Enerhash for Real-Time Energy Optimization in Renewable Power Grids

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Abstract: The integration of intermittent renewable energy sources (RES) into power systems continues to face challenges due to fluctuating supply and limited grid flexibility. This paper examines how Enerhash's modular Databox infrastructure provides a novel solution by operating as an AI-controlled, flexible consumer that supports grid stability while performing productive computing tasks. Unlike conventional data centers that act as constant loads, the Databox combines Bitcoin mining equipment with AI/HPC servers, transforming surplus electricity into economic value while allowing instantaneous demand-side adjustments in response to operator signals. The research applies a qualitative case study approach based on expert interviews, company documentation, and project data, with a particular focus on two deployments: participation in frequency regulation markets in Sweden and the utilization of flared gas in the United States. The Swedish project demonstrated the technological feasibility of including modular computing units in ancillary services markets, with sub-second response times confirming their capacity for primary frequency regulation. The U.S. deployment highlighted the environmental dimension by converting waste gas into electricity, thereby reducing CO_2 and methane emissions while generating digital outputs. Together, these cases show that the Databox model is both scalable and adaptable, offering benefits across regulated and decentralized contexts. At the same time, limitations remain concerning financing, regulatory heterogeneity, and long-term performance data. Future research should extend comparative analysis with other flexible demand-side technologies and explore the broader role of modular computing in sustainable energy transitions.

Keywords: AI-controlled Data Centers, Bitcoin Mining, Flexible Demand, Renewable Integration, Sustainable Energy Systems

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1. Introduction

The rapid growth of renewable energy production has brought fundamental changes to electricity systems, but has also introduced new vulnerabilities. Unlike fossil fuel plants, renewable sources such as solar and wind are weather-dependent and difficult to predict, which increases the risk of imbalances in power grids. Conventional balancing instruments are often unable to react fast enough to sudden changes, highlighting the need for flexible, real-time solutions (Szeberényi & Bakó, 2023). Research in recent years has emphasized that without advanced digital tools, the large-scale integration of renewables may lead to frequent curtailments and inefficiencies that undermine both environmental and economic goals (Bozsik et al., 2024). This situation has created demand for innovative technologies that can respond within seconds or even milliseconds to grid fluctuations.

Artificial intelligence and modular data infrastructures are among the most promising tools to meet these challenges. Studies show that AI-based systems can forecast supply and demand more accurately, optimize dispatch decisions, and provide automated responses that increase the stability of renewable-dominated grids (Garg et al., 2024; Zhang et al., 2023). Modular data centers, meanwhile, can act as controllable loads that consume surplus energy and participate directly in the balancing markets. Their sub-second reaction times position them as valuable resources for transmission system operators, while their dual-use computing capacity - typically combining Bitcoin mining with AI/HPC workloads - connects the digital and energy sectors in novel ways (Lödar-Miculeac et al., 2025; Li et al., 2022). These developments reflect a broader trend in which digitalization and energy transition are becoming increasingly intertwined, raising important questions about sustainability, efficiency, and scalability.

Enerhash, a company founded in Hungary, illustrates how these concepts can be put into practice. By combining AI-based control with modular data centers located at renewable plants or other energy production sites, Enerhash provides flexible energy demand which helps to stabilize grids and reduce wasted generation. Its projects in Sweden and the United States demonstrate how decentralized infrastructures can integrate into different market environments and contribute both to environmental goals and to the economic viability of renewable energy (Szeberényi et al., 2025). This study analyzes the Enerhash model with particular attention to real-time optimization, grid flexibility, and the practical challenges of implementation. The research is guided by three questions: how AI-driven systems can support renewable integration, in what ways modular data centers act as scalable balancing solutions, and what lessons can be drawn from Enerhash's international activities. The answers aim to contribute to current debates on the digital transformation of energy and to highlight the role of emerging actors in shaping sustainable power systems (Bozsik et al., 2025).

