak-grid and low-inertia conditions. Experimental evidence has shown that the dynamic behavior of converter-dominated systems can change materially when inertia, short-circuit strength, and grid impedance are varied within realistic ranges. In such conditions, control settings that appear acceptable in idealized software studies may lead to oscillatory or unstable behavior in more realistic weak-grid environments [3]. At the same time, European scenario studies have shown that system rotational inertia can no longer be treated as a uniform background quantity. In the 2030 European system, local inertia deficiencies may arise even when synchronous-area constraints are satisfied, and countries such as Spain, Portugal, and Germany were found to contribute zero synchronous inertia in the hour of lowest inertia in one modeled scenario [4]. These observations are directly relevant for the representation of external systems in dynamic studies.

In practical transmission-system studies, the entire synchronized system is rarely modeled with full dynamic transparency. In the Continental Europe synchronous area, a transmission system operator typically models its own control area in detail and represents the rest of the interconnected system through reduced models, boundary equivalents, or external grid elements. This is partly a matter of computational efficiency, but it is also linked to model confidentiality, incomplete access to neighboring controller data, and the repeated need to run many security studies under changing operating conditions [5], [6]. Consequently, the external grid is not merely a technical convenience. It is the formal interface through which the wider synchronous area enters the calculation.

That issue is not confined to frequency stability. External equivalents are used across load-flow, contingency, short-circuit, electromechanical transient, and electromagnetic transient calculations. In static studies, they preserve power exchange and voltage conditions at the boundary. In electromechanical transient studies, they must reproduce the exchange of active and reactive power together with the relevant inertia, damping, and synchronizing effects. In electromagnetic transient studies, the boundary may require frequency-dependent or wideband representation to capture converter-network interactions [6], [7]. Although the present manuscript focuses on frequency stability, the discussion is framed so that the role of the external grid remains connected to these broader calculation classes.

The literature already contains several lines of relevant work, but they do not yet form a sufficiently coherent basis for present-day practice. Reviews of low-inertia frequency stability explain why fast frequency control, synthetic inertia, and revised reserve concepts are needed, yet they usually treat system strength and boundary behavior at a rather aggregate level [1-2], [8-9]. Studies devoted specifically to external-grid representation show that different equivalents can materially alter the outcome of dynamic simulations, including fault ride-through and transient performance, but they are often framed around particular applications rather than frequency stability as such [5]. Reviews of dynamic equivalents and model reduction emphasize that reducing the external system is unavoidable in large-scale studies, but they also point out that maintaining dynamic fidelity becomes more difficult as inverter-based resources and fast controls spread across the network [6], [7]. More recent work has proposed adaptive, measurement-based, or reduced-order approaches to dynamic equivalents, yet these approaches have not been synthesized into a frequency-stability-oriented modeling discussion [10]–[12].

For that reason, the present manuscript is built around three connected aims. First, the physical background of external grid representations is clarified from the viewpoint of frequency stability. Second, the principal modeling approaches reported in literature are compared in a structured way, with particular attention to inertia, short-circuit strength, and impedance representation. Third, the case-study results are integrated as simulation-supported illustrations of the conceptual discussion.

The paper is organized as follows. Section 2 presents the methodological framework, including the physical background of external grid equivalents, a critical literature synthesis, and comparative tables. Section 3 discusses the implications of the reviewed approaches for present-day frequency stability analysis. Section 4 summarizes the Hungarian and IEEE 9-bus case studies and interprets their results in the light of the preceding analysis. Section 5 concludes the manuscript.

2. Methodology

Frequency stability is addressed here as the ability of the system to maintain acceptable frequency following a severe active-power imbalance. In electromechanical terms, the decisive early-period quantities are the power deficit, the available kinetic energy, the effective damping, and the timing of primary and fast frequency responses. The external grid enters this problem because it determines how much additional stiffness, inertia, and damping are seen at the model boundary. If the boundary is treated as infinitely strong, a portion of the real system's vulnerability may be suppressed. If it is represented as too weak, the simulated system may appear more fragile than it actually is.

