CLEAN ENERGY NEWSLETTER

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Editorial Note

On behalf of the Higher Education and Research Collaboration on Nanomaterials for Clean Energy (HRNCET)-NORPART project, we are immensely proud to present this edition of our newsletter. The HRNCET-NORPART initiative is a shining example of dynamic trilateral collaboration between academic institutions in India, Sri Lanka, and Norway, committed to advancing sustainable energy technologies and fostering impactful research. This newsletter is conceived as an extension of our mission, a space to share knowledge, showcase diverse contributions, and inspire the next generation of researchers and innovators. It is both an honour and a privilege to curate and present these articles, which embody the spirit of academic excellence, collaboration, and innovation.

Looking ahead, this newsletter will continue to evolve as a platform for diverse voices, perspectives, and stories. It will highlight pioneering efforts, demystify complex scientific ideas, and explore the vital intersections of technology, policy, and society. We envision it as a bridge connecting academic research with real-world impact, and as a forum that encourages dialogue, reflection, and collaboration.

We warmly invite you, our readers, to join us in celebrating the progress achieved and to actively engage with the challenges and opportunities that lie ahead. The future of sustainable energy is not a distant aspiration it is being built today, through discovery, dialogue, and collective effort. Together, we can shape a future that is cleaner, smarter, and more resilient for generations to come.

Prof. M. Thanihaichelvan
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Message from the Advisory Committee

It gives us great pleasure to introduce this edition of the Clean Energy Newsletter, which stands as a testament to the strong partnership between the University of Jaffna (UoJ), Sri Lanka, Coimbatore Institute of Technology (CIT), India, and Western Norway University of Applied Sciences (HVL), Norway. Since the signing of the Memorandum of Understanding between UoJ and HVL in 2017, this collaboration has flourished into a vibrant platform for advancing knowledge and innovation in clean energy science and technologies.

Over the years, our institutions have jointly organised three major international conferences in Jaffna and Coimbatore, bringing together hundreds of eminent researchers from across the globe in the field of clean energy to each conference. We have also facilitated numerous staff and student exchanges between our institutions and produced over a hundred publications.

These achievements reflect not only the academic excellence of our teams but also the dedication of the next-generation leaders of this initiative, Prof. M. Thanihaichelvan and Prof. P. Balraju, editors of this Newsletter, who are carrying it forward with renewed vigour. Their commitment ensures the continued dissemination of knowledge, the broadening of research horizons, and the nurturing of future leaders in clean energy.

This Newsletter is a product of that spirit. It brings together a diverse collection of articles authored by senior academics from various disciplines, each offering valuable insights into the pressing challenges and emerging opportunities in sustainable energy. From pioneering research in advanced materials to innovative approaches in energy systems and socio-economic perspectives, these contributions exemplify the interdisciplinary and collaborative ethos of our partnership. Notably, this edition also highlights the pioneering contributions of the world-renowned scientist Prof. K. Tennakone to the development of dye-sensitized solar cells. We firmly believe that initiatives such as this Newsletter play a vital role in strengthening academic networks, inspiring new ideas, and bridging the gap between research and real-world impact.

We extend our heartfelt appreciation to the editors, contributors, and all those who have worked tirelessly to bring this issue to fruition. We warmly invite our readers to engage with these articles, reflect on the progress achieved, and join us in advancing our shared mission of building a cleaner, more resilient, and sustainable future.

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AMCEHA | AMCEHA 2026 | JUNE 3-5, 2026

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Western Norway University of Applied Sciences

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June 3-5, 2026, Coimbatore Institute of Technology, India

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Unsung Pioneer: Sri Lankan Scientist's Early Works on Dye-Sensitized photovoltaic cells

Prof. Kirthi Tennakone was honored by Prof. K. Kandasamy (Emeritus Professor of Physics) at the Third International Conference on Advanced Materials for Clean Energy and Health Applications 2025 (AMCEHA 2025), held at the University of Jaffna, Sri Lanka, on March 27–28, 2025, where he delivered the plenary talk.