2. Literature Review

The large-scale integration of renewable energy into power systems has been studied extensively, as it raises both opportunities and operational risks. Solar and wind power are central to decarbonization strategies, yet their weather-dependent generation patterns often cause volatility that traditional grids were not initially designed to handle (Ellabban et al., 2014; Lund et al., 2015). When penetration levels of intermittent renewables rise, frequency stability becomes increasingly difficult to maintain, and grid operators must resort to new forms of flexibility. Reports from international organizations underline that balancing approaches now extend beyond conventional reserves to include demand-side management, distributed storage, and controllable loads that can absorb excess energy (IEA, 2023). These changes have altered the very structure of electricity systems, shifting attention toward digital tools and infrastructures that can react faster and more intelligently than legacy solutions.

Artificial intelligence has become a central element in this transformation. Algorithms based on machine learning are already improving the accuracy of renewable generation and demand forecasts, reducing the reliance on costly spinning reserves and enabling smoother grid operation (Garg et al., 2024). Applications of deep learning and neural networks have been tested for unit commitment, fault detection, and real-time dispatch, demonstrating greater efficiency and shorter response times than conventional optimization methods (Zhang et al., 2023; Sun et al., 2022). In parallel, digital twins have been introduced to simulate energy flows, anticipate failures, and optimize assets under varying renewable penetration scenarios (Wang et al., 2021). These developments suggest that AI is no longer an auxiliary tool but a critical component of grid management in renewable-dominated systems, where unpredictability and volatility demand near-instantaneous decision-making.

At the same time, modular infrastructures have gained prominence as flexible solutions capable of adapting to fluctuating supply conditions. Scholars have emphasized that high-load consumers such as data centers and electrolysers can be integrated into balancing strategies, acting as adjustable demand that complements storage and flexible generation (Li et al., 2022). Data centers in particular have attracted attention because of their dual function: while supporting digital economies, they can also serve as controllable energy assets that rapidly absorb or release load in response to system needs (Avgerinou et al., 2017). Empirical evidence from Northern Europe shows that modular, digitalized consumers can provide sub-second responses in ancillary service markets, exceeding the capabilities of traditional resources (Bozsik et al., 2024). These insights align with broader discussions of sector coupling, where digital technologies and energy systems increasingly converge to create new pathways for sustainability (Lödar-Miculeac et al., 2025).

Taken together, the reviewed studies demonstrate that renewable integration requires both predictive intelligence and physical adaptability. AI enables more accurate forecasts and automated controls, while modular infrastructures supply the flexibility needed to stabilize grids in real time. The combination of these elements is shaping a new generation of energy solutions and opens the door for companies such as Enerhash, which build their business models at the intersection of digitalization and renewable power. This literature provides the conceptual foundation for examining Enerhash as a case of applied innovation within the wider landscape of energy transition.

3. Methodology

This research applies a qualitative case study design to investigate how Enerhash integrates artificial intelligence and modular infrastructures into renewable power systems. The case study method is particularly appropriate for examining emerging business models in energy, as it allows for an in-depth understanding of processes and mechanisms within their real-world context (Yin, 2018). Rather than aiming at broad generalization, the study focuses on how Enerhash contributes to real-time grid optimization as a flexible consumer of electricity, and what lessons can be derived from its operations for renewable integration.

Data collection relied on multiple sources to enhance validity. A semi-structured expert interview was conducted in January 2025 with Balázs Jogg, Chief Operating Officer of Enerhash, focusing on technological implementation, operational challenges, and strategic choices. The interview format encouraged detailed elaboration while ensuring that core themes such as system response times, modularity, and regulatory adaptation were addressed. In addition to the interview, internal company documentation was analyzed, including technical descriptions of the modular Databox units, their performance parameters, and project outcomes in Sweden and the United States. External reports and media materials were also reviewed to triangulate findings and minimize bias from relying solely on internal perspectives (Flick, 2018).