This issue is closely related to, but distinct from, other stability classes. Rotor-angle stability is governed by synchronizing and damping torques and is likewise affected by the strength and dynamic order of the external equivalent. Voltage stability depends on transfer capability, reactive support, and load characteristics, all of which are influenced by the boundary impedance and by the retained or aggregated dynamic devices. In electromagnetic transient studies, especially those involving grid-following converters, the external grid may need a frequency-dependent representation because small-signal and harmonic interactions are shaped by the effective network impedance seen from the point of common coupling [7], [14]. Thus, although the present work is limited to frequency stability, the chosen focus remains physically consistent with the wider problem of boundary modeling across power-system calculations.

A. *Physical meaning of the external grid equivalent*

An external grid equivalent represents the electrical and dynamic influence of the part of the synchronized system that lies outside the explicitly modeled study area. Physically, at least four elements are embedded in that abstraction.

The first is the steady-state voltage source behavior at the boundary. This determines the operating point and the pre-disturbance power exchange. The second is the equivalent impedance, commonly characterized through short-circuit power and the R/X ratio. These parameters define how strongly the surrounding network resists voltage changes and how disturbances are electrically coupled across the boundary. The third is the frequency-related dynamic behavior, which reflects the aggregate inertia, damping, and control response of the external system. The fourth is the degree of dynamic richness that is retained or discarded during reduction, including whether coherent machines, converter controls, or frequency-dependent effects are represented explicitly or only approximately.

In traditional studies, the external grid has often been represented as a Thévenin source behind an impedance. Such a model is simple, transparent, and still useful, but it must be interpreted correctly. The Thévenin source is not a real generator. It is an equivalent boundary condition whose voltage magnitude, phase, short-circuit power, and impedance angle stand in for a much larger system. Preda et al. showed in dynamic connection studies that even for fault ride-through investigations the choice of short-circuit power and R/X ratio in the Thévenin equivalent can materially affect computed performance, and that single-machine or infinite-bus assumptions may be inadequate when realistic external dynamics are required [5]. That observation remains highly relevant for frequency stability.

The physical meaning of short-circuit power is especially important. A high short-circuit level reflects a strong electrical connection to the rest of the system, reducing the sensitivity of boundary voltage and phase to the local disturbance. A lower short-circuit level implies that local injections and withdrawals have a larger effect at the boundary, so the study area behaves more like a weakly interconnected subsystem. In converter-dominated environments this is not only a static strength indicator. It also affects the small-signal and transient interaction between converters and the network, as has been emphasized in impedance-based stability analysis [14].

Inertia plays a different role. It is not a property of the network impedance but of the rotating energy stored in synchronous machines. When the external system is reduced, that inertia may be omitted or misallocated. In frequency-stability studies, this omission directly distorts the early post-disturbance trajectory. If the equivalent inertia is too large, the computed RoCoF is artificially reduced and the nadir is optimistic. If it is too small, the converse occurs. In present-day systems, where converter-based generation displaces synchronous machines, the correct assignment of external inertia becomes more uncertain than in the past [1], [2], [4].

B. Literature synthesis and critical assessment

The published literature may be grouped into four partially overlapping strands. The first consists of broad reviews of low-inertia frequency stability. These papers explain the diminishing role of inherent synchronous inertia, the growing relevance of fast frequency response, and the challenges created by non-synchronous generation [1], [2], [8], [9]. They establish the physical necessity of better dynamic modeling, but they rarely translate that necessity into concrete guidance on external equivalents. The summary of the key findings are listed in Table 1.

The second strand concerns weak-grid behavior and experimental validation. Pant et al. provided a particularly valuable contribution by showing, on a physical microgrid testbed, that the interplay of inertia, short-circuit strength, and impedance ratio can materially alter the apparent stability of fast ancillary-service controls [3]. The significance of that result in the present context is not limited to ancillary services. It shows more generally that the external grid parameters are not passive background settings. They actively shape the observed dynamics. This makes them highly consequential in model-based stability studies.