Before the now-famous Grätzel cell captured global attention, a Sri Lankan research group was quietly laying the groundwork for dye-sensitization of wide-bandgap semiconductors a milestone in the worldwide effort for clean energy. **Prof. Kirthi Tennakone** and his teams at the University of Jayewardenepura, University of Ruhuna and the Institute of Fundamental Studies in Kandy, conducted pioneering research from the 1980s through the early 2000s. Their foundational work on solid-state dye-sensitized solar cells and the use of natural dyes served as a critical precursor to the high-efficiency solar technologies recognized today.

Returning from the United States in 1972 with a Ph.D. in theoretical physics, he began working as an assistant lecturer at the University of Jayewardenepura. His initial foray into photovoltaics was driven by a curiosity for solar cells made of cuprous oxide (Cu_2O).

He faced a challenge when attempting to uniformly coat copper plates with Cu_2O by heating them in air, despite thorough cleaning with acids and alkalis. He could not obtain reproducible films. In fact, he found the solution to this complicated problem of uniform oxide film formation from local street electroplaters who prepared copper alloy jewelry for plating. His insight came from observing them igorously brushing jewelry with a froth of soap and water. He deduced that the soap treatment used by street electroplaters to prepare copper, silver alloy ornaments left an ultrathin, protective, hydrophobic layer of stearic acid on the copper surface. By applying the same technique to his copper plates and heating them to 450C, he successfully obtained plates uniformly coated with oxide. He concluded that this oily film serves a dual purpose: preventing atmospheric oxidation before plating, and instantly dissolving in the alkaline cyanide gold bath, exposing a perfect, pristine metal surface for gold attachment. This simple, yet unreported, chemical understanding of surface cleaning provided him with a crucial method for making reproducible cuprous plates, which persuaded him to begin his serious photovoltaic research.

Before his work on dye-sensitized systems, Prof. Tennakone was working on the fundamental issue of stability of photoelectrochemical cells. In a 1982 paper, his group demonstrated a novel way to overcome the photocorrosion that plagued photoelectrochemical cells. They found that long chain aliphatic alcohols could suppress the degradation of a cuprous oxide photocathode, suggesting that simple surface adsorption could be a powerful tool for inhibiting corrosion. The team also made another foundational discovery in 1984, reporting that cuprous thiocyanate (CuSCN) a p-type semiconductor, a finding that would become crucial for their subsequent work. In 1986, another research highlighted a method to prevent the rapid photodegradation of adsorbed dyes, a major defect in early dye-sensitized systems. He discovered that the stability of a dye like methyl violet, adsorbed onto a p-type CuSCN photocathode, could be significantly improved by introducing a second fluorescent dye, such as rhodamine-B, into the electrolyte. This worksuggested a new mechanism of stabilization through energy transfer between dye molecules. In 1987, he explained an unusual phenomenon he observed in dye-sensitized solar based on thick dye layer as an excitonic effect different from monolayer dye sensitization.

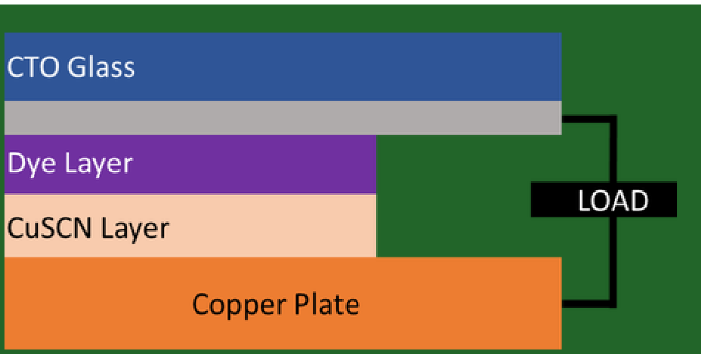

Figure 01: The Schematic of the all-solid-state dye sensitized photovoltaic device with CuSCN as the hole transporter reported in 1987 by Prof. Kirthi Thennakone's group.

