

# Powering the Future of AI – Leveraging Mukkudam SHP's Clean Energy for Sustainable Computational Intelligence

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## Abstract

The present work elucidates the engineering advantages of run-of-river generation schemes, which are characterized by predictability of the generation regime and lower dependence on large reservoirs, and analyzes architectural solutions that ensure co-location of computing capacity with hydrogeneration facilities. A particular emphasis is placed on ensuring base-load stability, which is fundamentally important for continuous computing processes, and on application of the Circular Energy Hub concept, oriented toward beneficial utilization of secondary heat from compute nodes within coupled local energy-consumption circuits. The objective of the study is to substantiate the effectiveness of small hydropower plants as a dedicated energy-supply source for the Green AI paradigm. To achieve the stated objective, methods of system analysis and synthesis of relevant international literature are employed; publications related to sustainable information-technology infrastructure and hydropower are examined. In the concluding part, the potential of the Mukkudam project is defined as a reproducible model capable of supporting implementation of ESG-oriented goals at a global scale, and the practical significance of the results for the domains of artificial intelligence, energy, and environmental management is documented. The article will be of interest to engineers in artificial intelligence and data center infrastructure, specialists in energy and renewable energy sources (especially small/run-of-river hydropower), ESG/sustainability and climate-policy managers, as well as stakeholders in regional development seeking practical models for implementation of green AI through co-location of edge computing capacity and reuse of waste heat within a closed-loop cycle.

**Keywords:** artificial intelligence; small hydropower; Mukkudam SHP; sustainable development; Edge Data Centers; base load; decarbonization; green energy; immersion cooling; Kerala.

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## **1. Introduction**

The development of artificial intelligence, primarily in the segments of deep learning, large language models (LLMs), and resource-intensive computational simulations, has driven an exponential increase in demand for electricity. Training of contemporary AI architectures can require volumes of energy comparable to the annual consumption of a substantial number of households, and in a number of cases exceeding it, which translates into a noticeable contribution to aggregate carbon emissions [1]. The emerging energy footprint becomes a systemic risk for the sustainability of the IT industry and renders urgent the need for a rapid transition to alternative energy strategies aimed at reducing the carbon intensity of computation.

As one of the most promising solutions in this context, small hydropower (SHP) is considered. Compared with intermittent generation sources, which include solar and wind power, run-of-river small hydropower plants exhibit higher predictability and are capable of forming a reliable base load under a low-carbon profile of electricity production. These characteristics make them technologically preferable candidates for continuous power supply of high-performance computing systems that are sensitive to power failures and fluctuations in power quality [2]. A representative example is the Mukkudam SHP project in the state of Kerala (India) with a capacity of 4 MW, demonstrating the potential of decentralized generation for territories with rapidly growing computational needs.

The work substantiates the necessity for a paradigmatic rethinking of the role of small hydropower plants: they should be interpreted not as standard participants of the national energy balance that supply electricity into the common grid, but as specialized energy providers for the rapidly expanding AI sector. Direct coupling of generation and consumption at the level of a specific computing site creates prerequisites for sustainable computational intelligence, reducing dependence on fossil fuels and minimizing anthropogenic impact on the climate through localized low-carbon energy support [3].

**The objective of the study** is theoretical substantiation and development of a model of direct integration of AI computing infrastructure with a small hydropower plant, considered as a representative solution for ensuring sustainable development of computational intelligence. To achieve this objective, analysis is envisaged of the operational characteristics of SHP as a source of stable base load, potentially satisfying the specific requirements of high-density AI computations; formation of an architectural model for co-location of edge data centers directly at the site of the hydropower facility; and assessment of the environmental and socio-economic effects of implementing the Circular Energy Hub concept, oriented toward utilization of secondary heat from computational processes.

**Scientific novelty** is defined by the proposal of a paradigmatic shift: small hydropower plants are considered not as peripheral suppliers of energy to the integrated grid, but as supporting components of an IT ecosystem in which electricity production and consumption are aligned and synchronized both at the physical level (through direct power supply to compute nodes) and at the logical level (through alignment of load profiles and infrastructure operating modes).

