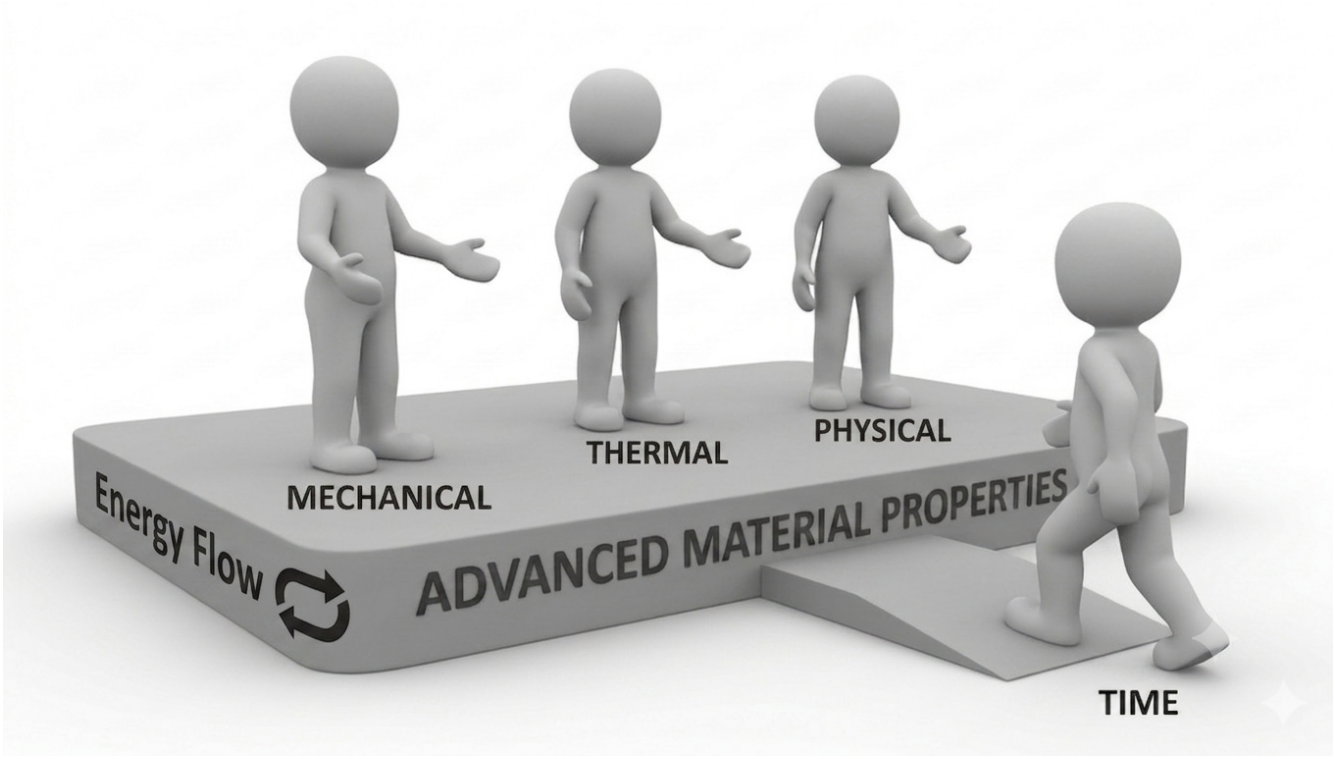


Energy, Materials & Time:

Temporal Geometry and Exergy Persistence in Functional Materials

By Paul R. Leonard

Developed in collaboration with the theoretical, experimental, and applied materials research of Prof. Vladimir B. Kopylov

Introduction

For more than a century, energy engineering has largely accepted one constraint without questioning it: the interval during which ordered energy remains available is effectively fixed. Once a molecule combusts, a nucleus fissions, an electron is excited, or a chemical bond is formed or broken, the resulting ordered energy exists only briefly before relaxing toward equilibrium. The engineering

challenge has therefore been to recover as much useful work as possible before that organization is irreversibly dispersed into Earth's ambient environment.

The duration of that opportunity is astonishingly brief. In many physical systems, the interval during which highly ordered electronic energy exists is measured in femtoseconds to picoseconds. Within that tiny window lies virtually the entire opportunity for extracting useful work before the ordered energy thermalizes and becomes part of the surrounding environment. From the perspective of exergy, this interval may represent one of the most fundamental constraints in all of engineering.

The consequence has shaped nearly every major technology of the industrial age.