Prof. Tennakone's contributions also extended to potential practical applications. In a 1987 paper, he and his team revealed a groundbreaking application of their work on photostable systems. They developed a dye-sensitized catalyst using p-type CuSCN coated with Rhodamine B and platinum. This catalyst was not only stable but was also capable of photogenerating oxygen from an aqueous persulphate solution under visible light, demonstrating a model system mimicking photosynthesis.

The following year, in 1988, Prof. Tennakone's research took another crucial turn with his paper on "Dye-sensitised solid-state photovoltaic cells." This was the first report on the concept of a dye-sensitized solid-state cell and provided a practical demonstration. His design utilized a solid p-type semiconductor to transport holes, proving that the dye-sensitization principle could be successfully applied in a solid-state architecture. In 1995, his group made another leap forward with "A dye-sensitized nano-porous solid-state photovoltaic cell." This paper marked the first time a dye-sensitized solar cell was built with a nanoporous structure. It was also the first to use cuprous iodide (CuI) as a transparent hole collector, and the paper described a novel method for its deposition. Building on this, his team published "Dye-sensitized solar cell with the hole collector p-CuSCN deposited from a solution in n-propyl sulphide" in 1999, which was the first report on a new method for depositing CuSCN to create a solid-state cell. The current use of CuSCN in research and application in solar cells and other optoelectronic devices, originated from the work of Prof. Tennakone and his team carried out in Sri Lanka.

Further refining the solid-state design, a 2002 paper, "Dye-sensitized solid-state solar cells: use of crystal growth inhibitors for deposition of the hole collector," introduced a method to reduce the crystallite size of the hole collector, allowing it to better fill the nanopores in solid-state dye cells.

Exploring new Materials and Device Concepts

His team continued to push the boundaries of materials and device concepts. In 1998, they published on the "Nanoporous n-selenium/p-CuCNS photovoltaic cell," which was the first "eta cell." This marked the first example of a concept later used in perovskite solar cells, where a thin layer of a low band-gap semiconductor is sandwiched between high band-gap n- and p-type semiconductors. The physical principle behind perovskite solar cells was pointed out in this paper. The paper specifically mentions that the fineness of the selenium film prevents bulk recombination. His work also expanded beyond the TiO_2 material. In 2001, "An efficient dye-sensitized photoelectro-chemical solar cell made from oxides of tin and zinc" reported the first high-efficiency dye-sensitized solar cell made from materials other than TiO_2. In the same year, a paper on Enhanced efficiency of a dye-sensitized solar cell made from MgO-coated nanocrystalline SnO_2 was the first to illustrate the barrier layer effect in dye-sensitized solar cells.

The use of natural sensitizers was a key focus as well. The 1998 paper, "Nano-porous solid-state photovoltaic cell sensitized with tannin" was the first report on the use of natural sensitizers in dye-sensitized solar cells. Other notable innovations include the first study of the cationic effect in polymer-based cells (1999), the first report of a new hole collector based on cuprous bromide (2000), a new concept to broaden the spectral response by sensitizing low band-gap semiconductors (2003), and the first report on the possibility of adopting molecular rectification to improve dye solar cells (2005). While the Grätzel cell's liquid electrolyte configuration would eventually become the subject of more widespread research, Prof. Tennakone's early solid-state models, his focus on interface engineering, and consistent efforts to solve the core challenges of instability and dye degradation were crucial in establishing the basic principles of the technology.

Prof. Tennakone’s research is more acknowledged overseas than in Sri Lanka. Many authors have quoted him as the first to introduce the concept of the dye-sensitized solid-state solar cell and demonstrate practical systems based on hole collectors he has envisioned. His papers based on work done in Sri Lanka have significant citation counts but not adequate in terms of originality and impact. Papers coming from the Third World are less likely to be cited. Foreign collaboration boosts citations. His paper reporting important original findings are based on work carried out exclusively in Sri Lanka without foreign collaboration and with very little facilities.