Within the **author's hypothesis**, the position is articulated that direct coupling of AI clusters with run-of-river

small hydropower plants possessing stable base load makes it possible to approach a practically zero carbon footprint while simultaneously reducing operational costs and decreasing data transmission latency, thereby forming a technological benchmark for a new Green AI standard.

## **2. Materials and Methods**

The methodological framework of the study is formed on the basis of an interdisciplinary approach in which provisions of hydropower engineering, principles of computing-system design, and the toolkit of environmental management are aligned.

Collection and verification of sources were carried out on the basis of targeted searches in the international bibliographic systems IEEE Xplore, ScienceDirect, SpringerLink, and MDPI. When forming the literature corpus, publications from recent years were prioritized, which ensured the relevance of the conclusions in the context of the dynamic development of AI technologies and the evolution of requirements for decarbonization of IT infrastructure. Selection focused on works analyzing the energy imperative of AI, metrics of energy-consumption efficiency of data centers, as well as contemporary approaches to reducing the thermal load of server systems and implementing alternative cooling schemes. Search strategies were based on English-language queries: sustainable AI energy, small hydro power data centers, decentralized renewable energy for edge computing.

The analytical stage included comparison of the technical parameters of small hydropower plants and the operational requirements of modern GPU clusters with high equipment placement density. To identify the systemic advantages of hydropower base load in comparison with stochastic renewable sources (solar and wind generation), procedures of system analysis were applied, oriented toward assessment of the stability of power-supply regimes and the sensitivity of computing circuits to power variations. Additional evidentiary support was provided by information from international energy agencies, as well as technical specifications of immersion-cooling solutions, which made it possible to move from a declarative problem statement to a holistic understanding of the engineering parameters of architectural integration.

A substantial methodological element was the use of the case study approach, in which the Mukkudam SHP is considered as a representative model of decentralized generation for territories with an emerging digital economy. Extrapolation of data on the hydrological regime of the region to energy profiles characteristic of training large language models was performed, which provided substantiation of the feasibility of the proposed co-location and its long-term economic viability.

In formulating the author's proposals, the method of conceptual modeling of cyber-physical systems was employed, within the framework of which the interaction contour of the energy and computing blocks was detailed, including the mechanism of utilization of excess heat. The collected information and analysis results are structured in such a way as to ensure verifiability of the initial hypothesis regarding the possibility of constructing an environmentally closed computing cycle that is functionally embedded in the local socio-economic environment.

### **3. Results**

#### ***3.1. Mukkudam SHP: A Dedicated Clean Power Source for AI***

The operational characteristics of the Mukkudam SHP make this facility exceptionally suitable for supplying artificial intelligence loads across several key dimensions.

#### ***3.2. Stable, Baseload Renewable Power***

The run-of-river nature of the Mukkudam SHP determines the plant's capability to provide continuous and highly predictable power output on the order of 4 MW [4]. The availability of stable base load is of fundamental importance for computing circuits oriented toward artificial intelligence tasks, because data center infrastructure imposes stringent requirements for continuity of power supply and its parametric stability. Disturbances in power quality, as well as short-term sags or interruptions in supply, can initiate cascading failures: forced stoppages of long training cycles, increased service recovery time, degradation of the integrity of computational states, and the risk of data loss, which translates into substantial direct and indirect costs [5].

These properties create a structural advantage of run-of-river SHP compared with stochastic renewable sources whose output is determined by weather variability and therefore requires either significant energy storage capacities or more complex mechanisms of grid balancing and reserve provision. As a consequence, small-scale hydrogeneration, when correctly coupled to a local consumer, can function not as an auxiliary but as a base element of energy supply for high-density computing loads, reducing the technological complexity of maintaining reliability and increasing predictability of operating regimes.