The third strand concerns external-grid representations themselves. Preda et al. compared a Thévenin equivalent, a multi-machine system, and wide-area dynamic equivalents based on Ward and Extended Ward reduction in the context of distributed-generation connection studies [5]. Although their application was fault ride-through rather than frequency stability, the methodological lesson is broader: simplified external representations can misrepresent the dynamic support of the rest of the system, whereas fuller multi-machine or coherency-based equivalents may better preserve stability margins.

The fourth strand concerns dynamic equivalents and reduction techniques. Aththanayake et al. reviewed power-system reduction techniques for planning and stability studies and emphasized that, in inverter-rich systems, reduced dynamic models are increasingly necessary but increasingly difficult to construct without loss of essential behavior [6]. Annakkage et al. surveyed dynamic system equivalents more generally and highlighted coherency-based reduction, frequency-dependent equivalents, and hybrid approaches as established tools in this domain [7]. Subsequent work by Osipov and Sun proposed adaptive nonlinear reduction for faster simulation [10], while Jiang et al. introduced measurement-based ARX equivalents that identify the external-area behavior from boundary measurements rather than from full structural knowledge [11]. Yesil and Irmak showed that extended REI-based reduction can provide substantial model-size reduction while preserving the essential study-area behavior for selected calculations [12].

A weakness nevertheless remains in the literature. Low-inertia frequency-stability papers do not usually distinguish sufficiently between the internal system model and the boundary equivalent. External-grid papers often discuss representation accuracy, but mostly in applications other than frequency stability. Reduction papers focus on preserving dynamic behavior in a generic sense, but frequency nadir and RoCoF are rarely treated as the central metrics by which the external equivalent is judged. The result is a fragmented body of work in which the technical pieces exist, but their integration into a stability-centered modeling framework remains incomplete.

Table 1. Key findings of selected journal and conference literature relevant to external-grid representation in frequency stability studies

Property	Synchronous generation	Non-synchronous generation	Consequence for external-grid modeling
Inertial response	Inherent and immediate through stored kinetic energy	Absent unless synthesized by control	External inertia must be represented explicitly when the surrounding area contains many converters
Primary frequency response	Naturally linked to governor-turbine dynamics	Control-dependent and resource-limited	Boundary response cannot be inferred from inertia alone
Short-circuit contribution	High and largely machine-driven	Lower and converter-limited	Short-circuit strength becomes more variable and more critical
Electromechanical mode structure	Dominated by synchronous-machine coupling	Increasingly influenced by converter controls and network strength	Classical machine-only equivalents may lose important dynamics
Sensitivity to R/X ratio and weak-grid effects	Usually moderate in RMS studies	Often high, especially for grid-following converters	Boundary impedance needs more careful parameterization
Dependence on operating point	Present, but often smoother and slower	Can change rapidly with dispatch, controls, and availability	Fixed external parameters become less reliable across scenarios

C. Comparison of external-grid representations

From the standpoint of frequency stability, the main external-grid representations may be compared by the physical effects they preserve and by the uncertainties they suppress. Table 2 summarizes that comparison.

The comparison shows that the common distinction between simple and detailed equivalents is not sufficient. What matters is whether the chosen equivalent preserves the dynamic mechanisms relevant to the study objective. For a screening calculation in a strong synchronous area, a Thévenin equivalent may be adequate. For a low-inertia islanding scenario, the same choice may be insufficient unless inertial support, damping, and possibly frequency dependence are added explicitly.

