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Methodology for Integrating Heterogeneous Equipment in Hybrid Energy Complex Management Systems

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Abstract

The article is dedicated to the methodological explanation of how heterogeneous equipment is integrated into a unified management environment of hybrid energy complexes. The relevance of the topic is determined by the growing use of multi-vendor storage, conversion, metering, and supervisory devices whose direct interoperability remains limited in practical deployments. The novelty lies in shifting the analytical focus from static architecture to the internal process through which incompatible interfaces, signal semantics, and operational constraints are transformed into a coherent control structure. The work describes the formation of a unified data model, the restructuring of communication flows, the redistribution of control logic under changing configurations, and the operational meaning of export-limiting and edge-based coordination. Special attention is paid to semantic normalization, gateway-mediated synchronization, and adaptive behavior under partial equipment availability. The goal is to explain the mechanisms that preserve system coherence in heterogeneous infrastructures. Analytical review, comparative interpretation, conceptual modeling, and synthesis were used. Open-access engineering publications were studied. The conclusion outlines integration principles applicable across repeatable sites. The article will be useful for designers, automation engineers, and energy management practitioners.

Keywords: *Hybrid Energy Complex, Heterogeneous Equipment Integration, Energy Management Systems, Unified Data Model, Industrial Communication Protocols.*

INTRODUCTION

Hybrid energy complexes increasingly combine battery systems, photovoltaic converters, smart meters, gateways, supervisory platforms, and cloud-level coordination tools supplied by different manufacturers and developed within different technical logics. This configuration expands functional flexibility, yet it introduces a persistent integration problem. Devices exchange signals, but they do not automatically share meaning. Communication may be established at the protocol level while control remains fragmented at the operational level. This discrepancy has become more visible as distributed energy infrastructures move from isolated pilot configurations to multi-component deployments where storage, conversion, monitoring, and grid compliance must operate as a single coordinated environment.

The relevance of the problem is linked to the practical instability created by heterogeneous device behavior. Different vendors encode similar electrical states through different registers, timing rules, scaling principles, and alarm semantics. In many cases, control failure does not originate in electrical equipment itself. It originates in the inability of the management layer to interpret and align incompatible representations of system state. Under such conditions, integration ceases to be a purely technical issue of connection. It becomes a methodological issue of transformation. The infrastructure needs a stable internal logic before it can operate coherently.

The purpose of the article is to explain the methodological principles through which heterogeneous equipment in hybrid energy complexes is transformed into a unified control structure that preserves coherent operation under variable technical conditions. To achieve this objective, the following research tasks are formulated:

– to identify the mechanisms generating integration inconsistency in heterogeneous energy infrastructures;

– to analyse how unified data models and communication architectures transform heterogeneous signals into a coordinated control environment;

– to assess the role of adaptive control logic in maintaining system integrity under dynamic operating conditions.

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The hypothesis of the study is that coherent integration in hybrid energy complexes emerges through a multi-layer transformation process in which heterogeneous signals are semantically normalized, communication flows are dynamically structured, and control constraints are continuously reinterpreted within a unified system state model.

The scientific novelty lies in formalizing integration as a continuous system-level process that links semantic data transformation, communication mediation, and adaptive control into a unified methodological framework, which is insufficiently addressed in existing engineering literature.

METHODS AND MATERIALS

The analytical base was formed around a practical observation: hybrid energy systems rarely fail because a single device cannot operate, but because independently designed devices cannot sustain a common control regime. Communication remains technically available. Coordination weakens. Signals that refer to the same physical state are encoded differently, transmitted at different intervals, and interpreted under different local constraints. For that reason, the methodological design combines analytical review with conceptual interpretation. The purpose of this combination was not to compare isolated technical solutions, but to reconstruct how integration is assembled across interacting system layers.

The reviewed material was drawn from Scopus-, Web of Science-, and IEEE Xplore–indexed engineering publications issued in 2022–2026, with priority given to open-access studies that describe implemented or experimentally validated energy management infrastructures. The search was guided by keyword clusters linking hybrid energy systems, heterogeneous device integration, communication protocols, supervisory control, and energy management through AND/OR combinations. This search logic produced an initial pool of roughly 40 publications, later reduced to 9 after filtering out studies limited to single-device optimization, narrowly electrical design, or abstract control models lacking implementation-level interaction between data, communication, and control environments.