#### ***3.3. Proximity to Demand and Low Latency***

Despite the fact that training of artificial intelligence models can be geographically distributed and performed at global computing sites, there is a persistent shift in demand toward real-time inference, edge computing, and territorially localized data processing. In such a configuration, a key parameter becomes minimization of latency and improvement of response-time predictability, which limits the applicability of remote centralized capacity in a number of scenarios. Deployment of AI infrastructure in immediate proximity to the Mukkudam SHP creates a dual effect: losses associated with transmission of electricity over long distances are reduced, and at the same time a low-latency communication contour is formed for regional digital services and mission-critical applications [6].

This approach acquires particular significance in areas where even short-term degradation of parameters of data or energy delivery can lead to decreased functional reliability and increased operational risks. Such domains include intelligent power grids requiring rapid analysis of telemetry and load management; autonomous transport that is critically dependent on fast decision-making and synchronization with infrastructure; and local predictive analytics oriented toward processing streaming data in immediate proximity to the source of its generation. Taken together, this makes spatial coordination of generation and computing not an auxiliary but a system-forming principle for sustainable deployment of AI in regions with growing requirements for response time and energy autonomy.

### ***3.4. Environmental Benefits of Direct Integration***

Direct power supply of AI computing circuits from the Mukkudam SHP leads to a substantial reduction in the carbon intensity of digital operations by excluding or sharply reducing the share of grid-mix energy associated with fossil generation. Within such a configuration, electricity consumption by the computing infrastructure is aligned with local renewable output, which creates the possibility of transparent attribution: every watt used in computation is covered by generation from a low-carbon source, ensuring verifiability of the declared green status of energy consumption and robustness of environmental claims to audit [7]. The achieved effect has not only technological but also managerial significance, because it facilitates fulfillment of corporate climate-policy requirements, including reduction of emissions across energy-consumption chains, and creates a foundation for reproducible practices of sustainable management of digital assets. As a result, achievement of environmental and ESG-oriented objectives (Environmental, Social, and Governance) is supported, and the institutional legitimacy of organizations is strengthened as responsible participants in the digital economy that integrate decarbonization into the architecture of computing systems rather than limiting themselves to compensatory measures.

## **4. Architectural Integration: Co-locating AI Compute with SHP**

For effective utilization of the clean energy of Mukkudam, a strategic architectural co-location model is proposed.

### ***4.1. Edge Data Center Co-location***

Placement of a compact high-density edge data center in immediate proximity to the Mukkudam SHP is considered as a basic architectural solution that ensures minimization of the physical gap between the generation source and the electricity-consumption contour [8]. Such a spatial layout reduces grid losses and limits the number of intermediate links in the power-supply chain, which increases predictability of power parameters and simplifies the operational model, because the energy and computing subsystems are coordinated at the site level.

The functional configuration of the Edge DC presupposes targeted optimization for dominant classes of AI workloads. As one scenario, training clusters based on high-density GPU nodes and intended for resource-intensive training of neural network models are distinguished, where decisive factors are continuity of power supply, thermal stability, and energy-use efficiency. A second scenario is associated with deployment of real-time inference engines, for which minimal latency and stable response time are critical, determining applicability of solutions in tasks of operational control and streaming analytics. A third scenario is oriented toward local data preprocessing, in which information arrays are processed at the place of origin prior to subsequent aggregation and transfer to a cloud environment, which reduces the volume of transit traffic and increases data governability at the periphery of digital infrastructure.

### ***4.2. Grid Interconnection and Redundancy***

Even when direct power supply from the SHP to the Edge DC is implemented, it is advisable to maintain physical interconnection to the integrated power system, forming a redundancy contour and increasing overall power-supply reliability. Such a topology ensures continuity of operation of the computing site during periods of

scheduled maintenance operations at the hydropower facility, as well as under the influence of extreme natural factors capable of temporarily limiting the generation regime or equipment availability. The presence of a grid connection in this case functions not as the primary energy source, but as an element of fault tolerance that makes it possible to maintain critical AI services within specified operating parameters.