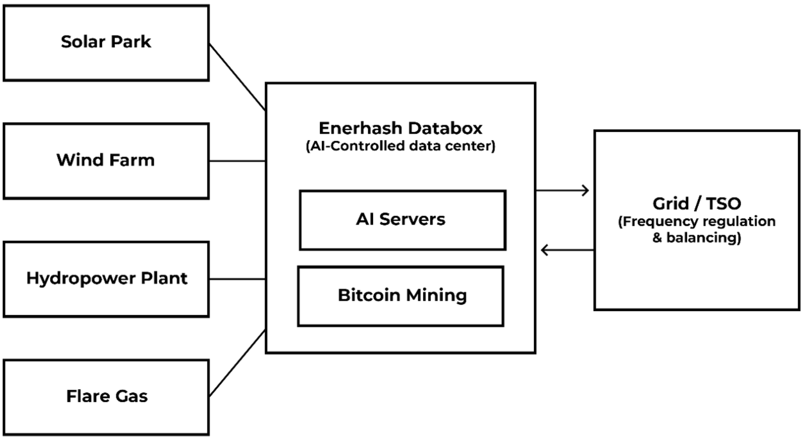
The analytical process utilized thematic coding, applied to both interview transcripts and documentary sources. Themes were identified around three main dimensions: technological performance (e.g., sub-second response times), infrastructural design (e.g., modular deployment and security features), and integration with electricity producers such as hydro plants, gas engines, and solar parks. Thematic analysis is particularly suitable for uncovering recurring patterns across qualitative material while maintaining flexibility in interpretation (Braun & Clarke, 2019). Treating Enerhash's projects in Sweden and the United States as embedded subcases made it possible to compare how the model performs under different market and regulatory environments. By combining primary insights from company leadership with technical documentation, the methodology ensures that the study captures both strategic and operational aspects of Enerhash's role as a controllable consumer within digital energy solutions.

4. The Enerhash Model

Enerhash has introduced a modular infrastructure concept designed to address one of the most pressing issues in renewable-based power systems: the absence of controllable demand that can adapt to variable supply. The company deploys containerized Databox units next to electricity producers such as solar parks, hydro plants, gas engines, or facilities where electricity is generated from flared gas. The Databox does not generate electricity on its own; it consumes power that has already been produced. What makes the system unique is its AI-based load management, which enables the unit to adjust consumption dynamically in response to grid frequency and operator signals. This allows electricity that might otherwise be curtailed or wasted to be redirected into productive computing tasks while simultaneously supporting grid stability. Figure 1 illustrates how the Databox operates as an AI-controlled flexible consumer, positioned between energy producers and the transmission system.

Inside each unit, Enerhash combines two main types of computing infrastructure. One stream is dedicated to Bitcoin mining, using application-specific integrated circuits (ASICs) to convert surplus electricity into cryptocurrency value. The other consists of AI and high-performance computing (HPC) servers, which can run machine learning workloads, industrial AI applications, or other computationally intensive processes (Enerhash, 2025). These computing tasks are designed to be interruptible: the AI controller can reduce or suspend operations within 0.2 seconds if the grid requires stabilization. This dual functionality - producing economic output through computing while acting as a flexible demand-side stabilizer - sets Enerhash apart from traditional data centers, which are

Figure 1 Conceptual model of the Enerhash Databox integrated into renewable power grids



typically inflexible, constant-load consumers (Morstyn & McCulloch, 2019; Buryk et al., 2015).

The adaptability of the Databox has been demonstrated across diverse international projects. In the United States, units are powered by electricity generated from flared gas, transforming a waste by-product into a productive input. In Sweden, they participate in frequency regulation markets alongside transmission system operators, delivering sub-second responses comparable to advanced battery systems. In Central Europe, Databox deployments cooperate with solar and hydro producers to provide balancing services in decentralized networks. These examples highlight the potential of modular computing infrastructures to enable sector coupling between energy and digital industries (Geels et al., 2016; Hepburn et al., 2020; Newell & Simms, 2019). From an operational perspective, Databox units are equipped with surveillance and redundancy systems to ensure security, while their modular architecture means that failures remain isolated without disrupting the wider system. Such design principles reflect the emerging consensus that decentralized and digitalized infrastructures will play a critical role in stabilizing renewable-dominated grids and shaping the future of sustainable power systems (Kittner et al., 2017; Goldthau et al., 2019).

