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Artikel

Sustainable Architecture Education in Southeast Asia: The Role of Photovoltaics in Developing Creative and Ecological Thinking

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Abstrak

Pendidikan arsitektur di Asia Tenggara memiliki peran strategis dalam menanggapi krisis energi dan tantangan perubahan iklim. Namun, pendidikan ini memiliki keterbatasan dalam mengintegrasikan teknologi energi terbarukan seperti fotovoltaik (PV) ke dalam kurikulum dan praktik desain di iklim tropis. Penelitian ini mengusulkan model pendidikan arsitektur berkelanjutan berbasis PV yang dapat menumbuhkan pemikiran ekologis dan kreativitas pada siswa melalui pendekatan studio berbasis proyek. Metode penelitian yang digunakan adalah studi kasus komparatif antara Universitas Bangkok di Thailand dan eksperimen prototipe independen di Indonesia. Data dikumpulkan melalui dokumentasi proyek, observasi langsung, dan tinjauan pustaka, kemudian dianalisis secara tematis. Hasil penelitian menunjukkan bahwa Universitas Bangkok telah berhasil menerapkan sistem pembelajaran transdisipliner yang mengintegrasikan PV dalam desain arsitektur melalui kompetisi Solar Decathlon Eropa. Sementara itu, di Indonesia, prototipe awal stasiun pengisian daya ponsel pintar berbasis PV menunjukkan bahwa sistem energi mandiri skala mikro sangat memungkinkan untuk dikembangkan. Pada penelitian ini, prototipe awalnya tidak memiliki struktur fisik permanen. Kedua penelitian menunjukkan bahwa PV dapat menjadi solusi teknis dan media pedagogis untuk meningkatkan kesadaran ekologis siswa. Studi ini menyimpulkan bahwa mengintegrasikan PV dalam pendidikan arsitektur dapat menjembatani kesenjangan antara eksplorasi kreatif dan eksperimen teknologi. Model ini memberikan kontribusi strategis bagi lembaga pendidikan tinggi di Asia Tenggara. Model pembelajaran ini dapat menghasilkan generasi desainer yang adaptif, kolaboratif, dan visioner menuju masa depan yang berkelanjutan.

Kata kunci

Arsitektur Berkelanjutan; Fotovoltaik; Prototipe; Pendidikan

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Abstract

Architecture education in Southeast Asia has a strategic role in responding to the energy crisis and climate change challenges. However, this education has limitations in integrating renewable energy technologies such as photovoltaic (PV) into the curriculum and design practices in tropical climates. This study proposes a model of sustainable architecture education based on PV that can foster ecological thinking and creativity in students through a project-based studio approach. The research method used is a comparative case study between Bangkok University in Thailand and an independent prototype experiment in Indonesia. Data were collected through project documentation, direct observation, and literature review, and then analyzed thematically. The results show that Bangkok University has successfully implemented a transdisciplinary learning system that integrates PV in architectural design through the Solar Decathlon Europe competition. Meanwhile, in Indonesia, an early prototype of a smartphone PV-based charging station shows that a micro-scale self-sufficient energy system is very possible to develop. In this study, the prototype initially did not have a permanent physical structure. Both studies show that PV can be a technical solution and a pedagogical medium to increase students' ecological awareness. This study concludes that integrating PV in architectural education can bridge the gap between creative exploration and technological experimentation. This model provides a strategic contribution to higher education institutions in Southeast Asia. This learning model can produce a generation of adaptive, collaborative, and visionary designers towards a sustainable future.

Keywords

Sustainable Architecture; Photovoltaics; Prototype; Education

Introduction

Architectural education plays a strategic role in responding to the energy crisis and climate change. The role can be played by integrating sustainability principles and renewable energy technologies such as photovoltaics (PV) into the curriculum and design practice. Global environmental challenges demand an educational approach that is aesthetically oriented and ecologically and socially transformative (Leal Filho *et al.*, 2021). Incorporating PV elements into architectural education allows students to understand the technical aspects of clean energy. In addition, architecture also internalizes a design approach that is efficient, visually appealing, and contextually relevant (Taleghani, Ansari and Jennings, 2010). Research shows that formal education that includes renewable energy can increase public awareness. In addition, formal education can also create a generation of leaders who are competent in decision-making related to sustainability (Putri, Setiawan and Nasrudin, 2022; Soares, Kang and Choo, 2024).