To preserve a low-carbon profile in the presence of two power sources, application of intelligent power-management systems is envisaged, implementing prioritization of local renewable generation and dynamic switching to grid supply only upon reaching boundary conditions with respect to power, energy quality, or plant availability. Such algorithms make it possible to align reliability with environmental performance: under normal conditions, the load is predominantly covered by Mukkudam energy, whereas recourse to the grid is forced and limited in nature, recorded and amenable to subsequent verification within sustainability reporting [9].

### **4.3. Sustainable Cooling Solutions**

High-density computing workloads are inevitably accompanied by formation of significant flows of low-grade heat, which under traditional cooling approaches is dissipated into the environment and thereby becomes a systemic energy loss. For AI-oriented infrastructure, where heat release per unit area and per rack reaches limiting values, application of advanced heat-removal technologies takes on the character not of an option but of an engineering requirement. In this context, liquid immersion cooling is considered as a critically important solution capable of increasing heat-transfer efficiency and simultaneously stabilizing the temperature regime of equipment, reducing the load on auxiliary energy-consuming subsystems and improving the overall energy performance of the site [10].

An additional methodological advantage of immersion schemes consists in creating a technological basis for implementation of the Circular Energy Hub, in which waste heat from server circuits is interpreted as a resource subject to beneficial use. Redirection of the heat flow into local consumer circuits makes it possible to integrate the computing infrastructure into the regional energy and economic environment: thermal energy can be utilized for the needs of the local community or for tasks of the agro-industrial sector, where stable sources of heat are demanded for technological processes. Thus, the linkage electricity generation — computing — heat utilization is formed, capable of simultaneously improving environmental efficiency, reducing aggregate energy losses, and strengthening the socio-economic return of the project through emergence of additional useful output in the form of a thermal resource [10].

## **5. Discussion**

Next, we consider how integration of the Mukkudam SHP can modify established principles of IT infrastructure design. The conceptual foundation of such an approach is reduced to formation of a symbiotic linkage between a local natural energy resource and digital computing circuits, within which the energy subsystem and the computing load are designed as complementary elements of a unified cyber-physical complex. As a result, generation ceases to be an external service with respect to computation, and the computing site ceases to be a passive consumer of the grid mix: a coupled architecture is formed in which energy sources, energy-consumption

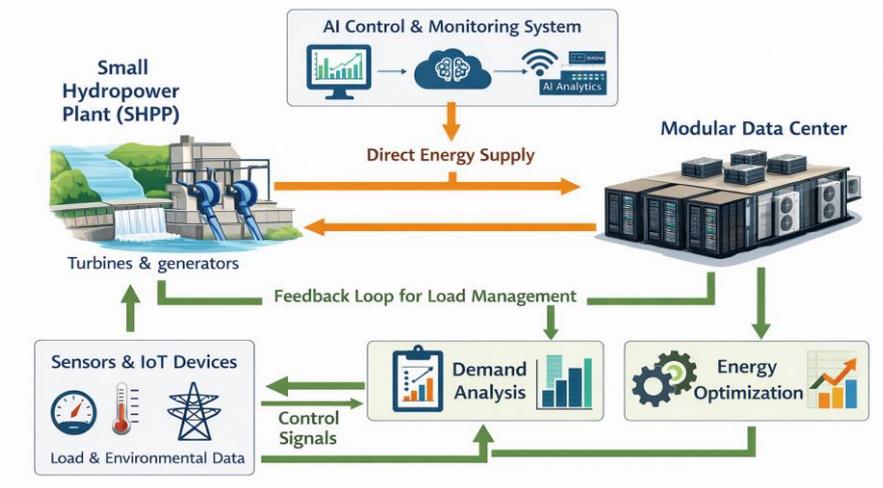
regimes, and heat flows are aligned at the site level, simultaneously ensuring reliability, predictability, and reduction of the carbon intensity of digital operations. First, we compare different concepts of power supply for AI.

