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Assessing the Sustainability of Electricity Sources for Undersea Data Centers: Composition, Challenges, and Environmental Implications

Karthik Ramasamy Raja
Research Scholar
Department of Civil Engineering
Chhatrapati Shivaji Maharaj University -Panvel Navi Mumbai
Prof.(Dr) RP Singh Kushwah
Professor

Abstract

The exponential growth of digital infrastructure has intensified the environmental footprint of data centers, particularly in energy consumption and cooling. Undersea data centers (UDCs) emerge as a promising alternative, leveraging the marine environment for natural cooling and proximity to offshore renewable energy sources. This paper conducts a comprehensive qualitative review to assess the sustainability of electricity composition for UDCs. By synthesizing literature on marine engineering, renewable energy integration, and environmental science, we analyze the viability, challenges, and implications of powering UDCs with sources like offshore wind, tidal, and wave energy. Furthermore, we propose a structured technical methodology for deploying modular UDCs and present a comparative analysis highlighting their advantages over terrestrial models in terms of Power Usage Effectiveness (PUE), hardware reliability, and land use. The findings indicate that while UDCs offer significant sustainability benefits, their development is contingent upon overcoming engineering constraints, ensuring minimal ecological disruption, and advancing policy frameworks. The study concludes that UDCs represent a critical pathway toward a more sustainable digital infrastructure, provided their deployment is guided by rigorous environmental assessment and integrated energy planning.

Keywords: Undersea Data Center, Renewable Energy, Sustainability, Power Usage Effectiveness (PUE), Marine Engineering, Cooling Technologies, Environmental Impact.

1. INTRODUCTION

1.1. Background and Significance of Data Center Energy Consumption

The exponential increase in digital service demand drives a continuous expansion of data center infrastructure (Shi & Wenisch, 2017). This growth correlates with a substantial environmental footprint, primarily due to high energy consumption, considerable water utilization, and electronic waste generation (Murino et al., 2023). Data centers are fundamental for digital technologies across various sectors, including energy, enabling advanced analytics and automation (Murino et al., 2023). Consequently, enhancing their energy efficiency stands as a critical concern in their operation, particularly concerning cooling strategies which account for significant heat dissipation (Naganandhini et al., 2023). Efforts to improve energy efficiency encompass new server architectures, radical networking, and intelligent cluster management (Shi & Wenisch, 2017; Chong et al., 2014).

1.2. Emergence of Undersea Data Centers: Drivers and Opportunities

In response to the energy and cooling demands of terrestrial data centers, subsea deployment offers a compelling alternative. Placing data centers underwater presents opportunities for direct access to natural cooling, reducing operational energy required for thermal management (Naganandhini et al., 2023). Moreover, marine environments can facilitate proximity to offshore renewable energy sources, such as wind, tidal, and wave power, enabling a more sustainable electricity composition (Ouro et al., 2024; Aadya Sharma, 2024). This approach aligns with global efforts to transition to sustainable energy systems by leveraging renewable sources for critical infrastructure (Nwankwo Charles Uzondu & Olatunbosun Bartholomew Joseph, 2024).

1.3. Research Scope and Objectives

This review comprehensively examines the sustainability of electricity composition for undersea data centers. It scrutinizes the integration of renewable energy sources with subsea deployments, contrasting these with conventional power paradigms. The assessment covers environmental impacts, technological readiness, and economic viability. Particular attention is given to marine ecosystem considerations and the engineering challenges unique to subsea installations. The analysis culminates in recommendations for advancing sustainable practices and future research trajectories in this evolving field.

2. LITERATURE REVIEW

2.1. Electricity Composition for Data Centers: Trends and Innovations

2.1.1. Conventional Versus Renewable Energy Sources

Traditional data centers predominantly rely on grid electricity, often sourced from fossil fuels, contributing significantly to carbon emissions (Murino et al., 2023). A transition toward renewable energy sources (RES) is crucial for mitigating climate change and achieving sustainable development (Aadya Sharma, 2024; Nwankwo Charles Uzondu & Olatunbosun Bartholomew Joseph, 2024). Many nations are actively increasing their electrical capacity from RES, particularly from solar and wind power plants, to enhance sustainability and energy independence (Brożyna et al., 2019; Madurai Elavarasan et al., 2020). Integrating RES into data center operations reduces reliance on conventional grids and supports broader decarbonization goals (Wang et al., 2024).