Combustion engines, steam turbines, nuclear power plants, industrial furnaces, chemical reactors, and much of modern manufacturing all begin by creating a significant departure from equilibrium. Ordered energy briefly becomes available. Engineering then races to harvest as much useful work as possible before relaxation completes its work. Over generations we have become extraordinarily successful at recovering useful exergy from events already disappearing.

In that sense, much of modern engineering has operated less as the creator of the event than as its remarkably efficient recovery system.

There is nothing irrational about this architecture. It reflects the scientific understanding and technological capabilities available throughout the industrial era. When greater performance was required, the engineering response naturally became to create larger spatial gradients: higher temperatures, greater pressures, stronger electric fields, larger reactors, and increasingly sophisticated infrastructure capable of sustaining those conditions. These remain among humanity's greatest engineering achievements.

Yet they all share a common assumption.

The useful interval itself is treated as fixed.

Cascade approaches the problem from a different direction.

Rather than asking how to create a larger initial disturbance, it asks whether the relaxation process itself can become part of the engineering architecture.

That distinction deserves careful attention.

This article is a conceptual synthesis rather than a conventional technical report. It draws on a body of experimental and theoretical work, primarily that of V. B. Kopylov, developed and applied over many years. The purpose is to articulate one coherent design perspective — the treatment of time and relaxation architecture as primary engineering variables — in clear English.

The paper does not present new catalyst formulations, new quantitative performance datasets, or detailed experimental protocols. Those remain the domain of ongoing materials development and application-specific optimization. What it offers is a structured way of thinking about why certain material architectures can sustain functional non-equilibrium states while others cannot, and how that distinction can guide design upstream of conventional kinetic optimization.

The framework does not propose slowing time, altering the fundamental laws governing quantum mechanics, or suspending thermodynamics. Individual electronically excited states continue to appear and relax according to conventional physics. Instead, the question becomes whether material architecture can deliberately organize the pathways through which energy flows, allowing electronically excited subsystems to exhibit persistent, non-equilibrium organization under steady operating conditions.

The distinction is subtle but fundamental.

The engineering objective is not to prevent relaxation.

It is to engineer the architecture of relaxation.

Particle-size distributions, defect populations, crystallographic geometry, local symmetry, electron-nuclear coupling, and surface architecture become significant not simply because they influence whether excitation occurs, but because they determine how electronically excited populations exchange energy with their surroundings. Rather than treating relaxation as an unavoidable endpoint, these structural features become tools for organizing where, when, and through which pathways energy is released.

From this perspective, persistence belongs not to individual excited states but to the organization of the subsystem itself.

A useful analogy is a waterfall. The waterfall appears permanent even though none of the individual water molecules remain in place. A flame appears continuous even though individual combustion events occur and disappear almost instantaneously. Biological organisms maintain stable identities while the molecules composing them are continually exchanged. In each case, persistence belongs to the organization rather than to the individual components.

Electronically excited subsystems may behave in much the same way. Individual quantum events continue unfolding according to conventional relaxation kinetics, while the subsystem maintains organized energetic behaviour through continual energy throughput. Nature already demonstrates that persistent activity can emerge from transient events. The engineering question is whether materials can be designed to do the same intentionally.

This shifts the problem in a profound way.