Table 1 presents the results of the analysis of energy sources for sustainable AI.

**Table 1:** Qualitative comparative analysis of energy sources for sustainable AI [8-10]

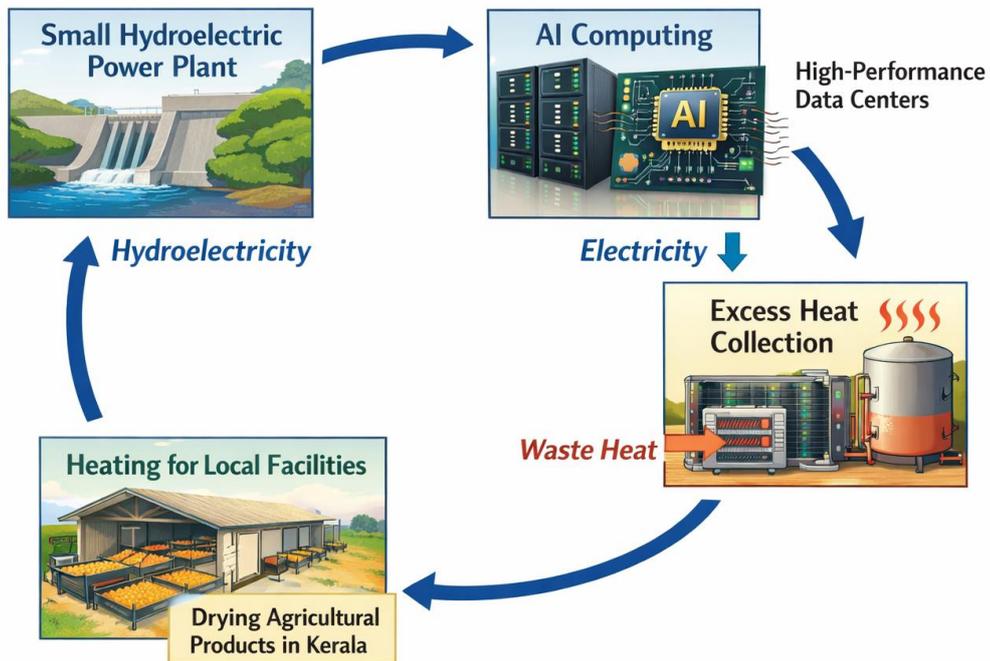
<b>Comparison parameter</b>	<b>Traditional grid (Mixed)</b>	<b>Solar/Wind energy</b>	<b>Mukkudam SHP (Small Hydroelectric Plant)</b>
Generation profile	Depends on fossil fuels	Stochastic (intermittent)	Base-load (continuous)
Carbon footprint level	High	Low	Minimal
Balancing complexity	Low (due to scale)	Very high	Low (local)
Stability forecast	Medium	Depends on weather	High

The comparison presented in the table demonstrates that the Mukkudam model within the small hydropower (SHP) class is characterized by a combination of operational stability and a low-carbon profile that is rare for decentralized renewable energy sources, as a consequence of which it proves methodologically and engineering-wise preferable for supplying power to mission-critical AI workloads. Figure 1 visualizes the proposed concept and captures the key linkages between the generation contour, the computing infrastructure, and the supporting subsystems, establishing an illustrative basis for subsequent consideration of architectural integration.



**Figure 1:** Integration diagram of the Mukkudam-AI cyber-physical system [8-10]

The author’s vision of the project is expanded through implementation of the Circular Energy Hub concept. In this model, the heat removed from GPU clusters through an immersion-cooling system becomes a useful resource. Below, Figure 2 presents a detailed elaboration of the Circular Energy Hub concept based on the SHP.