Prof. Tennakone's research at the Institute of Fundamental Studies and the Universities of Jayewardenepura and Ruhuna represents a vital chapter in the history of solar energy conversion. His work not only demonstrated novel paths for solar energy conversion but also highlighted the critical importance of material science and device architecture in developing next-generation photovoltaic technologies. As the world continues to search for efficient and affordable solar solutions, the early contributions from this Sri Lankan team will serve as a powerful reminder of how foundational science from unexpected places can shape the future. It is also a hint for Sri Lanka in its efforts to foster innovation. Creative minds with basic science insight is more important than specialization in technologies.

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Perovskite solar cells: A game changer in renewable energy

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The escalating global energy crisis and the mounting challenges of climate change demand rapid development and deployment of sustainable energy sources. Reducing dependence on finite fossil fuels and limiting environmental harm are now global necessities. Among renewable options, solar energy stands out for its abundance, cost-effectiveness, and minimal environmental impact, positioning it as a key pillar of future energy systems. Photovoltaic (PV) technologies, which directly convert sunlight into electricity, are central to this transition. While traditional silicon-based solar cells have long dominated the PV market and achieved efficiencies near the theoretical limit of about 27.3% for single junction silicon, close to their Shockley-Queisser limit1. However, their broader adoption has been constrained by high manufacturing costs, energy intensive processing, and material rigidity. The substantial capital investment and complex supply chains required for silicon production further add to these challenges.

To address these limitations, researchers have focused on more affordable and versatile alternatives, notably emerging photovoltaic (PV) technologies, with metal halide perovskite solar cells (PSCs) standing out as a leading candidate. Since their initial report in 2009 with a power conversion efficiency (PCE) of just about 3.8%, PSCs have rapidly advanced to achieve efficiencies of around 27% for single junction devices and nearly 35% in tandem configurations today [1-2]. This rapid progress, unmatched by any other photovoltaic material, highlights their transformative potential and the growing need for innovative, sustainable energy solutions. Their unique combination of high efficiency, low-cost production, and versatile applications positions PSCs as a promising next generation technology, even as challenges like long term stability and lead toxicity must still be resolved. This article explores the development and fundamental principles of perovskite solar cells, highlights their key advantages and current limitations and evaluates their potential to revolutionize the solar power industry and support a sustainable global energy future.

▶ Fundamental principles of perovskite solar cells

Perovskite solar cells are named after their perovskite-structured light absorbing material, a semiconductor with the general formula ABX3 (Figure 1(a)). In this structure, A is a monovalent cation, typically an organic ion such as methylammonium (CH3NH3+) or formamidinium ($CH(NH_2)^{2+}$), or an inorganic ion like cesium (Cs^+). B is a divalent metal cation, most commonly lead (Pb^{2+}) or, in some lead-free variants, tin (Sn^{2+}). X represents a halide anion, usually iodide (I^-), bromide (Br^-), or chloride (Cl^-). These ions assemble into a crystalline lattice where the metal (B) cations are each octahedrally coordinated by six halide ions, forming BX6 octahedra.

The larger A-site cations occupy the cuboctahedral cavities between these corner-sharing octahedra. This three-dimensional network is structurally similar to the mineral perovskite, CaTiO3, which gives this material family its name.

Two main device architectures are widely used in perovskite solar cells: the n-i-p structure and the p-i-n (inverted) structure (Figure 1(b)). In a standard perovskite solar cell (PSC), the perovskite film serves as the active light harvesting layer where incoming photons are absorbed to generate mobile charge carriers. When sunlight strikes the perovskite, its photons excite electrons from the valence band to the conduction band, creating electron-hole pairs. A key advantage of perovskite materials is their low exciton binding energy, which allows these pairs to separate into free carriers at room temperature. The perovskite layer is sandwiched between two charge selective transport layers that guide electrons and holes in opposite directions and prevent recombination.