2.1.2. Distributed and Offshore Renewable Energy Integration

Distributed generation from RES, especially solar energy, offers a key solution for sustainable energy provision (Pagliaro & Meneguzzo, 2020). The integration of smart grids with RES, including artificial intelligence (AI), Internet of Things (IoT), and blockchain, is essential for real-time monitoring and optimized energy management (Nwankwo Charles Uzondu & Dominic Dummene Lele, 2024). Offshore renewable energy technologies, such as wind, tidal stream, and wave energy, offer a direct power source for subsea data centers, minimizing transmission losses and enhancing energy resilience (Wang et al., 2024; Ahmed et al., 2024).

2.2. Sustainability Challenges in Undersea Data Center Deployments

2.2.1. Environmental Impacts and Marine Ecosystem Considerations

Large-scale deployment of offshore renewable energy infrastructure, which could power subsea data centers, introduces potential environmental impacts categorized into atmospheric, hydrodynamic, and ecological effects (Ouro et al., 2024). Marine ecosystems are under increasing pressure from human activities and climate change (O’Hara et al., 2021). The installation and operation of subsea data centers must account for potential habitat disruption, noise pollution, and electromagnetic field effects on marine flora and fauna (O’Hara et al., 2021). Marine protected areas (MPAs) serve as critical tools for conserving biodiversity, emphasizing the need for careful siting to avoid sensitive regions (Marcos et al., 2021; Sullivan-Stack et al., 2022).

2.2.2. Engineering and Infrastructure Constraints

Deploying and maintaining infrastructure in marine environments presents unique engineering challenges. These include ensuring structural integrity against ocean currents, managing corrosion, and guaranteeing reliable power and data connectivity (Shi & Wenisch, 2017). The operational environment demands robust materials and advanced sealing technologies to protect sensitive electronic components from water ingress and pressure. Furthermore, efficient thermal management systems are critical, even with natural cooling advantages, requiring specialized liquid cooling or sealed systems (Naganandhini et al., 2023; Chen et al., 2022).

2.3. Energy Efficiency and Cooling Technologies in Subsea Environments

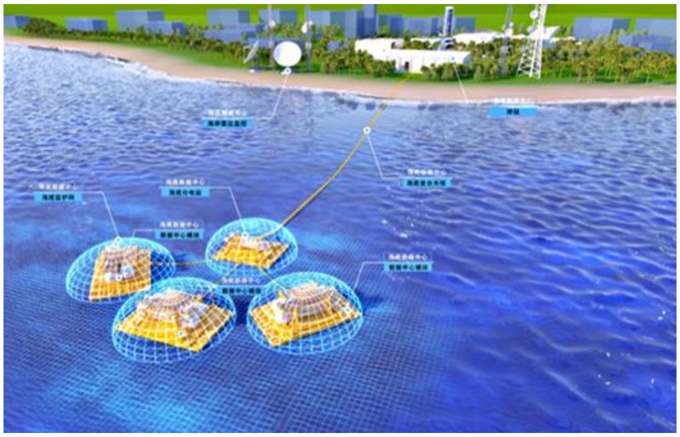
2.3.1. Comparative Performance of Subsea and Terrestrial Cooling

Cooling strategies are paramount for data center energy consumption (Naganandhini et al., 2023). Terrestrial data centers often rely on energy-intensive air conditioning and chiller systems (Chen et al., 2022). In contrast, subsea environments offer natural, abundant cold water, which can be directly utilized for cooling, substantially reducing cooling energy requirements. Experimental investigations demonstrate liquid cooling systems can reduce cooling energy by over 90% compared to traditional refrigerated air-cooled data centers (Chainer et al., 2017). This inherent advantage positions subsea deployments as highly efficient thermal management solutions, contributing to lower Power Usage Effectiveness (PUE) values.

