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A Perspective on Generative AI-Driven Transformation of Research and Education in Smart Energy Systems

Michelle Tan[1*], Adrian Goh[1]

Abstract

Making low-carbon energy systems a central pillar of global sustainable development targets is vital. As part of this decarbonization shift, smart energy systems have become a vibrant field of scholarship and instruction, positioned where artificial intelligence (AI) converges with energy science. This nascent domain confronts new hurdles in both investigation and pedagogy as knowledge continuously evolves. Within this dynamic, generative artificial intelligence (GAI) serves a crucial function in both learning and discovery activities. Nevertheless, the imprint of GAI on smart energy systems scholarship and teaching remains insufficiently examined. Its pedagogical influence, in particular, is rarely scrutinized relative to its research role. GAI reconfigures both the inquiry process and the respective parts played by instructors and students in the classroom. This perspective sheds light on the unfolding transformations in research and educational frameworks observed in the smart energy system sphere. It brings together current scholarship on "GAI for Science" and "GAI for Education" practices within this discipline. On the research front, GAI's consequences are explored at both macro- and micro-scales. In the educational realm, this piece investigates how a GAI-powered instructional model meets the specific pedagogical challenges of smart energy systems when set against conventional methods. The viewpoint offered here may contribute to broader discourse on how GAI is remolding research and teaching in energy science.

Keywords Smart energy systems, Generative artificial intelligence, Research, Education

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Introduction

Set against soaring worldwide energy consumption and the entwined climate emergency, smart energy systems [1]—indispensable for attaining carbon neutrality—have wrestled with a stubborn shortfall in genuine “smartness” even after many years of maturation. Established technology stacks lean heavily on automated instrumentation and information and communications technology, which boil down to an assemblage of proven tools. In recent times, trailblazing strides in generative artificial intelligence (GAI) have breathed new life into the field. Where traditional AI builds a bespoke dataset and model for each assignment, GAI taps into a reservoir of broadly pre-trained understanding and can adapt a task-focused model with sparser data and less effort. For smart energy systems, this spells swifter data throughput. More fundamentally, the shared knowledge bedrock unlocks fresh avenues for grappling with tangled, boundary-crossing problems. Today, by leveraging its capabilities for multimodal information handling, semantic understanding, and inventive synthesis, GAI is steadily being woven into the technical substrate of smart energy systems [2, 3]. This perspective maps the cognitive upheaval GAI is provoking in the field, lays bare novel paths for inquiry and teaching in smart energy systems, and furnishes reference points and insights for the low-carbon transformation.

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In research, energy systems are ballooning in scale under the pressure of economic and demographic forces. This expansion brings with it the strain of conventional technology frameworks buckling under mounting size and intricacy. Concurrently, the grafting-in of new components—hydrogen pathways, electricity markets, and vehicle-to-grid exchanges—has rendered energy systems not just physically elaborate but ever more tangled on the informational plane. GAI, through sweeping pre-training on an immense corpus of prior knowledge, competently navigates this dual-layered complexity across both the physical and informational dimensions.

Shifting to education, the standard approach has traditionally centered on the orderly conveyance of theoretical tenets. Yet when pitted against knotty, cross-disciplinary questions, established teaching modes have not succeeded in nurturing students' capacity to synthesize across fields [4]. Learners may walk away with a firm grounding in theory but commonly hit a wall when asked to meld disparate disciplinary insights into working solutions. On top of that, the traditional uniform instructional paradigm overlooks individual variability in students' curiosities, proficiencies, and learning rhythms, resulting in a poverty of tailored cultivation. This stunts the flowering of individual potential and leaves the field struggling to produce the integrative, creatively adept talent that the fast-morphing landscape of smart energy systems demands.

With this in mind, the present perspective focuses on the research and pedagogical deployments of GAI within smart energy systems. It probes the inventive uses of GAI across both the research enterprise and the classroom, highlighting the weighty role it now plays. Beyond that, this piece engages with the prospective hurdles and openings that GAI introduces for the onward trajectory of smart energy systems scholarship. The ambition is to galvanize a broader circle of investigators and educators to commit to this consequential arena, thereby fueling its forward momentum and enrichment.