Instead of asking,

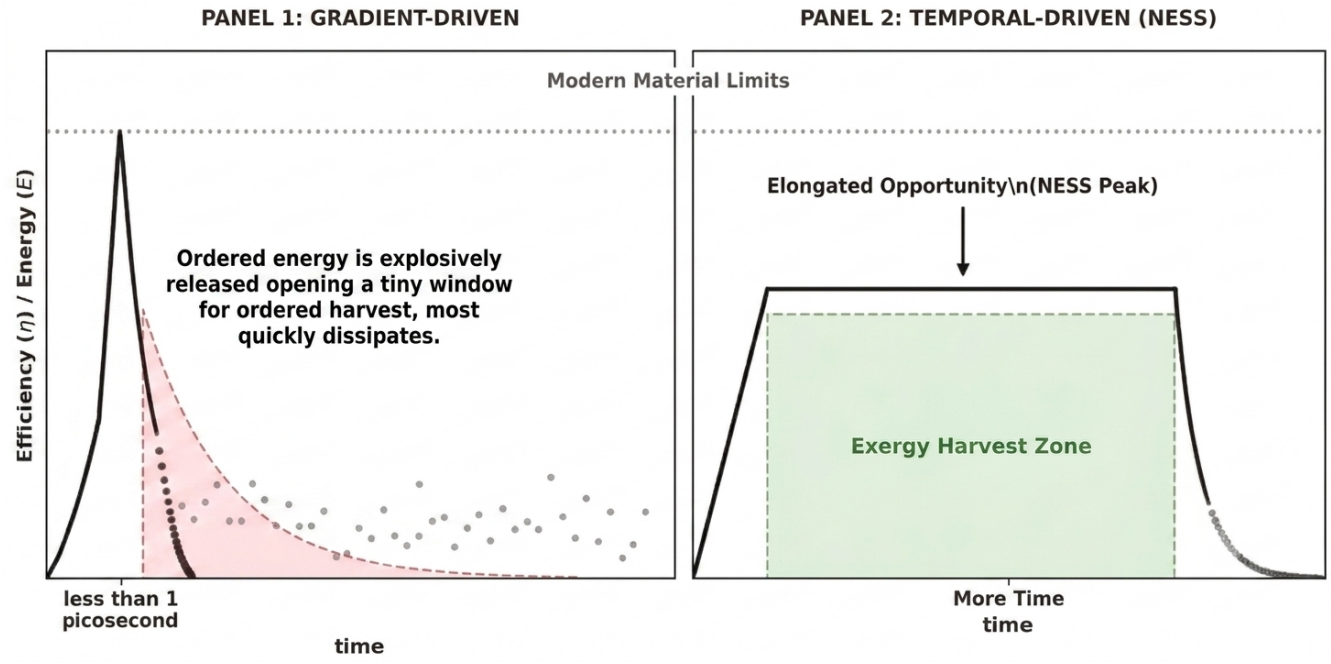
> **How much ordered energy can we create?**

we begin asking,

> **How can the architecture of a material organize ordered energy so that the opportunity to extract useful work persists for longer?**

Time, viewed this way, ceases to be merely the clock by which relaxation is measured.

It becomes part of the material's functional geometry.



Experimental Fingerprints of Activity

If persistent electronically excited subsystems become functional components of a material, an important consequence follows immediately.

Their presence should not remain hidden.

Because the subsystem continuously exchanges energy with the surrounding lattice, defects, electronic states, magnetic ordering, and surface chemistry, its existence should influence multiple physical measurements simultaneously. No single analytical technique need provide definitive proof. Rather, independent techniques should observe different manifestations of the same underlying subsystem.

This distinction is important.

Traditional materials characterization often treats spectroscopy, magnetism, electrical transport, calorimetry, and catalytic performance as largely separate domains of investigation. Each measures a different physical property and is frequently interpreted within its own theoretical framework. An active material suggests a more unified picture. If a persistent electronically excited subsystem exists, then each technique is observing a different projection of the same organized internal dynamics.

This perspective changes how experimental anomalies are interpreted.

Rather than viewing unexpected spectroscopic features, unusual magnetic behaviour, or non-classical relaxation kinetics as isolated curiosities, they become potentially related observations that should exhibit internal consistency. No individual measurement proves the existence of an active subsystem. Collectively, however, they may reveal an architecture that no single instrument can fully resolve.

This realization emerged gradually within our own work.

Long before we understood the broader implications, experimental results repeatedly suggested that conventional equilibrium descriptions were incomplete. Spectroscopic measurements revealed persistent excited-state behaviour. Magnetic measurements indicated unusual responses not easily reconciled with passive materials. Relaxation kinetics departed from simple exponential behaviour. Catalytic activity correlated with structural features that classical composition alone could not adequately explain. Rather than appearing as unrelated observations, these measurements increasingly suggested different windows into the same underlying organization.

The experimental record reveals this convergence across multiple independent measurement modalities. Evidence accumulated across luminescence, thermoluminescence, diffuse reflectance spectroscopy, infrared spectroscopy, Zeeman splitting, oxygen emission, magnetic susceptibility, electrical transport, calorimetry, relaxation behaviour, and catalytic performance. None of these techniques measures exactly the same physical phenomenon. Each interrogates a different aspect of the material. Yet all become relevant if the material contains a persistent electronically excited subsystem interacting continuously with its surroundings.

An important implication follows from this interpretation.

Activity should possess thresholds.

A material designed to sustain persistent electronically excited populations should not necessarily exhibit those populations under every condition. Architecture defines capability, but the surrounding environment determines whether that capability becomes active. Temperature, pressure, chemical environment, electromagnetic conditions, or other external variables may establish activation thresholds below which the subsystem remains effectively dormant and above which its behaviour becomes analytically observable.