Moreover, interdisciplinary approaches that combine art and technology can inspire innovative thinking. Interdisciplinary approaches can also open up collaborative opportunities, such as developing renewable energy-based communities that prioritize social engagement (Azarova *et al.*, 2019). Project-based courses that directly apply PV technology in the design process have been shown to deepen students' learning experiences. In addition, they can also make them more applicable and relevant to real-world challenges (Mihăescu *et al.*, 2023). In this context, redesigning design education by placing PV at the core of creative learning environments will prepare architects to face the future. It also strengthens higher education's contribution to the global sustainability agenda.

The gap between sustainable design education and the integration of renewable energy technologies such as PV reflects the need for a paradigm shift in architectural design education. Although sustainability principles have been widely adopted in curricula, applying concrete technologies such as PV is still uneven in higher education institutions (Chukwu *et al.*, 2022). It is due to the lack of a learning ecosystem that allows collaboration between creative exploration and technological experimentation. The separation between design studios and technology laboratories hinders interdisciplinary learning. Technology integration can enrich the learning experience and improve the quality of the resulting design solutions (Yi and Xu, 2023).

Studies have shown that using PV technology can broaden students' awareness of the environmental impacts of their design choices (Brzezicki and Jasiolek, 2021; Ummihusna and Zairul, 2022). In this context, a learning model that combines creative and technical aspects through multidisciplinary projects is considered more effective in forming future designers who are visionary and responsive (Xiang *et al*., 2020; Mihăescu *et al*., 2023). Education that integrates PV not only equips students with technical competence but also fosters a sense of ecological responsibility towards the construction industry's future. Therefore, academic institutions need to adopt innovative learning models that integrate renewable energy technologies into the creative process in design studios. It aims to produce graduates who are able to design aesthetic, efficient, and sustainable built environments (Altomonte, Rutherford and Wilson, 2014; El-Feki and Kenawy, 2018).

Although PV technology has made significant progress in efficiency and cost reduction, its application in architectural education still faces various limitations, especially in Southeast Asia. Studies such as Haghighi et al. (2021) revealed that the understanding of architects, including aspiring architects, towards the integrative approach of PV in building design is still minimal. It is also deepened by the lack of architectural literature that discusses PV from the perspective of aesthetics, creative process, and spatial considerations. Architectural education generally separates creative exploration in the studio from technological experimentation in the laboratory. So that this educational pattern will hinder the creation of integrated and applicable cross-disciplinary learning. Meanwhile, many previous studies have focused on the European and North American contexts. There is still relatively little attention to the tropical characteristics and specific challenges of the Southeast Asian region. In fact, with high solar radiation intensity, the potential for PV in this region is extensive, but it has not been systematically explored in the educational context (Celadyn and Filipek, 2020; Aguacil *et al*., 2024).

This study presents a novelty by proposing a PV-based sustainable architecture education model contextual to tropical climates. In this study, PV is positioned not only as a technical tool but also as a design exploration medium that is able to foster ecological thinking and sustainability awareness through project-based studio practices. Combining creative design and renewable energy technology in one learning process also answers the need to bridge the gap between sustainability values in the curriculum and concrete practices in building design. This study is an important contribution in strengthening the position of architectural higher education as an agent of ecological change. In addition, this study can encourage the birth of graduates who are not only technically competent but also aware of social and environmental responsibility in every design decision.

This study aims to explore and formulate a sustainable architecture education model that integrates PV technology into the design learning process. This study aims to identify how much PV can act as a technical solution for energy efficiency. In addition, it is also to provide an understanding of PV as a pedagogical instrument in fostering ecological thinking and creativity in architecture students. Through a case study approach and analysis of educational practices in institutions that have implemented PV integration in design studios, this study also aims to formulate curricular and strategic principles that can be replicated or adapted by other architecture education institutions. In addition, this study wants to explore the potential of PV integration in the context of interdisciplinary learning, as an effort to reduce the gap between design exploration and the application of renewable energy technologies. In addition, it is also to strengthen the contribution of higher education to the global sustainability agenda.