"GAI for Science" in Smart Energy Systems Research

The foremost expression of GAI's role in smart energy systems scholarship lies in its data wrangling prowess. Legacy approaches, hemmed in by finite computational muscle, routinely falter under large-scale data-processing demands—a shortfall that bites harder as systems grow. GAI squarely remedies this bottleneck through its high-octane data crunching and its ability to merge multimodal streams. Aligned with this, the perspective sorts GAI's applications in smart energy systems into micro- and macro-level tiers depending on operational breadth, as visualized in **Figure 1.** The logic behind adopting this micro-macro lens is to furnish a lucid interpretive scaffold that maps onto the dissimilar scales and ranges of challenge native to smart energy systems. Down at the micro tier, GAI aims to handle discrete scientific and engineering chores—modeling complex thermo-fluid behaviors or fast-tracking simulations—where gains are measured in precision and compute thrift. At the macro tier, GAI grapples with systemic, whole-grid concerns such as load projection, anomaly flagging, and streamlining operational protocols, where the premium lies in knitting heterogeneous data sources together, detecting cross-silo relationships, and reaching synthesized judgments. This two-level slice provides a more granular understanding of how GAI simultaneously advances core scientific principles and overhauls overall system behavior in the energy domain. The perspective will sift through the state of play at both planes, drilling into the parts GAI enacts and the ripples it sets off within these frames.

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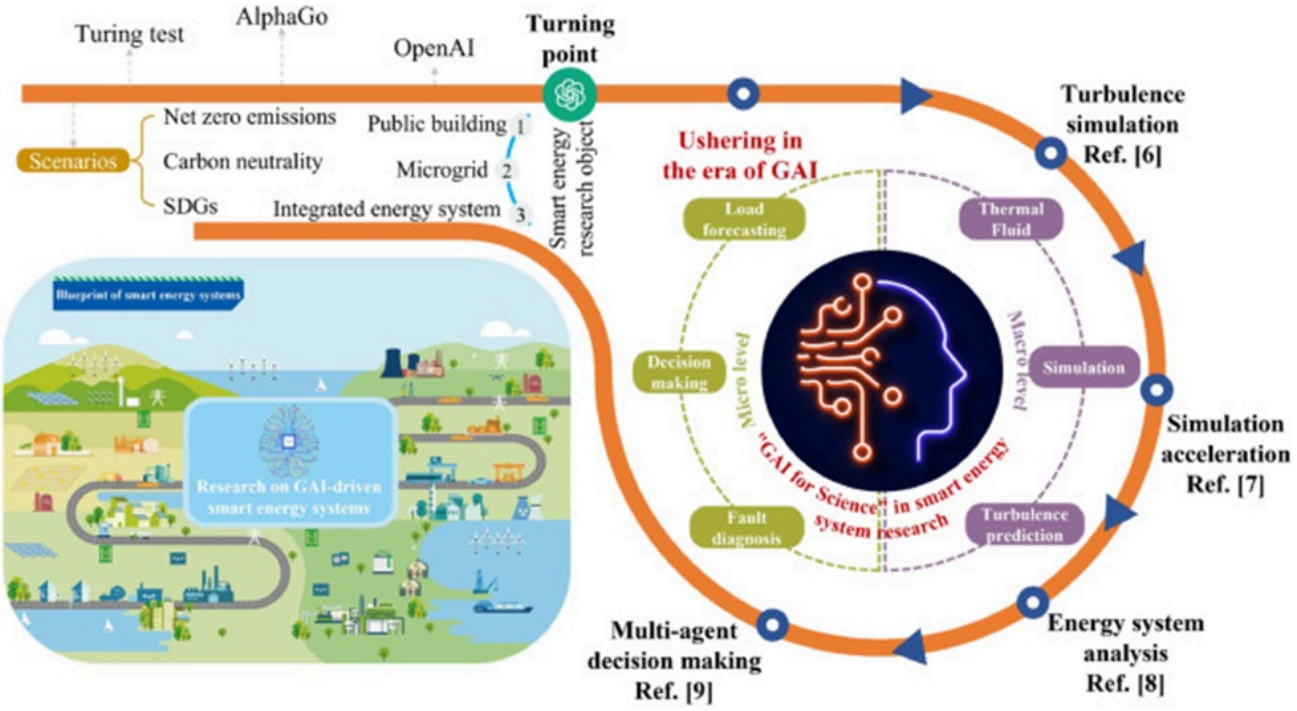

Figure 1. "GAI for Science" in smart energy systems research.