The retained sources do not form a perfectly uniform body of evidence. Some describe gateway-based protocol mediation in detail but say little about how normalized signals enter supervisory logic. Others construct unified data profiles or monitoring architectures, yet leave the redistribution of control constraints only partially explained. A smaller set addresses adaptive coordination under disturbance conditions and shows that response speed depends not only on algorithmic efficiency, but on where interpretation occurs inside the system. This difference in emphasis was analytically useful. It made comparison possible.

Close reading of the selected studies revealed several recurring technical observations. Heterogeneous measurements become operationally comparable only after semantic reconstruction within a shared representational layer. Multi-protocol communication environments remain unstable unless intermediate structures normalize message timing, priority, and format before supervisory processing begins. Control architectures, in turn, do not simply execute commands over a connected network; they continuously reconcile storage limits, converter behavior, and grid constraints inside a common decision space. Where distributed or edge-based processing is introduced, the literature repeatedly points to the same effect: local reassignment of analytical and control functions shortens the path between disturbance detection and system response.

What these publications describe with reasonable clarity are separate segments of the integration problem. What remains less clearly articulated is their coupling. Data representation is often treated as one task, communication mediation as another, and adaptive control as a third. Their interdependence is rarely explained as one internal mechanism of coherence. Several limitations should be acknowledged. The analysis relies on studies with different architectures, validation conditions, and technical scopes, which restricts direct comparability of reported results.

This is precisely where the present article begins. Comparison of the reviewed material made it necessary to move beyond a descriptive survey of interfaces and protocols and toward a methodological reconstruction of integration as an internal system process, where state, timing, and constraints are continuously reinterpreted rather than merely connected.

RESULTS

Heterogeneous energy complexes expose their internal inconsistency at the moment when independently operating devices are required to participate in a shared control regime. Signals do not align. Communication patterns diverge. Operational constraints conflict. Integration begins not with connection but with interpretation.

The initial observation reveals that field devices encode identical physical quantities through incompatible representations. Voltage may appear as instantaneous RMS values in one device, as filtered averages in another, and as scaled integer registers within legacy controllers. Update frequencies vary. State transitions are reported differently. In practice, these discrepancies prevent coordinated control even when communication links are established. The mechanism that resolves this condition relies on analytical decomposition of each device into three elements: interface behavior, signal semantics, and operational constraints. Only through this decomposition does the system acquire a stable reference frame in which signals can be reinterpreted rather than merely transmitted. The systematization of integration elements is presented below (Table 1).

Table 1. Structural components of heterogeneous equipment integration methodology (compiled by the author based on Gil et al., 2022; Milczarek and Możdżyński, 2024; Aghmadi et al., 2023)

Integration Layer	Core Function	Transformation Mechanism	Operational Outcome
Device Analysis Layer	Identification of inconsistencies	Decomposition into interfaces, semantics, constraints	Structured understanding of heterogeneity
Data Representation Layer	Unification of signals	Semantic alignment and abstraction	Coherent system state model
Communication Layer	Data transmission and synchronization	Protocol translation and prioritization	Stable and relevant data exchange
Control Layer	Coordination of system behavior	Constraint reconciliation and redistribution	Consistent operational decisions
Adaptation Layer	Response to system changes	Dynamic reconfiguration of roles and limits	System resilience under partial availability

This analytical stage does not produce a list of inconsistencies. It produces a transformation requirement. Each signal must be detached from its native encoding and reintroduced into a unified representational layer where its meaning becomes independent of the originating device. Such a layer emerges as a structured data model in which measurements, commands, states, and constraints are explicitly differentiated. Electrical variables originating from storage units, converters, and metering devices are reorganized into a consistent schema, where their functional role in system behavior determines their position within the model. A unified data profile allows load characteristics, power electronics parameters, and distributed generation signals to coexist within a single interpretative structure, eliminating ambiguity at the control level (Milczarek and Możdżyński, 2024).