This is entirely familiar to catalysis.

A catalyst resting on a laboratory shelf appears inactive. Place the same catalyst within its intended environment of use and its functional architecture becomes apparent. Active materials may behave similarly. The architecture is always present, but measurable signatures emerge only when sufficient energy throughput allows the persistent subsystem to organize itself.

This observation suggests something experimentally useful.

Rather than searching for a single decisive measurement, researchers might instead look for coherent changes appearing simultaneously across multiple analytical techniques as operating conditions cross predicted activation thresholds. Spectroscopy, magnetic response, relaxation kinetics, electrical transport, calorimetry, and catalytic behaviour should evolve together because they are responding to the same underlying subsystem.

That proposition is important because it transforms verification itself.

Instead of asking whether one experiment confirms the model, we begin asking whether independent measurements exhibit the degree of internal coherence expected if they are observing different manifestations of the same organized physical architecture.

In that sense, the experiments become less like isolated pieces of evidence and more like multiple perspectives on a single object.

From Discovery to Predictive Quantum Design

Every mature engineering discipline eventually undergoes the same transition.

It begins by discovering phenomena. Over time, those discoveries accumulate into patterns, those patterns become principles, and those principles eventually become design rules. The objective gradually shifts from finding things that happen to work toward specifying systems that are expected to work before they are ever built.

Aerodynamics followed this progression. Metallurgy followed it. Structural engineering followed it. Electronics followed it. Empirical observation never disappeared, but it increasingly became a means of validating design rather than replacing it.

Materials science has achieved extraordinary success through discovery, yet much of its most sophisticated work remains fundamentally empirical. New compositions are synthesized, characterized, modified, and tested. Computational methods and machine learning have accelerated this process enormously, but they still depend upon large bodies of experimental data from which useful relationships can be extracted.

Predictive quantum design proposes a complementary path.

Rather than beginning with candidate materials, it begins with the required function. The engineering problem becomes one of specification. If a material must perform a particular task within a defined environment of use, what electronic architecture, defect topology, crystallographic organization, and excitation dynamics must exist to support that function?

The distinction is subtle but important.

The goal is not simply to predict the behaviour of known materials more accurately.

It is to specify the architecture of materials that may not yet exist.

That shift changes the role of first principles.

Too often, first-principles physics is viewed primarily as an explanatory language. Once an interesting material has been discovered, quantum mechanics helps explain why it behaves as it does. Explanation is enormously valuable, but engineering ultimately asks a different question. Can the same physical principles be used prospectively to define the material architecture required to achieve a desired outcome?

That question has guided our own work from the beginning.

Catalysis provided an unusually demanding proving ground because every industrial catalyst operates under explicit economic, thermodynamic, and engineering constraints. Activity alone is never sufficient. Materials must remain selective, stable, manufacturable, economically practical, and capable of operating within real industrial environments. Success therefore requires more than identifying an interesting quantum phenomenon. It requires specifying an architecture that performs reliably under the conditions for which it was designed.

Seen in that light, catalysis becomes less an isolated application than an early demonstration of a broader methodology.

Every catalyst is already a quantum system.

Every catalytic event is already governed by quantum mechanics.

The novelty is not recognizing that fact. The novelty lies in asking whether quantum mechanics can become the engineering language used to specify functional material architectures before discovery rather than merely explain them afterward. Instead of engineering in the past tense—understanding why a material behaved as it did—we begin engineering in the present tense, using first principles to define the architecture required for the behaviour we seek.

Nature itself encourages this perspective.

The natural world is filled with materials whose remarkable behaviour emerges not from exotic chemistry alone, but from architecture operating within an appropriate environment of use. Photosynthetic complexes, enzyme systems, ion channels, mineral interfaces, and countless biological structures demonstrate that organization can be every bit as important as composition. These systems were not assembled through trial and error in the laboratory, yet they embody highly specific structural solutions to equally specific functional problems.

The objective is not to imitate biology.

Nor is it to suggest that engineered materials should become living systems.

Rather, nature reminds us that architecture is a legitimate engineering variable. Function need not reside solely in composition; it may emerge from the way energy, structure, and environment interact across multiple scales. In that sense, nature provides not a template to copy, but a proof that organized activity can arise through physical architecture while remaining entirely consistent with thermodynamic law.