Zooming into the microplane, GAI's deployment in smart energy systems clusters principally around thermal fluid science to underpin the examination of complex thermo-fluid phenomena, process arithmetic, and allied diagnostics. By Bucci and Markides [5]'s count, the output of publications in thermal fluid science and engineering with an AI accent has swelled at a yearly clip of roughly 60% since 2017. In contrast, the field's aggregate expansion rate sits at a mere 7% [5]. This gap spotlights both the latent promise and the pitch of investigative fervor in this niche. Surveying the relevant body of work, GAI's contribution at the micro tier can be distilled to that of an "engine." Rather than delivering wholesale method or framework reinventions, GAI chiefly harnesses already-ripened approaches to supercharge the pace and exactness of thermo-fluid formulation, emulation, and number-crunching. Fresh inroads made by expansive generative architectures—GPT-class models and diffusion formulations among them—have further stretched GAI's reach in thermal fluid science. These constructs, trained on colossal data repositories, can now yield high-confidence simulations and infer intricate fluid behavior with unmatched fidelity. Transformer-derived blueprints, as a case in point, have been repurposed to replicate turbulent streams, capitalizing on their knack for identifying far-flung dependencies within fluid-dynamics data. The upshot is sharper forecasts of chaotic flow fields and patterning, which carry high stakes for tuning smart energy systems. Alongside this, diffusion-style models—acknowledged virtuosos at synthesizing high-quality data—have been enlisted to generate artificial turbulence corpora, empowering investigators to train stronger surrogates even where experimental data are scarce. Ning *et al.* [6] laid out a non-intrusive fluid simulation quickening scheme grounded in diffusion probabilistic models, leveraging GAI mechanics to accelerate the convergence rate of computational fluid dynamics runs. Their inquiry shows that enlisting GAI not only nets a speed-up multiplier of up to 2.4 but also markedly lifts answer quality for historically stubborn-to-converge samples, serving as a potent and resilient accelerator stratagem for tangled flow emulations. Du *et al*. [7] employed conditional neural field encodings fused with latent diffusion models to realize high-verisimilitude stochastic turbulence synthesis by executing the diffusive process within a squeezed latent manifold. Trials confirm this construct shines across an array of convoluted geometries and turbulent regimes, leaving both legacy techniques and present-day deep-learning contenders clearly behind.

At the macro scale, GAI is increasingly focused on crafting original responses to emerging challenges. Typical illustrations span load projection, anomaly detection, and the refinement of decision workflows in energy systems. Where the micro scale privileges raw data-crunching horsepower, macro-oriented deployments draw more heavily on GAI's ability to sniff

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out hidden interdependencies among disparate variables, thus informing operational judgments and generating forward-facing counsel. In one demonstration, Lai *et al.* [8] bridged a pre-trained BERT model into a wind power forecasting context by mapping language representations to spatiotemporal measurements, successfully repurposing it for downstream load prediction. Along parallel lines, Xiao and Xu [9] marshaled the T5 architecture to estimate industrial users' carbon output, crafting a model that generalizes across diverse targets through prompt design and sparse fine-tuning. The fidelity and cross-context portability of generative language models bear directly on the efficient allotment of resources in decentralized energy settings and on readiness for progressively layered and heterogeneous circumstances.