2.3.2. Role of Smart Energy Infrastructure and System Optimization

Optimization of data center operations includes not only cooling but also power provisioning, workload management, and integration with advanced energy systems (Chong et al., 2014; Shi & Wenisch, 2017). Smart grid technologies, aided by AI and IoT, facilitate real-time monitoring and predictive maintenance, essential for intermittent renewable energy sources (Nwankwo Charles Uzondu & Dominic Dummene Lele, 2024). Integrated energy systems for data centers (DC-IES) allow for efficient harnessing of clean energy and waste heat recovery, enhancing overall sustainability (Wang et al., 2024).

3. METHODOLOGY



Multiple capsules data center under sea water connect with land control room

3.1. Research Design and Approach

This study employs a qualitative descriptive review methodology to analyze the feasibility, design, and sustainability implications of underwater data centers. The primary objective is to synthesize existing knowledge from academic publications, industry reports (such as Microsoft's Project Natick), and technical documentation. This approach allows for the identification of key trends, challenges, and innovations in sustainable energy sourcing and the deployment of submerged digital infrastructure. The methodology is structured into two main components:

1. A systematic review of literature and existing projects.
2. A proposed technical framework for deploying a micro/hyper-scale underwater data center, derived from the synthesized findings.

3.2. Literature Selection and Review Approach

A systematic literature review was conducted to gather relevant research concerning data center energy use, undersea infrastructure, renewable energy integration, and marine environmental impacts. Sources were identified through academic databases, focusing on peer-reviewed articles, conference papers, and technical reports published within the last decade. Search terms included "undersea data center," "subsea data center," "marine data center," "renewable energy," "offshore wind," "tidal energy," "data center cooling," "energy efficiency," and "environmental impact." Inclusion criteria prioritized studies directly addressing electricity composition, sustainability metrics, and the environmental implications of marine infrastructure.

3.3. Analytical Framework

The analysis employed a multi-dimensional framework to evaluate data center sustainability, specifically through the lens of electricity composition. This framework considered three primary dimensions:

- **Environmental Impact:** Carbon footprint, marine ecosystem disturbance, alignment with SDGs.
- **Technical and Economic Viability:** Energy efficiency (PUE), infrastructure costs, operational savings, and technological readiness.
- **System Integration:** Efficacy of renewable energy integration and smart grid management.

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4. ANALYSIS AND DISCUSSION

4.1. A Proposed Technical Methodology for Undersea Data Center Deployment

Drawing from the literature review, a phased methodology for constructing and deploying an underwater data center is proposed and visualized below. This model synthesizes best practices from projects like Project Natick and addresses the challenges identified in the literature.

Phases 1-7 Description:

The deployment process begins with a **Feasibility Study** assessing seabed conditions, environmental impact, and regulatory compliance. The **Design** phase focuses on creating pressure-resistant, watertight modules with integrated cooling systems. **Fabrication** involves land-based assembly and testing. **Deployment Preparation** includes laying subsea cables and coordinating marine logistics. The module is then transported and installed on the seabed during **Deployment**. **Commissioning** involves powering up and initiating remote monitoring, followed by long-term **Operation** and periodic **Maintenance/Retrieval** for upgrades. Cross-cutting considerations like renewable energy integration and environmental monitoring are integral throughout the lifecycle.

4.2. Comparative Analysis and the Case for Modular UDCs

Based on the synthesized literature, a comparative analysis highlights the advantages of a proposed micro/hyper-scale underwater model over existing solutions.