Methodology

This study employs an explorative qualitative approach using a comparative case study method. The author analyzes in depth how PV technology is integrated into sustainable architecture education across Southeast Asia. The author chose this approach to investigate how pedagogical strategies, technological infrastructure, and design methods support sustainability-based teaching. In addition, the study compares implementations in two different institutional settings.

The first case study examines Bangkok University in Thailand, where educators have systematically implemented project-based learning. They integrate this method with PV technology, particularly through participation in the international Solar Decathlon Europe 2021 competition. The study highlights how integrating PV into the architecture curriculum fosters cross-disciplinary learning, promotes industry collaboration, and strengthens students' ecological literacy. The electrical energy generated by PV is used for various daily needs, such as bathroom water heaters, air conditioners (AC), and lighting. This shows the practical application of renewable energy relevant to tropical climates. In addition, an energy monitoring system has been implemented to measure and optimize the solar panel system's performance in real time.

The second case study investigates a PV charging station prototype developed in Indonesia. The author initiated this project to combine product design with renewable energy systems to support the digital lifestyle in urban public spaces. Unlike the structured institutional context in Thailand, this case emphasizes an experimental and portable design approach tailored to tropical regions and areas with limited electricity access. In this experiment, the installation of PV considers the angle of incidence of sunlight, which varies between provinces in a country. This aims to optimize the absorption of solar energy. The author selected these two case studies to represent a broad spectrum of PV implementation, from structured formal education to individual experimental design. Through this comparison, the study provides a holistic understanding of both the potential and challenges of PV integration in architectural education. Ultimately, the study aims to recommend curriculum models that are relevant, adaptive, and applicable for institutions in regions facing similar sustainability challenges.

The author collected data through literature review, project documentation, and direct observation of educational practices in each study context. The author then analyzed the data using a thematic approach to identify patterns, gaps, and the potential for replicating sustainability-based curricula. This study focuses primarily on how educators use PV technology not only as a technical solution but also as a pedagogical medium to foster ecological awareness and creativity in students. The author selected the comparative case study approach to capture the dynamics and complexities of PV integration in architecture education from two distinct contextual perspectives. The first perspective reflects an institution with extensive experience in implementation, while the second represents the early stage of technological exploration. Through this dual lens, the study provides strategic mapping and adaptable curriculum principles for other institutions in tropical regions.

Result and Discussion

A. Innovative Pedagogical Frameworks

Design and architecture education in the 21st century demands a fundamental shift in pedagogical approaches. It aims to be able to answer the complex challenges facing global society, including the energy crisis, climate change, and digital transformation. Bangkok University responds to this need by designing an innovative pedagogical framework that places creativity, technology, and sustainability at the core of the curriculum. The educational model developed is theory-based and emphasizes direct experience through Project-Based Learning (PBL). This educational method allows students to learn by exploring real problems and applicable solutions. This approach aligns with Kolb's (1984) constructivist theory, which emphasizes the importance of concrete experience, reflection, abstract conceptualization, and active experimentation in learning.

One of the main strengths of this approach is its integration with design thinking and human-centered design. Both methods have been proven effective in enhancing students' critical thinking and empathy skills. Bangkok University encourages its students to understand the user context in depth. In addition, this university encourages its students to identify specific needs and design practical solutions. In this context, the university introduces PV technology as an integral component of sustainable and energy-efficient design strategies. Various student projects reflect this approach by incorporating solar panels into their design products and systems. Architectural installation projects for public furniture function as charging stations based on renewable energy.

This innovative pedagogical framework also strengthens the role of entrepreneurial education in architectural studies. Students are encouraged to develop their projects as aesthetic, technical works, and business prototypes that can be produced commercially. Thus, integrating the architecture curriculum with PV technology trains students' technical skills in developing renewable energy systems and forms an entrepreneurial mindset oriented towards innovative solutions. Campus infrastructure, such as the Creative Media Studio, Fablab, and Innovation Hub, provides real support in realizing students' ideas from concept to initial implementation. This educational framework shows how an institution can redefine the design curriculum into a transformative tool. This institution combines creativity, renewable energy technologies such as PV, social orientation, and business. In this context, architecture at this university is not only a dialogue about form, aesthetics, and function. This university also thinks about a sustainable future through an innovative, collaborative educational approach based on ecological values and entrepreneurship.