Relative to narrowly scoped sub-problems, whole-system operational choice-making puts the logical dissection and inferential horsepower of GAI on fuller display. While supplying recipes for optimizing decisions in distributed energy systems, established reinforcement learning and neighboring machine learning methods frequently run aground on issues such as stubborn convergence behavior and prohibitive training costs. Such methods habitually depend on drawn-out cycles of trial and feedback to surface optimal action guidelines. This path can squander resources or introduce needless risk in energy environments marked by high dimensionality and deep uncertainty. GAI, by contrast—especially GAI built on expansive pre-trained backbones—can achieve effective decision-making without resorting to large-volume supplemental retraining. These models can be rapidly deployed to specialized tasks and polished through surgical fine-tuning. Moreover, the strong generalizability inherent in GAI constructs renders them readily adaptable to a broad spectrum of settings, unconstrained by any singular energy system typology. Whether the goal is fine-tuning electricity dispatch, orchestrating battery storage arrays, or sculpting renewable generation mixes, GAI stands ready to deliver workable optimization roadmaps. For example, Xiao and Xu [9] fielded an LLM-powered multi-agent framework that autonomously tunes building energy systems via a three-phase workflow, returning dependable optimization outcomes at reduced cost.

"GAI for Education" in Smart Energy Systems Course

As the planetary push to erect new energy system skeletons gathers speed, the compartmentalized and dated knowledge cores that currently prevail in the energy field look increasingly mismatched with the talent-formation requirements of next-generation smart energy systems. To take one illustration, provisioning energy storage within an electrical network routinely draws on a sprawling knowledge base encompassing electrochemistry (choosing cell chemistries), control theory (regulating battery thermals), thermodynamics (efficient thermal exchange), and economics (expenditure tracking). There is an acute imperative to build a cadre of transdisciplinary professionals in the smart energy space who blend digital and information fluency with the capacity to knit together insights from multiple domains.

The instructional model prevalent today draws sharp boundaries around single-discipline content, and curricular material lags behind the galloping tempo of change in smart energy systems. Classroom practice remains largely a one-way broadcast of information, while students operate inside homogenized assessment containers. This fragmented architecture does little to stimulate cross-boundary thinking and falls well short of nurturing the generative problem-solving instincts that smart energy system development demands. GAI, outfitted with forceful knowledge-blending abilities, a native bent for inventive problem-cracking, and collaborative human-machine dialogic features, can jolt the conventional teaching template with fresh momentum, as illustrated in **Figure 2**. It carries the potential to dissolve disciplinary walls, lift instructional productivity, overhaul assessment structures, and galvanize the growth of learners' transdisciplinary cognition and inventive capacities, thereby furnishing a solid platform for cultivating boundary-spanning talent in the smart energy arena. A wealth of GAI-for-education instantiations already populate the field. AI-driven environments like Knewton [10] provide real-time responsiveness and dynamically reshape learning sequences based on learner behavior, constructing study journeys that are more interactive and self-directed. In a comparable spirit, tools such as Gradescope [11] leverage GAI to track learner development and detect patterns, easing the bureaucratic burden on instructors while providing deeper diagnostic windows into student learning.

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Furthermore, Wu *et al*. [12] built a web-accessible K-12 GAI learning ecosystem called “Mo,” aimed at two stubborn bottlenecks: the downward translation of GAI practices from university settings into K-12 classrooms and the geographically uneven availability of GAI learning provisions. By delivering functions such as a virtual learning sphere, resource pooling, and communal support, the platform has undergone pilot deployments across multiple schools, earning a positive reception and demonstrating tangible impact. These GAI-for-education exemplars highlight how GAI is reconfiguring long-standing educational templates and laying the groundwork for a more encompassing, responsive, and potent learning landscape.