This transformation alters the nature of communication. Protocol heterogeneity does not disappear. It becomes encapsulated. Distributed energy systems simultaneously employ LoRaWAN for geographically dispersed sensing, MQTT for lightweight asynchronous exchange, HTTP for service-level interaction, and OPC UA for structured industrial communication. Each protocol retains its domain-specific function. None is replaced. Their coexistence introduces a condition where communication no longer serves as a direct channel between devices, but as a layered environment where messages are normalized, translated, and aligned before entering the unified data model. Integration occurs inside this environment, not at its boundaries (Gil et al., 2022). The integration flow across system layers is illustrated below (Figure 1).

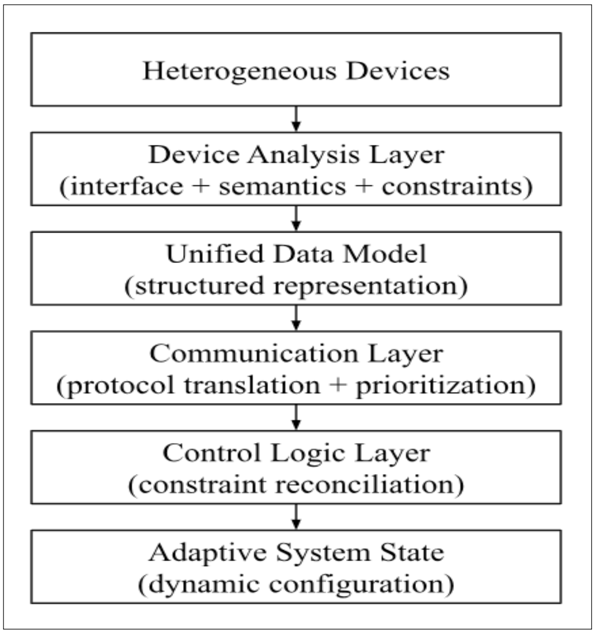

Figure 1. Process scheme of heterogeneous equipment integration in hybrid energy systems (compiled by the author based on Gil et al., 2022; Silva et al., 2022; Saleem et al., 2023)

The communication layer therefore acquires an active role in resolving incompatibility. Gateways positioned between field devices and supervisory systems do not simply relay information; they construct a dynamic representation of system state. A MODBUS-based environment illustrates this mechanism clearly: field devices transmit data through RTU or CAN interfaces, while a gateway reorganizes these inputs into a coherent register map accessible via TCP/IP.

This register map is not a mirror of device memory. It is a reconstructed state space where heterogeneous signals are synchronized and contextualized.

The necessity of this reconstruction becomes evident under bandwidth and latency constraints. Uniform polling strategies inherent to MODBUS treat all parameters equally, producing congestion and delaying critical updates. The integration mechanism adapts by introducing contextual prioritization. Parameters such as temperature, voltage, and state of charge are classified according to their operational relevance, and their update frequencies are dynamically adjusted. Critical signals propagate with minimal delay. Secondary data is throttled. Communication becomes selective. This modification preserves compatibility with existing EMS logic while fundamentally changing the temporal structure of data exchange (Arroyo-Valle et al., 2025).

Signal acquisition itself undergoes transformation. Data streams originating from heterogeneous devices arrive at different sampling rates and with varying stability characteristics. A feature extraction stage processes these streams, identifying variance, rate of change, and threshold exceedance. These derived features redefine raw measurements as dynamic indicators of system behavior. The data layer no longer reflects instantaneous values alone. It captures trends and deviations. Integration extends from structural alignment to behavioral interpretation.

Once a unified representation and stabilized communication environment are established, control logic begins to operate as a coordination mechanism rather than a set of isolated commands. Hybrid energy complexes combine storage systems, converters, and distributed generation under overlapping constraints. Storage units impose limits on charge and discharge cycles. Converters define power conversion boundaries. Grid interfaces enforce export restrictions. These constraints intersect within the control layer, where decisions must reconcile them in real time.

A supervisory system integrating a photovoltaic installation of 37 kWp with a battery storage unit rated at 15 kW/45 kWh demonstrates how such reconciliation unfolds in practice. Data acquisition, processing, and visualization are distributed across independent computational nodes, allowing the system to maintain operational continuity even when individual components fail. The separation of functional layers prevents local inconsistencies from propagating across the system, while unified data interpretation ensures that control decisions remain coherent (Silva et al., 2022). The system does not rely on a fixed configuration. It adapts.