Table 2. Comparison of external-grid representations from the viewpoint of frequency stability

Representation	Physical concept	Main preserved effect	Main limitation for frequency stability
Infinite bus	Ideal voltage source with fixed frequency	Boundary voltage and angle held perfectly stiff	External inertia effectively infinite; local vulnerability suppressed
Thévenin equivalent	Voltage source behind lumped impedance	Boundary strength via short-circuit level and R/X ratio	Dynamic support only indirect unless inertial behavior is imposed
Single equivalent machine	Aggregated synchronous support behind boundary	Explicit inertial and damping response	Inter-area structure and converter diversity largely lost
Multi-machine external model	Reduced but still physical external area	Better preservation of electromechanical modes and coherency	High modeling effort and data demand
Ward / Extended Ward dynamic equivalent	Network reduction with retained boundary effects	Efficient preservation of selected study-area dynamics	Frequency accuracy depends on retained states and tuning
Measurement-based or ARX equivalent	Identified from boundary responses	Can reproduce observed dynamic transfer behavior	Uncertain outside trained operating conditions
Frequency-dependent network equivalent	Frequency-varying boundary admittance	Appropriate for converter interaction and EMT behavior	Often too detailed for routine RMS frequency studies

D. Comparison of synchronous and non-synchronous generation from the viewpoint of boundary modeling

The principal implication is that the external grid in a high-non-synchronous-generation system is not simply a smaller version of a traditional synchronous system. It is a dynamic environment whose apparent inertia, strength, and response characteristics vary more widely, and whose interaction with the study area may be substantially more nonlinear and operating-point dependent. Table 3. summarizes the key findings of the references found most relevant to the topic.

Table 3. Comparison of synchronous and non-synchronous generation with emphasis on external-grid representation in frequency stability studies

Ref.	Main focus	Principal finding	Relevance to this manuscript
[1]	Low-inertia frequency control review	Frequency behavior becomes increasingly sensitive to reduced kinetic energy and fast controls	Need for boundary models that do not mask low-inertia effects
[2]	Stability of low-carbon minimum-inertia systems	Frequency and voltage stability challenges intensify as synchronous generation is displaced	Supports the broader system-level interpretation
[3]	Weak-grid experimental validation	Variable inertia, short-circuit strength, and R/X ratio materially change observed dynamic behavior	Demonstrates practical significance of external-grid parameters
[4]	European inertia variability	Continental-scale constraints can mask local inertia deficiency	Provides numerical evidence that external inertia is highly variable
[5]	External-grid representation in dynamic studies	Thévenin, multi-machine, and Ward-type equivalents yield different dynamic outcomes	Shows that the external equivalent is a decisive modeling choice
[6]	Reduction-technique review	Reduced dynamic models are indispensable but harder to justify in renewable-based systems	Frames the problem of reduced external areas
[7]	Survey of dynamic equivalents	Coherency-based, frequency-dependent, and hybrid equivalents are established but application-dependent	Provides the conceptual taxonomy
[10]	Adaptive nonlinear reduction	Fast reduced models can preserve important dynamic features	Route toward better practical equivalents
[11]	Measurement-based ARX equivalent	Dynamic behavior can be retained from boundary measurements	Relevant where neighboring dynamic data are unavailable
[12]	Extended REI reduction	Significant element reduction is possible while maintaining selected behavior	Shows continued relevance of structured reduction
[13]	Dynamic IEEE 9-bus wind study	IEEE 9-bus remains a useful benchmark under non-synchronous penetration	Supports the use of the IEEE 9-bus case

3. Discussion

The reviewed literature and the physical analysis point toward a common conclusion: the external grid should be treated as an explicit modeling uncertainty in frequency stability studies, not merely as a technical closure of the network. This is particularly true when the study concerns weak interconnections, islanding, high shares of converter-interfaced generation, or situations in which neighboring systems cannot be modeled in detail.

A first consequence is methodological. The widespread use of a single nominal external-grid setting is no longer defensible for many low-inertia studies. The case for sensitivity analysis is strong because the external parameters are not fixed in reality. Short-circuit strength varies with switching state, outage pattern, and dispatch. The effective inertia of the surrounding system varies with synchronous commitment and renewable availability. The R/X ratio seen from the boundary changes with the electrical path through the network. The European inertia study by Mehigan et al. is especially instructive in this respect because it demonstrates that even when synchronous-area limits are respected, geographically local inertia deficiencies can still occur [4]. For a TSO studying its own area with a reduced external system, that means the correct external inertia is not a single constant but a scenario-dependent quantity.