B. Photovoltaics as a Foundation for Sustainable Architecture Education

Architecture education in Southeast Asia needs to address the energy and climate crisis challenges concretely. The real manifestation is that PV technology is the primary foundation of sustainable design practices. A case study at Bangkok University shows an innovative approach that integrates PV technology into a multidisciplinary design project. The project actively involves students from various disciplines, such as architecture and engineering, as well as strategic partners from the industry, such as the Thai Green Building Institute (TGBI), Siam Cement Group (SCG), SALIOT by Minebeamitsumi, and the Federation of Thai Industries (FTI). This cross-sector collaboration became real in the "Solar Jury Day" activity on October 21, 2019. In this activity, students presented PV-based design concepts to sponsors, industry partners, and academics as an evaluation step before participating in the Solar Decathlon Europe (SDE) 2021 competition. Figure 1 represents the project that was presented in SDE 2021.

Figure 1. Visualisation of the Design Challenge

The activity presents a holistic approach that emphasizes the technical aspects of PV installations. In addition, this activity also implements aesthetic, social, and ecological aspects as a whole. Students receive direct input and assessment from industry experts and academics. Thus, this activity has created an interactive and applicable learning process. By implementing the ten evaluation criteria of the Solar Decathlon, students can develop energy-independent design solutions. At the same time, students are simultaneously able to answer the challenges of sustainability. Through this authentic experience, students gain a deep understanding of how architectural design and PV technology can be

integrated holistically in the context of the tropical environment of Southeast Asia. Through this activity, they also strengthen their competence in designing innovative solutions relevant to future global challenges.

In the context of Southeast Asian countries with high solar intensity characteristics and increasing urbanization challenges, the approach used by Bangkok University has high relevance and potential to be applied more widely. Educational institutions can build a real learning ecosystem by creating creative learning environments supported by innovative facilities such as FabLab, Design Garage, Innovation Hub, and Think Space. Students can experiment and validate PV-based design ideas in a realistic environment. This kind of learning ecosystem can enrich students' experiences technically. Such an ecosystem can also improve ecological literacy, so students can think critically about the environmental impact of their design work. The project-based approach also equips students with multidisciplinary skills and adaptation to local and global contexts. Through this activity, they can communicate across cultures, all essential competencies for future design. Therefore, this study emphasizes the importance of effectively repositioning the architecture curriculum to combine creative, technological, and ecological aspects. These three aspects are applied in an education system that is adaptive, collaborative, and visionary to today's global challenges.

C. Case Study: Closing Gaps

Bangkok University's participation in the Solar Decathlon Europe 2021–2022 offers an intense case study in bridging the gap between renewable energy technologies and architectural education practices in Southeast Asia. The team's vision emphasizes delivering human-centric, tropically responsive, modular, and energy-efficient housing. They do not view PV technology as merely a technical component, but as an integral part of a design strategy that addresses urban communities' functional, social, and ecological needs. This vision provides a foundation for developing a contextual solution that reflects the values of sustainable architecture learning that can be replicated in regions with similar challenges.

In dense urbanization and space constraints in Southeast Asian cities, the team developed a micro-living approach responsive to urban mobility and post-pandemic environmental challenges. They integrated a modular housing concept compatible with public transportation, e-mobility, and green spaces in response to changing urban lifestyles. In addition, their design was thoroughly tested through ten Solar Decathlon challenges, including energy efficiency, spatial comfort, sustainability, innovation, and socio-economic viability. This process involved students in design activities, technical experiments, industry collaborations, and public communication. Through this process, students were able to enrich their cross-disciplinary learning experience and develop a comprehensive understanding of the principles of integrated sustainable design.

Through its project in the Solar Decathlon Europe competition, Bangkok University designed an energy-independent residential unit. The team also presented adaptive solutions to specific urban challenges. The case study focused on Wuppertal, Germany, an educational city with dense urban space and dynamic community activities. Through a context-based approach, the team designed a site concept that connects two city parks through a pedestrian-friendly connecting path. The design also considered the needs of green mobility, such as providing underground parking areas and electric vehicle (EV) charging stations. In its design, the House Demonstration Unit (HDU) integrates passive and active design strategies to maximize energy efficiency in the cooler European climate. In Figure 2, the team used a multi-layered approach, such as passive solar heat gain, solar shading on the windows, and utilization of internal heat gain. The design includes a hybrid floor heating system contributing to sustainable interior thermal comfort. In the outdoor area, they even provide a solar-powered e-scooter charging facility. Thus, the team has expanded PV's function as a sustainable transportation system. The basement is also designed as a social zone protected from the outside climate, offering a thermally stable community gathering place.