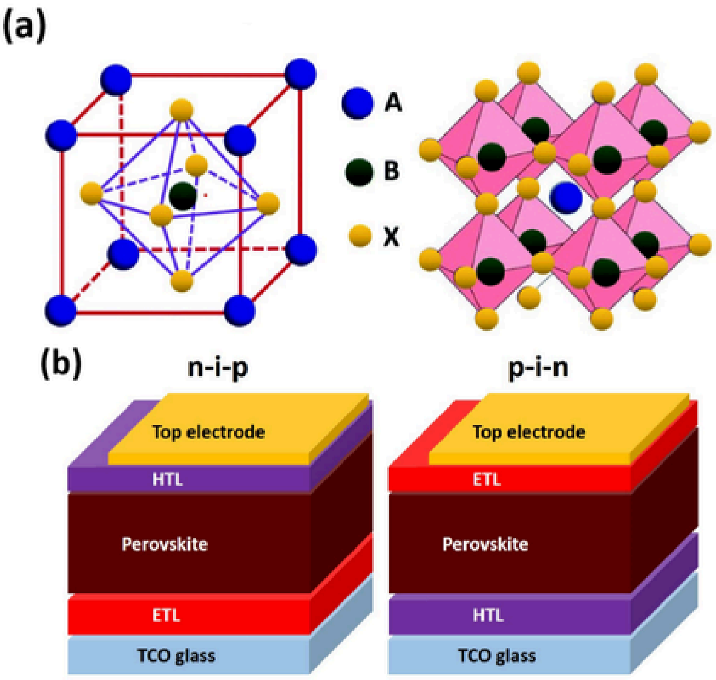

Figure 1: (a) Schematic representation of the perovskite crystal structure (ABX_3) and (b) Typical n-i-p and p-i-n (inverted) perovskite solar cell structures.

In the n-i-p architecture, an n-type electron transport layer (ETL) is deposited below the perovskite absorber to collect and conduct electrons, while a p-type hole transport layer (HTL) is placed above the perovskite to extract holes. The energy levels are carefully aligned: the conduction band of the ETL is slightly lower than that of the perovskite to accept electrons, and the valence band of the HTL is slightly higher than the perovskite's valence band to accept holes. Typical ETLs for n-i-p PSCs include metal oxides such as TiO_2, SnO_2, or ZnO; common HTLs include organic semiconductors like Spiro-OMeTAD and PTAA, or inorganic materials such as NiO_x and CuSCN. [3] This architecture is popular in high efficiency devices and is compatible with mesoporous scaffold layers.

In contrast, the p-i-n architecture reverses this stack order: a p-type HTL is deposited first onto the transparent conducting electrode, followed by the perovskite absorber and then an n-type ETL on top. This structure is favoured for low-temperature, solution-processed fabrication and is commonly used for flexible or tandem devices. For p-i-n PSCs, typical HTLs include PEDOT:PSS, PTAA, Self-assembled monolayers (SAMs) or NiO_x, while commonly used ETLs are fullerene derivatives like PCBM (phenyl-C61-butyric acid methyl ester), C60, or inorganic nanoparticles such as ZnO or SnO_2.[4] Both architectures are capped with electrodes: a transparent front electrode (commonly indium tin oxide(ITO), or fluorine-doped tin oxide (FTO)) allows light to enter and collects charge carriers, while a metal back electrode (typically silver or gold) completes the circuit by collecting the opposite carrier type. The built-in potential across the junction drives electrons and holes to their respective contacts, generating a photocurrent and voltage. What makes perovskites special is the exceptional quality of the semiconductor: high light absorption, long carrier diffusion lengths, low trap densities, and tolerance to defects, all achieved in a material that can be deposited from solution at low cost. [3] These properties allow PSCs to generate a high open-circuit voltage (Voc) and current, resulting in high efficiency even in simple device architectures.