A second consequence is conceptual. The same external equivalent cannot be expected to serve equally well across all calculation types. A Thévenin equivalent that is acceptable for short-circuit screening may be too crude for a frequency-stability study. A dynamic equivalent that reproduces inter-area electromechanical modes may still be inadequate for electromagnetic transient converter interaction. The distinction between load-flow, contingency and transient studies is therefore not just procedural. It should inform the chosen form of external equivalencing.

A third consequence concerns practical model governance. Because TSOs and researchers often lack access to the full dynamic data of adjacent systems, there is a strong case for using structured reduction and identification approaches rather than ad hoc parameter setting. The literature on adaptive nonlinear reduction, AutoRegressive with eXogenous inputs (ARX) equivalents, and dynamic aggregation indicates that more credible external equivalents can be obtained even when the full neighboring model is unavailable [10]–[12]. That does not eliminate uncertainty, but it makes that uncertainty traceable.

The problem of external-grid representation should not be framed only as an academic modeling concern. It has direct practical implications for reserve dimensioning, frequency-security margins, and the interpretation of simulated islanding events. If the external grid is modeled too strongly, the required fast frequency support may be underestimated. If it is modeled too weakly, remedial actions may be overdesigned. In both cases, the external equivalent shapes the engineering decision.

4. Case study

The case-study material used here as a simulation-supported illustration of the conceptual findings. Two test systems were considered. The first was a Hungarian islanded microgrid-type system with approximately 2000 MWs kinetic energy. Its operating point during the tests was P = 100 MW and Q = 13 Mvar. The large synchronous generator G4 remained connected to represent the bulk-system machine in isolated operation, with a nominal apparent power of 210 MVA. The wind power plants were capable of supplying a total of 50 MW. The model contained voltage levels of 400, 120, 20, and 10 kV, together with parallel lines and transformers and consumer data based on measured profiles. The second test system was the IEEE 9-bus system, equipped with IEEE-type excitation control, a built-in thermal governor model, six transmission lines, six transformers, and three impedance-type loads. The total load was 315 MW and 115 Mvar.

The studies were carried out as RMS electromechanical simulations in DIgSILENT PowerFactory 15.1.2. For both systems, a scenario matrix was defined by combining ten values of load imbalance and ten values of external-grid inertia. The active-power imbalance ranged from 5% to 50% of the local load in order to generate electromechanical frequency events. The external-grid inertia constant was varied from 1 s to 10 s. In this way, the parameter sweep covered both relatively strong synchronous support and highly reduced rotational support, corresponding to a wide range of non-synchronous penetration assumptions.

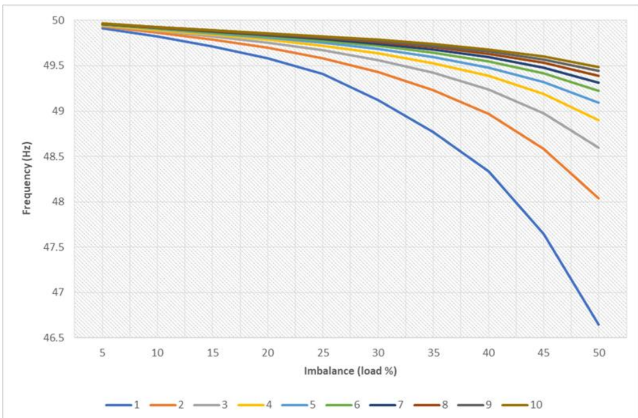

Figure 1. Frequency curves for the Hungarian test system under different external-grid inertia values and active-power imbalance levels

The output metric was the frequency nadir measured on the selected busbar during the transient. Governors were retained in the models, but their contribution was limited in the very early phase because of the time needed for primary frequency response to develop. The results in both systems showed a consistent pattern. Higher assumed external inertia resulted in a higher nadir and a less severe transient, whereas lower assumed inertia deepened the nadir and accelerated the frequency decline. In the more extreme combinations, especially above about 30% power imbalance and at low inertia values, the nadir fell below 49 Hz, which would imply automatic load shedding under standard European settings.