Adaptation becomes explicit when components are excluded or partially unavailable. Hybrid systems rarely operate under ideal conditions. Devices may enter maintenance states, communication links may fail, and operational limits may restrict participation. The integration mechanism responds by re-evaluating the unified data model and control constraints in real time. Remaining components redistribute functions. Available capacity is recalculated. Control rules persist without contradiction. System integrity is preserved.

Export-limiting control illustrates this dynamic particularly clearly. Grid constraints impose strict limits on power injection, requiring coordinated response across multiple devices. Measurements from metering units, state information from storage systems, and control capabilities of converters must converge into a single decision. Discrepancies in signal timing or semantics can lead to violations of grid requirements. Integration resolves this by aligning measurement interpretation, synchronizing control actions, and ensuring that commands reflect a consistent system state. Compliance emerges from coordination, not from individual device behavior.

The temporal dimension of integration becomes critical under disturbance conditions. Centralized control architectures introduce delays that weaken responsiveness in rapidly changing environments. Edge-based processing restructures this dynamic by relocating decision-making closer to data sources. Embedded nodes calculate stability indicators such as Voltage Deviation Index and Rate of Change of Frequency locally, allowing immediate reaction to disturbances. Under severe voltage fluctuations, coordinated storage interventions restore stability within 300 ms while maintaining compliance with EN 50160 power quality standards (Lazar et al., 2026). Reaction is no longer delayed by communication latency. It is embedded within the system itself. The distribution of response time and system performance parameters is presented below (Figure 2).

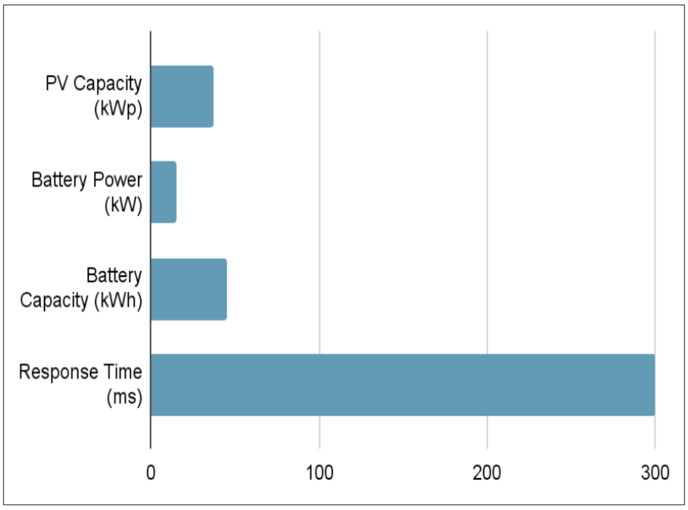

Figure 2. Numerical representation of system performance parameters in integrated hybrid energy system (compiled by the author based on Silva et al., 2022; Lazar et al., 2026)

Monitoring infrastructures extend integration into distributed environments where both intelligent and legacy devices coexist. Battery energy storage systems deployed in residential and commercial contexts rely on heterogeneous hardware platforms with differing communication capabilities. Integration is achieved by abstracting device-specific features into standardized monitoring variables, enabling centralized supervision without requiring uniform device design. The monitoring system captures operational states, detects anomalies, and transmits control commands through a unified interface, regardless of the underlying hardware diversity (Burgio et al., 2023).

The integration pathway expands further when cloud-based coordination is introduced. Data streams from distributed assets are aggregated and processed in cloud environments, where demand-side management strategies reshape consumption patterns in response to system conditions. This introduces a multi-layered control structure: local acquisition, edge-level processing, and cloud-level optimization operate simultaneously. The system evolves into a continuous data-processing pipeline, where each layer refines the interpretation of system state and contributes to coordinated control actions (Saleem et al., 2023).

Security constraints impose additional conditions on integration. The coexistence of multiple communication standards increases exposure to cyber threats, requiring coordinated protection across all layers (He et al., 2024). Authentication mechanisms, encryption protocols, and secure communication channels must be embedded within the integration architecture itself. Maintaining interoperability while enforcing security introduces a structural tension: openness enables integration, while restriction ensures protection. Resolving this tension requires balancing accessibility with controlled data exchange, particularly in systems combining legacy protocols with modern IoT frameworks (Aghmadi et al., 2023).