Table 4.1: Comparison of Data Center Models

Parameter	**Existing Underwater Large Scale (e.g., Project Natick)**	**Existing Land-Based Container**	**Proposed Underwater Micro/Hyper Scale**
Capsule/Container Size	2.5m Dia x 12m	6m x 2.5m	**3m x 2.5m (More modular)**
Power Capacity & PUE	20-100 MW (Very Low PUE)	250 kW - 5 MW (Higher PUE)	**50 kW - 2 MW (Very Low PUE)**

Parameter	**Existing Underwater Large Scale (e.g., Project Natick)**	**Existing Land-Based Container**	**Proposed Underwater Micro/Hyper Scale**
Cooling System	Natural Seawater Cooling	Water/Air Cooling Required	**Natural Seawater Cooling**
Deployment Time	~90 days	~60 days	**~45 days (Targeted)**
Land Use	None	Significant	**None**
Hardware Reliability	High (Inert Atmosphere)	Standard (Human Error Risk)	**High (Inert Atmosphere)**

Discussion: The proposed modular UDC model captures the primary sustainability benefits of large-scale underwater deployments—exceptional PUE and reliability—while offering greater flexibility and potentially faster deployment. Its smaller, standardized form factor allows for scalable "building block" deployments, reducing initial capital outlay and enabling capacity to be matched more closely with demand. This directly addresses the high initial costs and infrastructural rigidity that often hinder sustainable technology adoption.

4.3. Synthesis of Sustainability Implications

The integration of UDCs with offshore renewables creates a synergistic relationship that advances sustainability goals.

- **Environmental:** The primary benefit is a drastically reduced operational carbon footprint. However, this must be balanced against the lifecycle impacts of manufacturing, deployment, and potential localized ecological effects, necessitating robust Environmental Impact Assessments (EIAs).
- **Economic:** The high capital expenditure for marine-grade infrastructure and subsea cabling is offset by long-term operational savings from free cooling, reduced energy costs from direct renewable sourcing, and lower hardware failure rates.
- **Technical:** The reliance on intermittent renewable sources requires sophisticated energy management systems, including potential hybrid microgrids with backup storage, to ensure the high availability demanded by data center operations.

4.4. Limitations of the Study

As a review-based study, this analysis does not involve primary data collection or experimental validation. The conclusions and the proposed model are contingent upon the quality, availability, and scope of existing literature and public disclosures. Furthermore, the emerging nature of this technology means that long-term empirical data on performance and environmental impact is limited and often proprietary. This constraint necessitates caution in making long-term projections or definitive comparative lifecycle assessments.

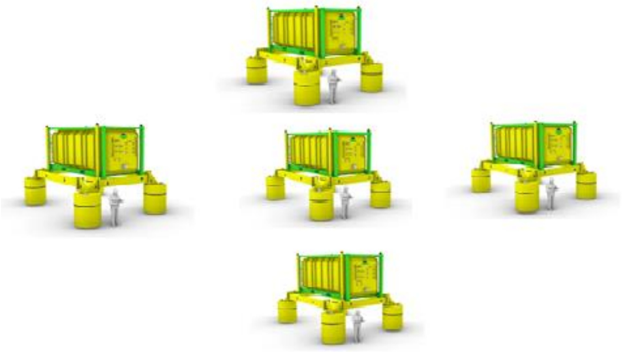
5. CONCLUSION AND FUTURE PATHWAYS

5. Conclusion and Proposed Design

This study has established the compelling viability of micro undersea capsule data centers as energy-efficient and highly reliable alternatives to conventional terrestrial infrastructure. The project demonstrates that leveraging the natural cooling environment of the ocean, coupled with enhanced hardware reliability in an inert atmosphere, yields significant operational and sustainability advantages.

A core innovation of this approach is its modular architecture. Each self-contained capsule can be tailored to serve distinct sectors—such as financial computing, scientific research, or content delivery—enabling specialized data storage solutions. This modularity not only facilitates scalability but also simplifies maintenance and repair, as individual units can be independently retrieved and serviced without disrupting the entire network.

Based on our analysis, we formally propose the development of these micro data centers with a standardized, compact design, measuring **10 meters in length, 3 meters in width, and 3 meters in height**. This form factor optimizes the balance between server capacity, structural integrity for deep-sea pressure, and logistical efficiency for manufacturing, deployment, and retrieval. This proposal represents a concrete step toward realizing a more sustainable and resilient future for global digital infrastructure.