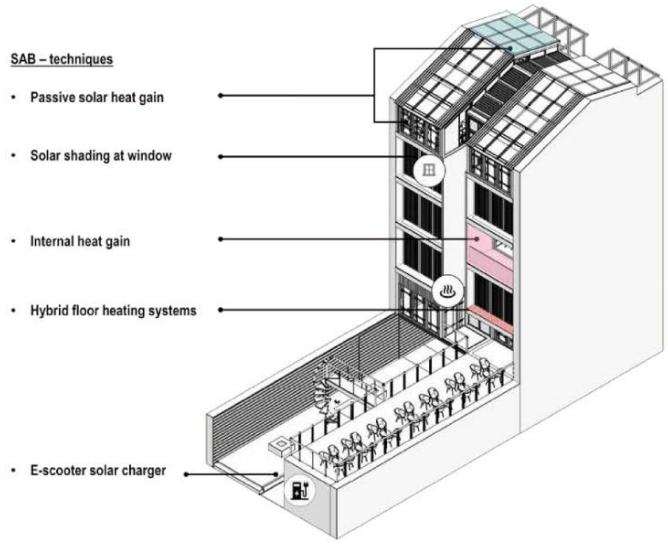

Figure 2. Urban context and mobility

The whole concept is realized as an HDU. This house is a prototype of a positive energy modular house completely designed and reassembled by students. The purpose of making this prototype is to meet international competition standards. HDU displays the integration of PV technology as the primary energy source. HDU is also a pedagogical instrument explaining how architecture can contribute to the energy transition. The design integrates structural efficiency, thermal comfort, and spatial flexibility in a tropical context. Moreover, HDU proves that a project-based learning model and challenges like this can close the gap between design theory and practical reality. The learning method inspires other architectural education institutions to build adaptive, collaborative, and visionary learning systems for a sustainable future.

D. Early Stage Prototype of a PV-Based Charging Station for Smartphone

In previous research, the author designed and developed a prototype of a smartphone charging station (Pramono *et al*., 2022). The author intended this prototype for public spaces as part of smart city infrastructure. The prototype is a multifunctional locker unit that supplies power to recharge mobile phone batteries. The author also equipped the prototype with a biometric fingerprint-based security system. This system uses Arduino Mega, which connects to a locking solenoid and an electrical socket. The system enables users to open and close the locker securely using registered fingerprints by implementing Arduino Mega as a microcontroller. Each locker unit operates independently and automatically removes power without a verified fingerprint. This design reduces misuse and enhances energy efficiency. Although the author has not yet conducted extensive public testing, the prototype demonstrates how basic microcontroller-based technology and PV can function effectively in future development. This technology supports the digital lifestyle of urban communities in a secure, efficient, and environmentally friendly way. The study provides a critical foundation for developing innovative furniture products that integrate PV to meet micro-energy needs in urban spaces.

In subsequent research in Indonesia, the author also developed a prototype of a solar panel (PV)-based smartphone charging system. The prototype remains early and does not yet include a permanent container design or physical structure. However, this system has successfully demonstrated the working principle of energy-independent charging. This prototype uses one 30-wp monocrystalline solar panel unit connected to a solar charge controller, then connected to a 12.8V direct current (DC) lithium iron phosphate (LiFePO4) battery as energy storage. From the battery, energy flows to a 220V inverter, which allows DC to be converted to alternating current (AC) to charge various electronic devices, including smartphones. The details of how it is working can be seen in Figure 3. The author designed this system as a modular and portable model. This system does not depend on conventional electricity grids. The experimental results

show that the stored energy can charge several smartphone units alternately or simultaneously. The findings show the great potential for PV integration in small-scale public charging systems, especially in open spaces or remote locations without electricity access.