Several limitations should be acknowledged. The analysis relies on heterogeneous implementations where system configurations, communication delays, and hardware capabilities differ significantly. Direct comparison of performance indicators remains constrained by these variations. Evaluation environments often rely on simulation or controlled testbeds, which do not fully reproduce operational complexity.

These observations do not remain confined to the operational description of integration. They indicate a structural shift in how heterogeneous systems construct coherence. The reconstructed data layer, the selective communication mechanisms, and the adaptive control logic together form a condition where system behavior is no longer derived from predefined compatibility, but from continuous reinterpretation of state. Integration begins to operate as an internal mechanism of system organization rather than an external engineering procedure. This shift requires further examination at the level of underlying principles and constraints.

DISCUSSION

The behavior of hybrid energy complexes under integration conditions reveals a structural shift that cannot be reduced to connectivity or protocol compatibility. Systems that appear functionally connected at the communication level often fail to produce coordinated control actions. Signals circulate. Decisions remain inconsistent. This discrepancy indicates that integration operates at a deeper layer where meaning, timing, and constraint interpretation intersect. Earlier research on microgrid architectures frequently emphasized interoperability as a sufficient condition for system cohesion, yet practical implementations demonstrate that communication alignment does not automatically produce operational coherence. Integration unfolds within the interpretative layer where data is reshaped before it becomes actionable.

The internal mechanism responsible for this transformation develops around the reinterpretation of signals as elements of a shared state space. Data streams originating from heterogeneous devices do not carry stable meaning across system boundaries. Their interpretation depends on context, timing, and interaction with other variables. Previous studies on unified data models have attempted to standardize representations, introducing structured schemas for loads, converters, and storage systems. These approaches reduce ambiguity, but they do not eliminate the need for contextual interpretation. In many operational environments, identical parameters acquire different roles depending on system conditions. A voltage measurement may act as a stability indicator under one regime and as a control constraint under another. The data layer becomes conditional. It adapts.

This observation modifies the understanding of data standardization itself. A unified schema does not finalize integration; it initiates a process in which data is continuously reinterpreted relative to system dynamics. Earlier work on IoT-based energy systems often assumes that once data is normalized, higher-level control can operate deterministically. Evidence suggests a different mechanism. Control logic remains dependent on how data is interpreted within changing operational conditions. Static representations provide consistency. They do not resolve conflict. Integration persists as an ongoing process.

Communication infrastructures reinforce this dynamic by introducing temporal variability into data interpretation. Multi-protocol environments are often described as stable configurations where different standards coexist. In practice, each protocol introduces its own timing behavior, message structure, and reliability profile. Data transmitted through LoRaWAN, MQTT, or industrial protocols does not arrive with identical temporal relevance. Delays, jitter, and synchronization mismatches alter the effective meaning of signals. A parameter received outside its operational window loses its validity. Communication networks therefore influence not only data availability but its interpretative value.

Prior research addressing communication efficiency has focused on optimizing throughput and reducing latency.

Selective prioritization mechanisms extend this approach by restructuring the visibility of system processes. When high-priority parameters are updated more frequently, the system effectively allocates attention unevenly across its own state space. Some processes are observed in detail. Others recede. This uneven resolution affects control decisions, shaping how the system responds to disturbances and constraints. Integration begins to influence perception itself, not only transmission.

The control layer captures the cumulative effect of these transformations. Traditional models describe control algorithms as deterministic mappings between inputs and outputs. Observations from integrated environments suggest a more fluid mechanism. Control logic operates within a continuously evolving constraint space where storage limits, converter capacities, and grid requirements interact dynamically. No single constraint dominates. The control system interprets and redistributes these constraints in real time, producing coordinated actions that reflect the current configuration of the system rather than a predefined rule set. Control becomes adaptive. Stability emerges through continuous adjustment.

The ability of integrated systems to maintain coherence under partial availability provides further insight into this mechanism. Previous studies often interpret resilience as a function of redundancy or fault tolerance. A different pattern becomes visible when examining how systems respond to component exclusion. Integration does not rely solely on backup elements. It relies on the flexibility of interpretation. When a device becomes unavailable, the system recalculates its internal representation, redistributes functional responsibilities, and adjusts control constraints accordingly. The structure remains operational because it is not rigidly bound to specific components.