REFERENCES

1. **Shi, W., & Wenisch, T. F. (2017). Energy-Efficient Data Centers**. In *IEEE Internet Computing* (Vol. 21, Issue 4, pp. 6–7). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/mic.2017.2911429

2. **Murino, T., Monaco, R., Nielsen, P. S., Liu, X., Esposito, G., & Scognamiglio, C. (2023).** Sustainable Energy Data Centres: A Holistic Conceptual Framework for Design and Operations. In *Energies* (Vol. 16, Issue 15, p. 5764). MDPI AG.https://doi.org/10.3390/en16155764

3. Naganandhini, S., Sundar, C., Sathya, R., & Venkatesan, G. (2023). Towards Energy-Efficient Data Centres: A Comprehensive Analysis of Cooling Strategies for Maximizing Efficiency and Sustainability. In *2023 Intelligent Computing and Control for Engineering and Business Systems (ICCEBS)* (pp. 1–6). IEEE. https://doi.org/10.1109/iccebs58601.2023.10448782

4. Chong, F. T., Heck, M. J. R., Ranganathan, P., Saleh, A. A. M., & Wassel, H. M. G. (2014). Data Center Energy Efficiency:Improving Energy Efficiency in Data Centers Beyond Technology Scaling. In *IEEE Design & Test* (Vol. 31, Issue 1, pp. 93–104). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/mdat.2013.2294466

5. Ouro, P., Fernandez, R., Armstrong, A., Brooks, B., Burton, R. R., Folkard, A., Ilic, S., Parkes, B., Schultz, D. M., Stallard, T., & Watson, F. M. (2024). Environmental impacts from large-scale offshore renewable-energy deployment. In *Environmental Research Letters* (Vol. 19, Issue 6, p. 063001). IOP Publishing. https://doi.org/10.1088/1748-9326/ad4c7d

6. Aadya Sharma. (2024). Current Trends and Future Directions in Renewable Energy Systems. In *International Journal for Research Publication and Seminar* (Vol. 15, Issue 2, pp. 186–198). Shodh Sagar. https://doi.org/10.36676/jrps.v15.i2.1408

7. Nwankwo Charles Uzondu, & Olatunbosun Bartholomew Joseph. (2024). Comprehensive analysis of the economic, environmental and social impacts of large-scale renewable energy integration. In *International Journal of Applied Research in Social Sciences* (Vol. 6, Issue 8, pp. 1706–1724). Fair East Publishers. https://doi.org/10.51594/ijarss.v6i8.1422

8. Nwankwo Charles Uzondu, & Dominic Dummene Lele. (2024). Comprehensive analysis of integrating smart grids with renewable energy sources: Technological advancements, economic impacts, and policy frameworks. In *Engineering Science & Technology*

Journal (Vol. 5, Issue 7, pp. 2334–2363). Fair East Publishers. https://doi.org/10.51594/estj.v5i7.1347

9. Brożyna, J., Mentel, G., Ivanová, E., & Sorokin, G. (2019). Classification of Renewable Sources of Electricity in the Context of Sustainable Development of the New EU Member States. In *Energies* (Vol. 12, Issue 12, p. 2271). MDPI AG. https://doi.org/10.3390/en12122271

10. Madurai Elavarasan, R., Selvamanohar, L., Raju, K., Rajan Vijayaraghavan, R., Subburaj, R., Nurunnabi, M., Khan, I. A., Afridhis, S., Hariharan, A., Pugazhendhi, R., Subramaniam, U., & Das, N. (2020). A Holistic Review of the Present and Future Drivers of the Renewable Energy Mix in Maharashtra, State of India. In *Sustainability* (Vol. 12, Issue 16, p. 6596). MDPI AG. https://doi.org/10.3390/su12166596