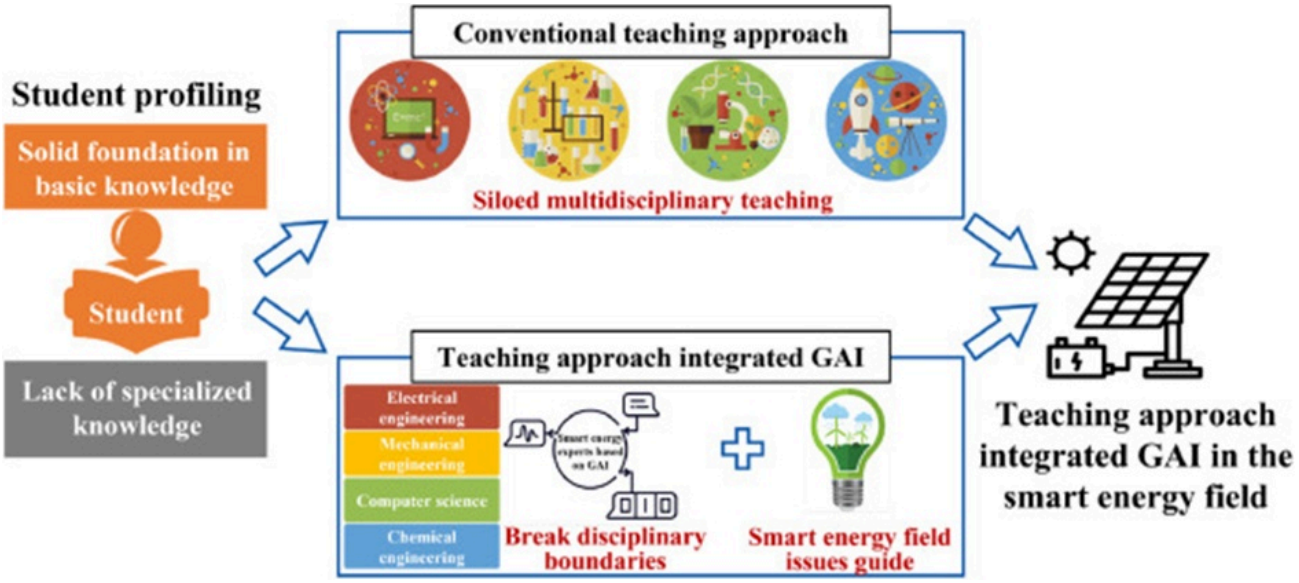

Figure 2. "GAI for Education" in smart energy systems course.

Inside the energy science disciplinary cluster, Stecyk and Miciuła [13] train their attention on the temporal dovetailing of GAI with smart energy pedagogy, charting the historical trajectory of energy instruction—from the engineering specialties of the early 1900s through the energy research thrusts of mid-century, and onward into the sustainability and energy systems engineering paradigms of the early 2000s. In the most recent stretch, with the interpenetration of AI and GAI toolkits, energy education has begun to shift toward intelligent, cross-disciplinary approaches. An even more vivid exhibit is provided by Popadić *et al*. [14], who investigated the extent to which GAI and knowledge graph formalisms can resolve information management and interoperability frictions in the energy sector, mapping out their potential utility in energy education and stewardship. Pan [15], in the newly released book “Artificial Intelligence 2.0,” presents a case study of GAI’s pedagogical integration into the context of smart energy systems. The case study partitions learners into three archetypes: the first set possesses AI familiarity but lacks grounding in the energy landscape; the second has a solid energy background but is short on programming skills; and the third holds dual-domain expertise and actively seeks demanding assignments. In light of the divergent profiles of these three learner bands, an integrated energy advisor (IEA) is constructed. The IEA is, in essence, a large language model companion deployed for smart energy teaching, produced by fine-tuning a pre-trained model on a corpus of smart energy domain material. In the instructional setting, it is made accessible to students as a query-resolution resource and as a springboard for exploring out-of-the-box answers to layered problems. These ventures in applying GAI to smart energy systems pedagogy collectively highlight its vast potential to drive educational reinvention, deepen students’ interdisciplinary capacities, and address the complex challenges inherent to smart energy systems.

Challenges and opportunities

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GAI-fueled smart energy system instruction persists as a fledgling domain hungry for fresh thinking. Nonetheless, substantial stumbling blocks and future pathways span a wide range from curricular transformation to technical invention to talent grooming. The three cardinal challenges GAI poses across the smart energy continuum—spanning deployment, research and development, and classroom practice—are cataloged in this perspective as captured in **Figure 3.**

• Challenge #1 in GAI for education: Multimodal general "large" language model integrated with professional "small" language models