If that principle can be deliberately applied to engineered materials, then the implications extend well beyond catalysis. Electronic devices, electrochemical systems, sensors, energy conversion technologies, magnetic materials, and entirely new classes of functional composites may all be viewed through the same design philosophy. The individual applications will differ, but the engineering question remains remarkably consistent:

What architecture must exist if a particular function is required?

That is ultimately the transition from discovery to specification.

Not the abandonment of empirical science, but its elevation into a more predictive engineering discipline—one in which experiment increasingly validates architectures derived from first principles instead of searching blindly for them.

Conclusion

Scientific progress is often described as the accumulation of knowledge.

Engineering progresses somewhat differently.

Its greatest advances frequently occur when familiar observations are reorganized into a more useful framework. Steam, electricity, semiconductors, flight, and digital computation did not emerge because humanity suddenly discovered entirely new laws of physics. They emerged because existing physical principles were organized into architectures capable of performing functions that had previously been impossible.

Materials science may now be approaching a similar transition.

For generations, our greatest successes have come from discovering remarkable materials and then learning why they behave as they do. That approach has transformed civilization, and it will undoubtedly continue producing important advances. Yet discovery alone has never been the ultimate objective of engineering.

Engineering seeks specification.

It asks not merely why something works, but what must exist if a particular function is required.

That distinction shifts attention away from composition alone and toward architecture. Instead of treating electronically excited states as transient curiosities that briefly interrupt equilibrium before disappearing, we begin asking whether persistent electronically excited subsystems can themselves become functional components of engineered materials. Rather than viewing defects solely as imperfections, we ask whether they may become deliberate architectural elements governing the organization of energy flow. Instead of treating relaxation simply as an unavoidable consequence of excitation, we ask whether relaxation pathways themselves become legitimate engineering variables.

None of these questions require abandoning established physics.

They require asking different engineering questions of the same physics.

If persistent electronically excited subsystems can be deliberately specified through material architecture, then catalysis represents only one early demonstration of a much broader design philosophy. Electronic materials, electrochemical systems, sensors, functional composites, energy conversion technologies, and entirely new classes of engineered materials may eventually be understood through the same architectural framework. Whether that framework ultimately proves broadly applicable remains, as always, a matter for continued experiment.

That is precisely how engineering should proceed.

Perhaps the most encouraging aspect of this perspective is its relationship with the natural world. Nature has spent billions of years discovering architectures capable of sustaining organized activity while remaining fully consistent with thermodynamics. Living systems continuously demonstrate that

persistent function emerges not by escaping physical law, but by organizing matter, energy, and environment with extraordinary precision. Engineering need not imitate biology directly to learn from that lesson. Nature reminds us that architecture itself can become a design variable.

The broader implication extends beyond any single technology.

When engineering begins asking what functional architecture must exist rather than simply searching for materials that happen to work, the practice of materials science becomes increasingly predictive. Experiment remains indispensable, but its role gradually shifts. Instead of wandering through an immense landscape hoping to discover useful behaviour, we begin testing architectures derived from first principles against the behaviour nature actually permits.

That transition—from empirical discovery toward predictive specification—may ultimately prove more important than any individual catalyst, alloy, semiconductor, or functional material that emerges from it.

Because once architecture itself becomes the object of design, the question is no longer simply what materials exist.

Perhaps the next chapter of materials science will not be written by discovering new substances, but by learning the geometry through which matter organizes activity itself.

#EnergyEngineering #MaterialsScience #QuantumMaterials #NonequilibriumSystems #Exergy

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Paul R. Leonard writes Big Quantum Nerd, a LinkedIn blog exploring structural clarity through a thermoeconomic lens. His work traces seemingly disparate issues — homelessness, innovation, affordability, healthcare, sovereignty, and institutional failure — back to their common root in energy pathways and surplus dynamics, and how non-equilibrium design principles can restore human agency and resilience.

Paul is co-founder, President & CEO of Cascade Catalysts, Inc., a company developing quantum-effect catalysts and advanced materials for industrial applications. He is also founder of Activate Biophysics Corp., advancing non-toxic, systems-level health technologies. Drawing on decades of applied work across physics, energy, materials, and complex systems, Paul works with leaders in government, industry, and research to move beyond symptom management toward structural solutions that expand surplus and amplify human effort rather than consume it.

References (Extended)

The eight references in *Energy, Materials & Time* are not decorative citations. Together, they trace the conceptual terrain from which this paper emerges: classical reaction kinetics, structure–electronic-state coupling, nonequilibrium self-organization, irreversibility and time, dynamic energy landscapes, and our own subsequent work on active materials and electronically excited-state catalysis.