5. Results

The empirical findings from Enerhash's projects in Sweden and the United States illustrate how modular computing infrastructures can operate under different regulatory and technical conditions while delivering both environmental and economic benefits. These findings are important because they provide early evidence that flexible computing loads can contribute not only to energy efficiency but also to wider sustainability goals. The cases also demonstrate that the Databox model is adaptable across contexts, from integration into highly regulated electricity markets to deployment in remote areas where surplus energy would otherwise be wasted.

The Swedish deployment focused on frequency regulation and cooperation with the national transmission system operator (TSO). Databox units were installed near renewable production facilities and connected to the balancing market, where their AI-based load management enabled them to react instantly to grid signals. Field tests confirmed that the units achieved sub-second responsiveness, qualifying them for primary frequency regulation, a service normally provided by batteries or fast-ramping generation assets. Such performance is remarkable given that conventional data centers are typically designed as steady, inflexible loads. While the computational tasks carried out in the Databox included both revenue-oriented processes, as well as and AI-driven workloads, their core contribution was the ability to suspend or resume operations at any moment, ensuring that grid stability was prioritized over computation whenever necessary.

The United States deployment highlighted a different dimension of the Enerhash approach: the utilization of electricity generated from flared gas. At oil production sites, excess natural gas is often released through flaring, producing significant greenhouse gas emissions and wasting energy that could otherwise be put to use. By installing Databox units powered by generators that convert flared gas into electricity, Enerhash created a dual benefit: reducing emissions by capturing gas that would otherwise be wasted, and redirecting the electricity into productive computing tasks. The project further demonstrated that modular computing can be established quickly in remote or harsh environments, a factor that increases its appeal to energy producers looking for scalable solutions. The ability to halt consumption instantaneously in response to local grid constraints further underscored their stabilizing role, showing that environmental and system benefits can be achieved simultaneously.

A comparison of the Swedish and U.S. projects reveals important differences in scale, regulation, and market access. The Swedish model was tightly embedded in regulated markets, focusing on proving that modular computing facilities could qualify for balancing services. In contrast, the U.S. project leveraged more flexible regulatory environments to demonstrate environmental and economic gains from repurposing wasted energy. As shown in Table 1, the Swedish project was relatively small in capacity but technologically significant, while the American deployment achieved greater scale by installing multiple Databoxes in oil-producing regions. This indicates that the Enerhash model is both scalable and adaptable: it can serve as a grid service in formal markets or as a decentralized consumer in off-grid or under-regulated environments.

Table 1 Comparison of Enerhash Case Projects in Sweden and the United States

Source: *Own edited table based on primary research, 2025.*

Parameter	Sweden	United States
Energy source	Renewable producers (solar, hydro)	Electricity from flared gas (oil sites)
Integration model	Ancillary services (TSO balancing market)	Off-grid/remote deployment with generators
Response time	< 0.2 seconds (primary regulation)	< 0.2 seconds (local load management)
Main computing tasks	Bitcoin mining + AI workloads	Bitcoin mining + AI workloads
Key benefit	Improved frequency stability	Reduced emissions from flaring
Scale	Small, pilot-oriented	Larger, multi-site deployments

The broader lessons from these deployments also highlight the diverse contexts in which modular computing units can operate. While the Swedish and U.S. projects represent two ends of the regulatory spectrum, Enerhash's model is not limited to these scenarios. As shown in Table 2, Databox units have already been tested or considered in multiple use cases, including renewable integration, flared gas utilization, AI/HPC workloads, and cryptocurrency mining. This versatility underscores that the model is not tied to a single market or technology but rather offers a flexible architecture for combining computing demand with sustainable energy use.