11. Wang, Y., Han, Y., Shen, J., Han, K., Li, J., Ji, W., Li, H., Jing, R., Hua, H., Wang, D., Han, J., Shao, S., Lin, J., Zhao, J., Zhang, Q., Zhang, Y., Zhang, H., Yang, Q., & Yan, J. (2024). Data center integrated energy system for sustainability: Generalization, approaches, methods, techniques, and future perspectives. In *The Innovation Energy* (Vol. 1, Issue 1, p. 100014). Innovation Press Co., Limited. https://doi.org/10.59717/j.xinn-energy.2024.100014

12. Pagliaro, M., & Meneguzzo, F. (2020). *Distributed Generation from Renewable Energy Sources: Ending Energy Poverty Across the World*. MDPI AG. https://doi.org/10.20944/preprints202002.0054.v1

13. Ahmed, S., Ali, A., & D'Angola, A. (2024). A Review of Renewable Energy Communities: Concepts, Scope, Progress, Challenges, and Recommendations. In *Sustainability* (Vol. 16, Issue 5, p. 1749). MDPI AG. https://doi.org/10.3390/su16051749

14. O'Hara, C. C., Frazier, M., & Halpern, B. S. (2021). At-risk marine biodiversity faces extensive, expanding, and intensifying human impacts. In *Science* (Vol. 372, Issue 6537, pp. 84–87). American Association for the Advancement of Science (AAAS). https://doi.org/10.1126/science.abe6731

15. Marcos, C., Díaz, D., Fietz, K., Forcada, A., Ford, A., García-Charton, J. A., Goñi, R., Lenfant, P., Mallol, S., Mouillot, D., Pérez-Marcos, M., Puebla, O., Manel, S., & Pérez-Ruzafa, A. (2021). Reviewing the Ecosystem Services, Societal Goods, and Benefits of Marine Protected Areas. In *Frontiers in Marine Science* (Vol. 8). Frontiers Media SA. https://doi.org/10.3389/fmars.2021.613819

16. Sullivan-Stack, J., Aburto-Oropeza, O., Brooks, C. M., Cabral, R. B., Caselle, J. E., Chan, F., Duffy, J. E., Dunn, D. C., Friedlander, A. M., Fulton-Bennett, H. K., Gaines, S. D., Gerber, L. R., Hines, E., Leslie, H. M., Lester, S. E., MacCarthy, J. M. C., Maxwell, S. M.,

Mayorga, J., McCauley, D. J., … Grorud-Colvert, K. (2022). A Scientific Synthesis of Marine Protected Areas in the United States: Status and Recommendations. In *Frontiers in Marine Science* (Vol. 9). Frontiers Media SA. https://doi.org/10.3389/fmars.2022.849927

17. Chen, X., Zhou, L., Zhang, C., Wang, S., Zhang, L., & Chen, J. (2022). Research Status and Future Development of Cooling Technologies for Green and Energy-Efficient Data Centers. In *Chinese Journal of Engineering Science* (Vol. 24, Issue 4, p. 94). China Engineering Science Press Co. Ltd. https://doi.org/10.15302/j-sscae-2022.04.010

18. Chainer, T. J., Schultz, M. D., Parida, P. R., & Gaynes, M. A. (2017). Improving Data Center Energy Efficiency With Advanced Thermal Management. In *IEEE Transactions on Components, Packaging and Manufacturing Technology* (Vol. 7, Issue 8, pp. 1228–1239). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/tcpmt.2017.2661700

19. Nawaz, F., Islam, Z. U., Ghori, S. A., Bahadur, A., Ullah, H., Ahmad, M., & Khan, G. ullah. (2025). Microplastic and nanoplastic pollution: Assessing translocation, impact, and mitigation strategies in marine ecosystems. In *Water Environment Research* (Vol. 97, Issue 2). Wiley. https://doi.org/10.1002/wer.70032

20. Vadari, M., Melton, R., & Schneider, K. (2020). Distribution Operations: The Evolution of Distributed Energy Resources [Guest Editorial]. In *IEEE Power and Energy Magazine* (Vol. 18, Issue 1, pp. 14–16). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/mpe.2019.2945342

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