**Figure 2:** Concept of a Circular Energy Hub based on a small hydroelectric power station [8-10]

Utilization of by-products of computational processes transfers heat flows from the category of inevitable losses to the category of a useful resource, which makes it possible to approach practically complete resource efficiency at the site level. Under such a configuration, energy performance is determined not only by the share of low-carbon generation, but also by the degree of closure of material-and-energy contours, when excess heat becomes

part of the local supply system, reducing the need for external sources of thermal energy and increasing the overall return of the infrastructure. Table 2 summarizes how the proposed model affects key dimensions of sustainable development, including environmental indicators, social effects, and the economic viability of the project.

**Table 2:** Analysis of the impact of the Mukkudam-AI model on sustainable development [5, 8, 9]

Impact aspect	Traditional approach	Mukkudam-AI model	Transformation result
Ecology	High CO2 emissions	Neutral balance	Decarbonization of IT
Economics	High grid tariffs	Low LCOE cost	OPEX optimization
Infrastructure	Centralized data centers	Decentralized edge nodes	Increased fault tolerance
Regional development	Digital divide	Technology hub in Kerala	Social progress

The developed analytical construct substantiates the advisability of using the Mukkudam SHP as a representative site for validation of the decentralized Green AI paradigm. Run-of-river generation with a predictable power profile forms a stable base load required for high-density computing circuits, whereas application of immersion cooling shifts thermal management from a mode of compensatory energy consumption to a mode of technological optimization, reducing the share of auxiliary expenditures and increasing operational stability. Supplementing this linkage with a contour for beneficial use of secondary heat completes formation of a closed energy and resource scheme in which wastes of the computational process become an input for external consumers.

Taken together, these elements define a cyber-physical system in which generation, computation, and heat exchange are aligned at the site level and are amenable to measurable verification against criteria of low carbon intensity, efficiency, and controllability. For this reason, the proposed configuration demonstrates potential competitiveness relative to traditional centralized cloud approaches specifically in terms of sustainability and resource performance, because it reduces grid dependence, increases transparency of green-energy attribution, and expands the useful energy output of the project through engagement of the thermal resource.

## 6. Impact and Future Vision for Sustainable AI

### 6.1. Decoupling AI Growth from Carbon Emissions

The proposed model provides a direct response to the energy paradox of AI by forming a practice-oriented scheme for decoupling growth in computational intensity from an increase in carbon emissions. The approach is based on shifting the center of gravity from compensatory measures and indirect greening mechanisms to structural

reconfiguration of the energy contour of computation: the computing load relies on a dedicated renewable source with predictable generation regimes, and associated heat flows are treated as a manageable resource within a closed-loop energy logic. Such a configuration makes it possible to фиксировать the environmental effect at the site level and to link it with the operational parameters of the infrastructure, which increases verifiability of claims regarding reduction of carbon intensity and reduces dependence on the quality of the grid mix.

At the same time, a fundamentally scalable methodology is demonstrated, suitable for adaptation to other renewable-energy facilities provided that the generation profile is aligned with the characteristics of target computing loads and that engineering solutions are available to improve energy efficiency and utilize secondary flows. In this sense, the proposed approach can be considered a transferable design framework for decentralized green computing clusters for different regions and technological contexts, providing a basis for replication of sustainable digital-infrastructure practices at a global scale.

### **6.2. Economic Advantages**

Reduction of dependence on grid electricity supply through reliance on a stable renewable source creates prerequisites for noticeable optimization of operational expenditures (OPEX) of data centers serving AI workloads. The economic effect is achieved through increased predictability of the cost and availability of energy, reduced sensitivity to price volatility and grid constraints, and decreased share of costs associated with ensuring reliability through complex balancing and reserve schemes under variable generation. In addition, with a properly designed power path and thermal-regulation system, the load on auxiliary subsystems is reduced, which translates into lower costs for cooling and maintenance of engineering infrastructure.

A separate source of economic performance is associated with reuse of secondary heat from computation. When transitioning from dissipation of heat flows to their targeted utilization, additional value is formed, because an energy by-product becomes a resource suitable for integration into local production cycles. As a result, the possibility arises for partial replacement of external heat sources in local technological processes, enhancement of the territory's energy provision, and creation of an additional revenue or quasi-revenue effect through use of heat as a factor of reducing the cost of goods and services in adjacent sectors.