Export-limiting scenarios highlight the interaction between distributed interpretation and global constraints. Grid requirements impose strict limits on power injection, requiring synchronized response across heterogeneous devices. Earlier approaches typically enforce these limits through centralized control structures. Integrated systems demonstrate that coordination can emerge through distributed interpretation of shared constraints. Measurements, storage states, and conversion capabilities converge within a unified decision framework that continuously aligns local actions with global requirements. Compliance is produced through coordination. It is not imposed externally.

The introduction of edge-based processing further modifies the distribution of control functions. Earlier research has framed edge computing primarily as a means of reducing latency. Its structural effect is more significant. Analytical functions migrate closer to data sources, allowing local nodes to interpret system conditions and initiate responses without relying on centralized coordination. Disturbance detection and response become localized processes. The system reacts faster. It also becomes structurally decentralized. Decision-making is redistributed across the network.

Cloud-based coordination introduces an additional temporal dimension to integration. Previous studies often present cloud platforms as scalable repositories for data aggregation. In operational environments, cloud systems contribute to cross-site learning and long-term adaptation. Data collected from multiple installations informs control strategies beyond a single system boundary. Integration expands from real-time coordination to cumulative learning. System behavior evolves over time as patterns are detected and incorporated into operational logic.

Security constraints introduce a structural tension within the integration process. Open communication architectures facilitate interoperability, yet they increase exposure to cyber threats. Protective mechanisms such as authentication, encryption, and access control impose additional layers of processing within data flows. These mechanisms affect latency, accessibility, and system flexibility. Integration must incorporate security as an operational parameter rather than an external requirement. Communication is no longer neutral. It is conditioned by protection mechanisms that reshape how data is transmitted and interpreted.

Several limitations should be acknowledged. The analysis relies on previously published studies with heterogeneous system configurations, ranging from small-scale microgrids to distributed IoT-based infrastructures. Differences in hardware capabilities, communication latency, and control strategies restrict direct comparison of observed behaviors. Many implementations are validated under controlled experimental conditions, where environmental variability and large-scale disturbances remain limited. Real-world deployments introduce additional complexity that is not fully captured in these studies.

Another limitation concerns the absence of standardized metrics for evaluating integration quality. Existing research primarily focuses on performance indicators such as efficiency, latency, and reliability. These metrics do not directly capture the degree of semantic alignment or interpretative coherence achieved within integrated systems. As a result, methodological differences remain difficult to quantify, and comparative analysis across implementations remains constrained.

CONCLUSION

The conducted analysis clarified the first research objective by showing that integration inconsistency in hybrid energy complexes arises from three tightly connected sources: interface divergence, semantic mismatch of signals, and non-uniform operational constraints. Devices may exchange data and still remain methodologically incompatible because their variables are structured, updated, and interpreted according to different internal logics. The source of fragmentation is not only technical. It is representational.

The second objective was addressed through the reconstruction of the mechanisms that convert heterogeneous device outputs into a coordinated management environment. The analysis showed that a unified data model performs more than a formatting function. It creates a shared state space in which measurements, alarms, commands, and limits become interpretable across equipment classes. Communication architecture performs a parallel function. It stabilizes exchange through gateways, protocol mediation, selective prioritization, and synchronization of temporally uneven data flows. System coherence emerges when these two layers operate together.

The third objective was resolved by explaining how adaptive control logic preserves operational integrity under unstable conditions. Control does not remain fixed to a predefined equipment set. It recalculates available functions when devices are excluded, communication is delayed, or export limits tighten. In this structure, resilience is linked to redistribution of roles and reinterpretation of state rather than to static redundancy alone. Edge processing strengthens this logic by shortening the path from measurement to action and by supporting localized reaction under disturbance.

The hypothesis was confirmed in analytical terms. Coherent integration is produced not by direct interoperability between heterogeneous devices, but by a layered transformation of signals, communication behavior, and control constraints. Hybrid energy complexes do not become unified because their components are identical. They become operational because their differences are methodically reorganized.

Several limitations remain. The analysis relied on previously published studies with different configurations, validation conditions, and performance criteria. Direct comparison was restricted by this heterogeneity. Even so, the reconstructed methodology captures a stable pattern. Integration does not remove diversity from the system. It changes the conditions under which diversity can be controlled.

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