Historical Foundations: Kinetics & Symmetry Breaking

[1] Hinshelwood, C. N. *The Kinetics of Chemical Change.* Oxford University Press, Oxford, 1940.

Relevance: Provides the classical kinetic foundation against which the present framework is considered. Hinshelwood's work helped establish the quantitative treatment of reaction rates, activation processes, and the influence of temperature on chemical change. In this paper, that classical framework provides the historical starting point: energy is introduced, reactions proceed through transient states, and the system evolves toward equilibrium.

[2] Jahn, H. A.; Teller, E. Stability of Polyatomic Molecules in Degenerate Electronic States. *Proc. R. Soc. Lond. A* **1937**, *161*, 220–235.

Relevance: Provides a foundational example of the coupling between electronic state and physical structure. The Jahn–Teller effect demonstrates that electronic degeneracy can drive structural distortion, establishing an important principle for materials design: electronic behaviour and material geometry cannot always be treated as independent variables. For the present framework, that relationship is important because engineered structure can influence the energetic states and pathways available within a material.

Theoretical Framework: Non-Equilibrium Thermodynamics & Self-Organization

[3] Nicolis, G.; Prigogine, I. *Self-Organization in Nonequilibrium Systems.* Wiley, New York, 1977.

Relevance: Provides a foundational treatment of self-organization in open systems maintained away from equilibrium through continual energy and matter exchange. This work establishes an important physical precedent for persistent organization under throughput: a system need not be in equilibrium to maintain a stable macroscopic state. That distinction is central to the concept of an active material as an open, dynamically maintained subsystem.

[4] Prigogine, I. *From Being to Becoming: Time and Complexity in the Physical Sciences.* W. H. Freeman, San Francisco, 1980.

Relevance: Places time, irreversibility, and dynamical evolution at the center of physical description. For this paper, its importance is conceptual: time need not be treated merely as the parameter used to measure a process. The evolution of a system through time can itself be part of the physical structure we seek to understand—and potentially engineer.

Functional Matter: Dynamic Energy Landscapes

[5] Frauenfelder, H.; Sligar, S. G.; Wolynes, P. G. The Energy Landscapes and Motions of Proteins. *Science* **1991**, *254*, 1598–1603.

Relevance: Provides a powerful example from biological physics in which function emerges from the interaction between molecular architecture, energy landscapes, and dynamical motion across multiple timescales. The relevance here is not that synthetic materials should behave like proteins, but that nature already demonstrates an important engineering principle: **architecture can determine how a system moves through its available energetic states over time.**

Applied Paradigm: Active Solid-State Systems & Catalysis

[6] Kopylov, V. B.; Leonard, P. R. *Emergent Materials Design and Electronically Excited-State Catalysis.* Cascade Catalysts, Inc.
DOI: https://zenodo.org/records/18115403

Relevance: Develops the framework for electronically excited-state catalysis and emergent materials design that supplies the principal technical foundation for the present discussion, connecting material architecture, excited-state behaviour, relaxation, and catalytic function.

[7] Kopylov, V. B.; Leonard, P. R. *Can Smart Matter Be Modeled by Design? Turning Passive Solids into Active Systems.* Cascade Catalysts, Inc.
DOI: https://zenodo.org/records/1779153

Relevance: Extends the framework toward predictive materials design. The central question is whether first-principles modelling can be used not merely to explain observed material behaviour, but to specify architectures capable of producing desired behaviour before synthesis.

[8] Kopylov, V. B.; Leonard, P. R. *New Materials Design Using Excitonic Quantum Effects: Applications for Fuel Cells, Catalysts, Superconductive and Bioactive Materials.*
DOI: https://doi.org/10.26434/chemrxiv.14755380.v1

Relevance: Extends the design framework beyond catalysis toward other functional-material applications. Its importance to the present paper lies in the broader proposition that engineered excitonic and nonequilibrium behaviour may constitute a transferable materials-design principle across different environments of use.

Taken together, these references describe a progression rather than a single intellectual lineage:

kinetics → structure and electronic state → nonequilibrium organization → time and irreversibility → dynamic energy landscapes → engineered active materials.

The first five sources establish the classical and theoretical background. The final three take the question into engineered active materials operating through sustained non-equilibrium electronic organization and develop it into an explicit architectural design framework.

Energy, Materials & Time sits at that applied end of the sequence. Its purpose is not to claim novelty for the earlier fields, but to ask what becomes possible when their established insights are treated as engineering variables rather than as separate descriptions of nature.

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