### **6.3. Pioneering a Green AI Standard**

The Mukkudam SHP can be considered a demonstrative benchmark for the Green AI paradigm, in which sustainability is not appended to computing infrastructure post factum through compensatory mechanisms, but is constructed at the level of the primary architecture of power supply, thermal management, and spatial organization of computation. Under such a logic, the low-carbon profile is ensured not declaratively but through the physical linkage of generation and consumption, high predictability of the base-load regime, and controllability of secondary energy flows, which makes the environmental outcome measurable and verifiable within operations.

The resulting effect has the significance of a precedent for the industry: a reproducible model is formed that is capable of redefining the criteria of responsible AI in a material dimension, where computing power is scaled synchronously with the availability of clean energy and the resource efficiency of the site. This increases the

practical applicability of the ESG approach for AI developers and organizations oriented toward responsible technological development, because it provides a concrete design template in which environmental and governance requirements are integrated into the infrastructure contour and are amenable to subsequent verification and audit.

#### **6.4. Broader Applicability**

The Mukkudam case can be interpreted as a transferable project framework for other decentralized energy solutions oriented toward the role of direct enablers of sustainable IT infrastructure, including small wind power and solar stations in combination with storage. Transferability is ensured not by literal copying of the technological configuration, but by reproducibility of key principles: local coupling of generation to computing load, alignment of generation and consumption profiles, formation of redundancy contours and management of energy flows at the site level, as well as integration of the thermal economy of the compute node into the surrounding economic environment.

The particular practical significance of such an approach manifests in regions with limited availability of centralized power supply or low reliability of grid infrastructure. Under such conditions, decentralized generation coupled with edge computing capacity can simultaneously increase the digital autonomy of the territory and reduce the carbon intensity of data processing. When adapting to wind and solar sources, the decisive factor becomes ensuring a functional analogue of base load through a combination of storage, intelligent demand management, and correct temporal distribution of computing tasks, which preserves the original logic of the model: sustainability is achieved through architectural alignment of energy and computation, rather than through external compensation of the consequences of high loads.

#### **7. Conclusion**

The integration of the Mukkudam small hydropower plant with artificial intelligence infrastructure confirms the viability of the “Green AI” paradigm, in which sustainable development is embedded in the system architecture itself. The study demonstrates that diversion-type generation schemes provide a stable baseload required for the continuous operation of high-density computing clusters, distinguishing them favorably from stochastic sources such as solar or wind. Direct, site-level coupling of generation and consumption (co-location) makes it possible to minimize transmission losses and achieve ultra-low signal latency—an attribute that is critical for regional edge scenarios demanding near-instantaneous response.

In contrast to existing works that emphasize indirect compensation of the carbon footprint, the author’s position centers on the necessity of “hardware-level integration” of eco-standards. The implementation of the Circular Energy Hub concept shifts waste heat from the category of unavoidable losses to that of a valuable asset. The use of immersion cooling systems to capture and redistribute thermal energy for the needs of the local agro-industrial sector delivers near-complete resource efficiency and strengthens the project’s socio-economic contribution to territorial development, effectively transforming the data center into an active participant in the local economy.

Synthesizing the obtained results with global experience in IT infrastructure design indicates that the Mukkudam

model functions as a scalable template for decentralized systems. It shows that technological growth can be decoupled from the growth of carbon emissions not through declarative measures, but through foundational engineering solutions. While contemporary scientific literature largely concentrates on software-level optimization of algorithms, the present study substantiates the synergy of physical infrastructure as the only reliable pathway toward achieving a verifiable net-zero carbon footprint at the scale of the industry as a whole.