Table 2 Use cases of Enerhash Databox units

Source: *Own edited table based on primary research, 2025.*

Use Case	Description	Location
Renewable integration	Absorbing surplus electricity from solar or hydro plants, reducing curtailment and stabilizing the grid	Northern Sweden, Central Sweden
Flared gas utilization	Turning wasted natural gas into electricity for computing, mitigating CO_2 and methane emissions	USA
AI/HPC workloads	Running machine learning and industrial applications with flexible, interruptible computing capacity	Multiple (energy-service partnerships)
Bitcoin mining	Generating direct revenue streams while acting as a controllable load for the grid	New Zealand, Central Hungary

Together, the findings confirm that Enerhash's Databox model is not only a technological innovation but also a strategically versatile infrastructure. It demonstrates technical feasibility in regulated markets, environmental benefits in off-grid settings, and the capacity to integrate different forms of computing demand into energy systems. By aligning digital infrastructures with sustainability goals, the case illustrates how flexible consumption can become an active tool in managing renewable power grids.

6. Limitations and Future Research

Although the Enerhash case projects demonstrate the technical viability and adaptability of modular computing infrastructures, the study is not without limitations. One of the most persistent challenges has been access to financing and investor perception. Because a significant part of the company's early business model relied on Bitcoin mining, traditional financial institutions often regarded the projects as too volatile or reputationally risky. Securing loans or long-term credit lines was particularly difficult, which forced Enerhash to rely on alternative funding structures and private capital. This pattern is not unique:

earlier studies have noted that blockchain-related projects face systematic barriers in accessing conventional financial instruments, even when their technical contribution is independent of cryptocurrency price fluctuations (Catalini & Gans, 2019; Yermack, 2017). While Enerhash mitigated this challenge by diversifying into AI/HPC services, financing remains a central bottleneck for scaling.

Another limitation arises from the heterogeneous regulatory environment. The Swedish project operated under a well-defined regulatory framework, where eligibility for participation in frequency regulation markets was clearly codified. In contrast, the U.S. deployment in oil fields depended on weaker oversight, enabling faster implementation but also raising questions about long-term regulatory stability. Within the European Union, a growing debate surrounds the environmental footprint of data centers and digital infrastructure, with proposals to impose stricter energy efficiency standards and carbon reporting requirements (European Commission, 2023; Andrae, 2020). Such measures could constrain large-scale expansion in certain regions if Databox units are not recognized as grid-stabilizing assets. Conversely, in under-regulated markets such as parts of the Middle East, the lack of clear rules creates uncertainty about market entry, despite the high potential for renewable integration.

For future research, several strategic directions are worth highlighting. First, geographic expansion is a key objective: the company has already established projects in Europe, the United States, and New Zealand, with plans to extend activities in the Middle East and Africa, where renewable capacity is rising but balancing resources are scarce. Second, the diversification of computing workloads beyond Bitcoin mining toward AI training, machine learning, and industrial applications is expected to improve both revenue stability and societal value. By shifting the computing focus, Databox units can increasingly position themselves as providers of essential digital infrastructure rather than speculative financial services. Third, the long-term sustainability of the model depends on integrating into wider digital energy ecosystems, where data centers, storage, and flexible loads collectively support decarbonized grids (Burger et al., 2020; Sovacool et al., 2022). This direction aligns with broader transitions toward smart grids and sector coupling, in which modular infrastructures will serve as building blocks of a more resilient and low-carbon energy system.

The limitations identified in financing, regulation, and market positioning highlight that the Enerhash model is not a universal solution but an evolving innovation whose success depends on institutional acceptance and continued technical refinement. Future studies should therefore compare Databox deployments with other flexible demand resources, assess long-term economic impacts under various regulatory frameworks, and examine how AI-driven load management can be scaled to national or regional grid levels. By addressing these questions, the role of modular computing in renewable energy integration can be clarified and strengthened, advancing both technological and sustainability agendas. By revealing how Enerhash's model bridges the gap between surplus renewable energy and productive digital use, this research not only highlights a pathway where sustainability and economic value creation reinforce each other, but also demonstrates why such solutions are essential for the future of resilient and decarbonized energy systems.

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