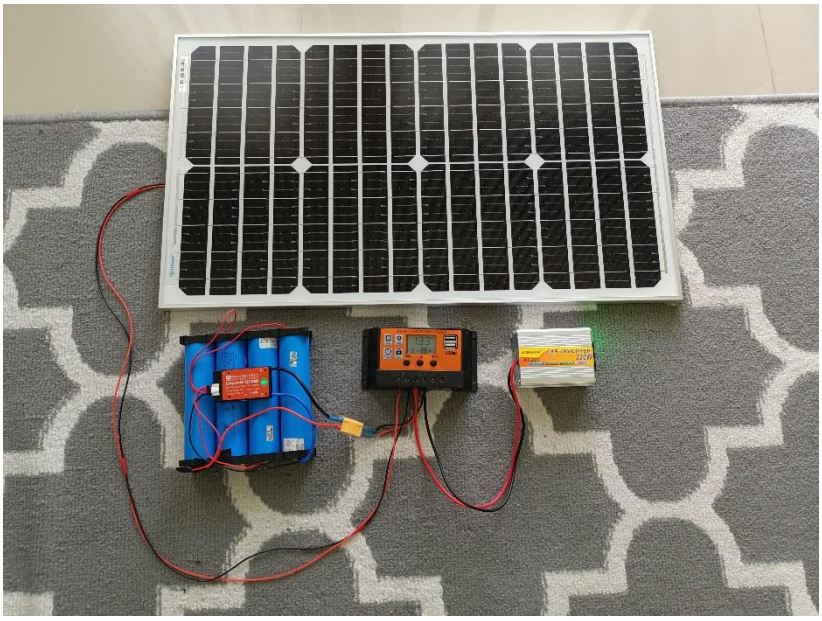

Figure 3. Early stage prototype

Indonesia's geographical conditions on the equator provide its own advantages in developing PV-based renewable energy systems. Sunlight is available almost all year round, even during the rainy season. Although the light intensity is reduced compared to the dry season, solar radiation remains and can be utilized by solar panels, especially with technology that can work at low intensity. It makes the application of PV-based charging stations very promising to be optimized in various regions of Indonesia, both in urban and rural areas. If in the initial stage this system is used for charging smartphones, then in further development, a similar system can be increased in capacity to charge the batteries of other devices. The development of charging stations can be carried out on several devices, such as electric scooters, electric bicycles, electric motorbikes, and electric cars, on a limited scale.

Conclusion

This study highlights the main problems in architectural education in Southeast Asia. The issue is the limited integration of renewable energy technologies, such as PV, into creative and contextual architectural design curricula. Although many institutions have widely adopted sustainability principles in theory, they still inconsistently implement design exploration and technology experimentation in architectural education. This gap worsens because educational systems often fail to provide a learning ecosystem supporting cross-disciplinary collaboration. In addition, there is also a lack of studies relevant to Southeast Asia's tropical climate context.

The study results show that integrating PV into the architecture curriculum can bridge the gap between creative design exploration and technological experimentation. Bangkok University, Thailand, has implemented it. The project-based learning model and challenges such as the Solar Decathlon prove the effectiveness of a holistic approach in education. This learning model can improve students' technical and ecological literacy. In addition, it can also form cross-disciplinary competencies and strong social awareness. Understanding the effects of human activity on ecosystems, such as the greenhouse effect and carbon neutrality, fosters ecological thinking in pupils and increases their responsibility to use clean and renewable energy. This discussion addresses several issues brought on by a lack of knowledge about environmental sustainability.

In addition, the author's development of an early prototype of a PV-based smartphone charging station in Indonesia shows the great potential for using renewable energy on a micro scale. This application is relevant to the needs of urban communities and remote areas. This technology can support a sustainable digital lifestyle. In addition, this technology is also an initial foothold for designing innovative products based on clean energy. Indonesia's advantageous equatorial location increases the potential for broader renewable energy uses, such as air conditioning, hot water systems, and lighting solutions beyond charging stations. Indonesia's year-round ample solar radiation increases the potential for broader renewable energy uses, such as air conditioning, hot water systems, and lighting solutions beyond charging stations. Thus, this study emphasizes the importance of redesigning architectural education in Southeast Asia by integrating PV technology. These findings provide a strategic contribution for higher education institutions to strengthen their role in the global sustainability agenda. In addition, it can also form a future generation of designers who are adaptive, collaborative, and visionary.

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