Despite the achieved outcomes, the system requires further systematic refinement with respect to managing seasonal fluctuations in water flow. To ensure guaranteed service availability at the 99.999% level during drought periods, hybrid backup schemes—such as small hydrogen storage units or integrated battery arrays—must be introduced. Such measures would smooth consumption peaks without resorting to the carbon-intensive main grid, thereby preserving the full environmental integrity of the computing process throughout the calendar year.

Additional attention is warranted for the standardization of interaction interfaces between the compute node and heat consumers. At the current stage, the logistics of transferring low-grade heat to end users remains a challenging engineering task, requiring the development of unified protocols and compact heat-exchanger modules. Resolving this issue would convert the theoretical concept of a circular hub into a technology suitable for rapid replication, applicable across diverse geographic and climatic conditions.

In the long-term perspective, the Mukkudam project should serve as a foundation for shaping a new international standard of responsible AI. Further research is advisable in the direction of developing comprehensive efficiency metrics that account not only for PUE, but also for the degree of beneficial utilization of secondary resources. In this framing, small hydropower ceases to be merely a source of electricity and becomes the systemic ядро of future intelligent infrastructure, in which generation, computation, and heat exchange are integrated into a single, environmentally neutral cyber-physical complex.

## References

- [1]. J.M.A. Minoza, R.G. Laylo, C.F. Villarin, & S.C. Ibanez. “ML-EcoLyzer: Quantifying the Environmental Cost of Machine Learning Inference Across Frameworks and Hardware”. *arXiv preprint arXiv:2511.06694*, 2025. <https://doi.org/10.48550/arXiv.2511.06694>.
- [2]. M. Todera. “Artificial Intelligence for Sustainability: A Systematic Review and Critical Analysis of AI Applications, Challenges, and Future Directions”. *Sustainability*, vol.17(17), 2025. <https://doi.org/10.3390/su17178049>.
- [3]. U. Azimov, & N. Avezova. “Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply”. *Renewable and Sustainable Energy Reviews*, vol. 167, 2022. <https://doi.org/10.1016/j.rser.2022.112726>
- [4]. E.R. Patro, T.S. Kishore, & A.T. Haghghi. “Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India”. *Energies*, vol. 15(4), 2022. <https://doi.org/10.3390/en15041473>.
- [5]. C. Guo, F. Luo, Z. Cai, & Z.Y. Dong. “Integrated energy systems of data centers and smart grids: State-of-the-art and future opportunities”. *Applied Energy*, vol. 301, 2021.

- <https://doi.org/10.1016/j.apenergy.2021.117474>.
- [6]. C. Jiang, T. Fan, H. Gao, W. Shi, L. Liu., C. Cérin, & J. Wan. “Energy aware edge computing: A survey”. *Computer Communications*, vol. 151, pp.556-580, 2020. <https://doi.org/10.1016/j.comcom.2020.01.004>.
- [7]. R. Manhibi, & K. Tarisayi. “The Precarious Pirouette: Artificial Intelligence and Environmental Sustainability”. *Acta Infologica*, vol. 8(1), pp. 51-59, 2024. <https://doi.org/10.26650/acin.1431443>.
- [8]. R. Verdecchia, J. Sallou, & L. Cruz. “A systematic review of Green AI”. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, vol. 13(4), 2023. <https://doi.org/10.1002/widm.1507>.
- [9]. S. Pimenow, O. Pimenowa, & P. Prus. “Challenges of Artificial Intelligence Development in the Context of Energy Consumption and Impact on Climate Change”. *Energies*, vol. 17(23), 2024. <https://doi.org/10.3390/en17235965>.
- [10]. P. Huang, B. Copertaro, X. Zhang, J. Shen., I. Löfgren, M. Rönnelid, & M. Svanfeldt. “A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating”. *Applied energy*, vol. 258, 2020. <https://doi.org/10.1016/j.apenergy.2019.114109>
- [11]. M. Koot, & F. Wijnhoven. “Usage impact on data center electricity needs: A system dynamic forecasting model”. *Applied Energy*, vol. 291, 2021. <https://doi.org/10.1016/j.apenergy.2021.116798>