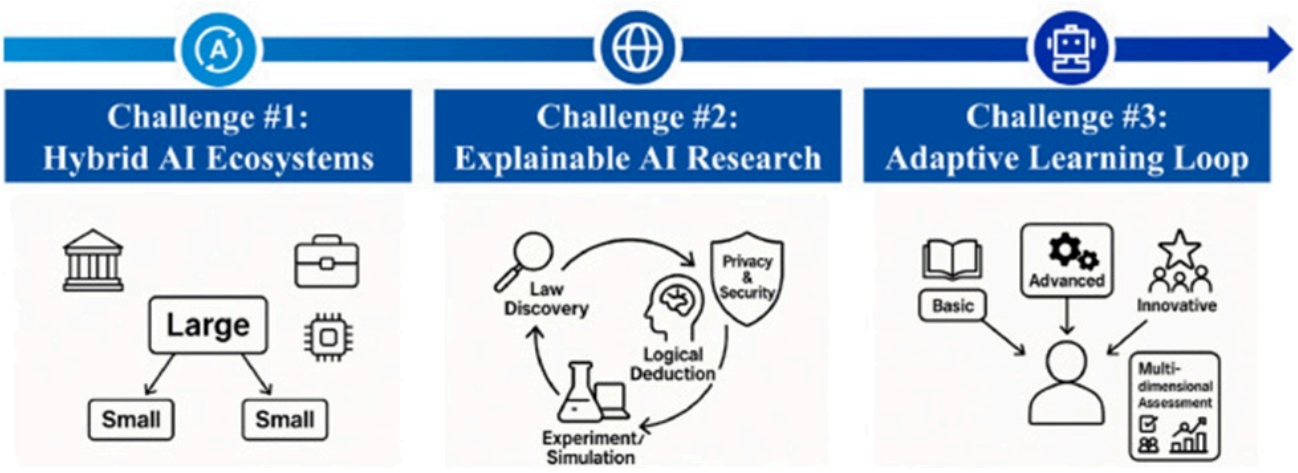

Figure 3. The challenges that GAI brings to the smart energy field.

Existing energy-domain teaching is short on capstone-style, systematically integrative coursework that helps learners chain together multiple specialized offerings and deploy them within a consolidated project environment. Accordingly, domain-anchored "small" language models and broad-coverage "large" language models are required to reshape the instructor-led, conventional classroom transmission format. Beyond that, engineering such intricate systems necessitates joint undertakings among elite universities, leading industrial entities, GAI technology firms, and hardware infrastructure players.

• Challenge #2 in GAI for science: Interpretable GAI-driven new paradigm for scientific research and interdisciplinary knowledge integration

Today's AI-propelled new scientific inquiry paradigm lacks full-cycle validation, ranging from principle discovery and deductive reasoning to experimental or simulation-based confirmation. E has called attention to the necessity of bolstering the overarching design of China's GAI for Science [16]. In the near future, smart energy systems will exceed the traditional energy envelope and face a pressing need for cross-domain synergy among mechanics, control engineering, artificial intelligence, and allied disciplines. An additional obstacle is ensuring privacy and security within GAI for science. This includes data encryption and storage compartmentalization, as well as achieving security fortification and cradle-to-grave data auditability for the GAI system.

• Challenge #3 in GAI for students: Student-in-the-loop personalized learning and multi-dimensional learning quality assessment tools

There is a need to put the GAI educational framework to work in breaking through the deadlocks of conventional pedagogy and in engineering tailor-made instructional material across graduated strata—foundational, advanced, and trailblazing. Through analytic processing, the nested interrelations of common sticking points across a student cohort can be rendered visible, and the signatures of core knowledge nodes can be captured quantitatively. GAI-grounded evaluation instruments hold promise for performing many-sided assessments of students' learning journeys, inventive proposals,

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collaborative dynamics, and subject-matter absorption. Even so, impartial evaluative benchmarks and rubric systems remain largely absent.

With the onward march of GAI technology, a transformative upheaval will occur in the teaching and scientific investigation of future smart energy systems. Cornerstone models tailored to distinct specialized subdomains will be assembled through GAI. The question of how GAI can be orchestrated to realize cross-field invention and cohesive application within smart energy systems will take on heightened importance, given its power to radically puncture the traditional boundaries of the energy realm and to meet the grand tests posed by global climate disruption and ecological endurance.

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Conflict of interest

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Ethics statement

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