The Hungarian system exhibited the stronger practical message because the external-grid element in that model directly encoded the assumed level of synchronous support in the surrounding system. The inertia sweep therefore illustrated how the same network and disturbance can produce materially different frequency trajectories solely because the external equivalent is changed.

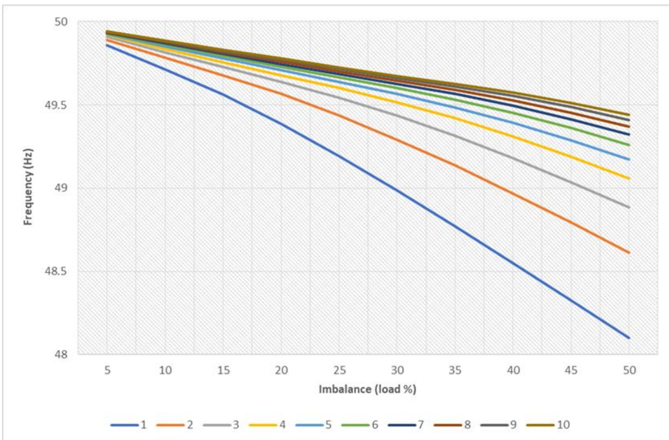

Figure 2. Frequency curves for the IEEE 9-bus system under different external-grid inertia values and active-power imbalance levels.

The IEEE 9-bus system showed the same qualitative trend in a more compact benchmark environment. This is useful because it indicates that the sensitivity is not peculiar to one network model but is rooted in the underlying electromechanical physics.

These results support the central argument of the manuscript. Even when the study objective is limited to frequency nadir, the external grid cannot be reduced to an afterthought. A relatively small modeling inaccuracy in the equivalent inertia is sufficient to alter the computed transient curve and, in severe scenarios, the security conclusion. The case studies also suggest that further work should not stop at inertia alone. Additional sweeps of short-circuit power, R/X ratio, and alternative dynamic reductions could further strenghten these findings as a future work.

4. Conclusion

The manuscript has examined the role of external grid representations in frequency stability studies of power systems with high non-synchronous generation. It has been shown that the external grid is not a neutral model boundary. In low-inertia conditions it directly affects the computed RoCoF, frequency nadir, and the interpretation of dynamic security margins.

The reviewed literature indicates that the technical building blocks for better modeling already exist. Low-inertia frequency-stability studies explain why dynamic sensitivity has increased. External-grid studies demonstrate that different equivalents can materially alter the result. Reduction literature provides a range of dynamic-equivalent approaches, from coherent aggregation to measurement-based identification. What has been missing is a stability-centered synthesis that connects these strands and treats the external equivalent as a first-order modeling decision.

The case study supported that conclusion. In both the Hungarian islanded system and the IEEE 9-bus benchmark, the calculated frequency nadir depended strongly on the assumed inertia of the external grid. Under sufficiently large imbalance and sufficiently low external inertia, the simulated system crossed the 49 Hz threshold. The result is not that one universal equivalent should now replace all others. Rather, the result is that the external-grid model must be chosen in a way that is consistent with the study objective, the available data, and the plausible variability of the surrounding system.

For present-day practice, the most important implication is that sensitivity to external-grid parameters should be treated as part of the study design. Inertia, short-circuit strength, and impedance angle are not fixed background constants in converter-rich systems. They are scenario-dependent properties of the wider network. Frequency-stability studies that neglect that fact risk assigning excessive confidence to results that are, in reality, conditional on the chosen equivalent.

Acknowledgement

This research was supported by the EKOP-25-4-II-BME-245 University Research Scholarship Programme of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

Istvan Vokony and Istvan Taczi acknowledge the support of CELSA (eight call) 2023 scholarship.

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