Another important aspect of perovskite absorbers is their tunable bandgap. By varying the halide composition (I/Br/Cl) or mixing cations, the bandgap of perovskite films can be adjusted anywhere roughly from ~1.12 eV up to 3 .55 eV.5-6 Figure 2(a) presents a schematic energy level diagram of various metal halide perovskite materials, highlighting their ideal bandgap values. It clearly shows how compositional variations, such as changes in the halide or cation content, can tune bandgap. Meanwhile, Figure 2(b) shows UV-Vis absorbance spectra for films of $FAPb[I_{1-x}Br_x]_3$ and $FA_{0.83}Cs_{0.17}Pb[I_{1-x}Br_x]_3$, respectively. The gradual blue shift of the absorption edge with increasing bromide content demonstrates the corresponding increase in optical bandgap, directly supporting the concept of bandgap engineering through halide tuning. For example, formamidinium lead iodide (FAPbI3) has a bandgap around 1.51 eV, well-suited for single junction solar cells, while partial substitution with bromide increases the bandgap, ideal for wide bandgap top cells in tandem architectures. This bandgap flexibility not only means the spectral response of the cell can be tuned, but it also opens the door to multi junction (tandem) cell designs. One can stack a wider bandgap perovskite on top of a lower bandgap bottom cell (another perovskite or silicon), so that each absorbs a different part of the solar spectrum, surpassing the efficiency limit of a single junction. Actually, perovskites are now at the forefront of tandem solar cell research due to this compatibility and tenability.

Key advantages of perovskite solar cells

Perovskite solar cells (PSCs) stand out in next generation photovoltaics thanks to their remarkable power conversion efficiency, cost-effective manufacturing potential, and versatile material properties. One of their most striking advantages is how quickly their efficiency has advanced: in just over a decade, solid state single-junction PSCs have climbed from under 10% to about 27% in the lab, matching monocrystalline silicon's performance, an achievement that took silicon technology decades to reach.1, 8 Even more impressively, perovskite-silicon tandem devices have pushed beyond the limits of single junction silicon; small-area tandem cells have recently achieved a record 34.9% efficiency, while industrial scale cells have surpassed 31%. For instance, in April 2025, Trinasolar announced a new world record of 31.1% efficiency for its large area industrial grade 2-terminal perovskite-silicon tandem cell.9 These rapid efficiency gains are possible because perovskites offer excellent optoelectronic qualities such as strong light absorption, low non-radiative recombination, and exceptional defect tolerance. Together, these traits allow even solution processed perovskite films to perform like quality semiconductors.

Beyond their outstanding performance, PSCs promise low-cost, scalable manufacturing. Unlike silicon wafers, which demand high temperature crystal growth and energy intensive processing, perovskite thin films can be deposited via low temperature techniques such as spin coating, slot-die coating, inkjet printing, or vapor deposition, often below 150 °C. This opens the door to roll-to-roll (R2R) production on flexible substrates, similar to how newspapers are printed, enabling high-throughput fabrication at lower cost. The raw materials are also more abundant and inexpensive compared to refined silicon or rare III-V semiconductors. Pilot lines and demonstration plants have proven that large-area modules with respectable efficiencies are achievable, and the first commercial perovskite-silicon tandem panels develop by Oxford PV (with around 24-25% module efficiency) began shipping in 2024.[10] PSCs are expected to drive down the cost per watt of solar power, making clean energy more accessible worldwide.

Equally important is the exceptional tunability and design flexibility of perovskite materials, which enable a wide range of applications. By adjusting chemical composition, manufacturers can fine-tune the bandgap, stability, colour and transparency of the films. This versatility supports innovations such as all-perovskite multi junction cells for ultrahigh efficiency, lightweight flexible modules for portable electronics and aerospace, and semitransparent panels for building-integrated photovoltaics which can function as windows or architectural façade components. Their lightweight design makes them ideal for rooftops with limited load capacity, drones, or off-grid installations where transporting heavy glass modules is impractical. Together, these advantages position PSCs as a truly transformative technology set to expand the reach of solar energy far beyond the capabilities of traditional silicon, powering everything from city rooftops to futuristic energy harvesting buildings.

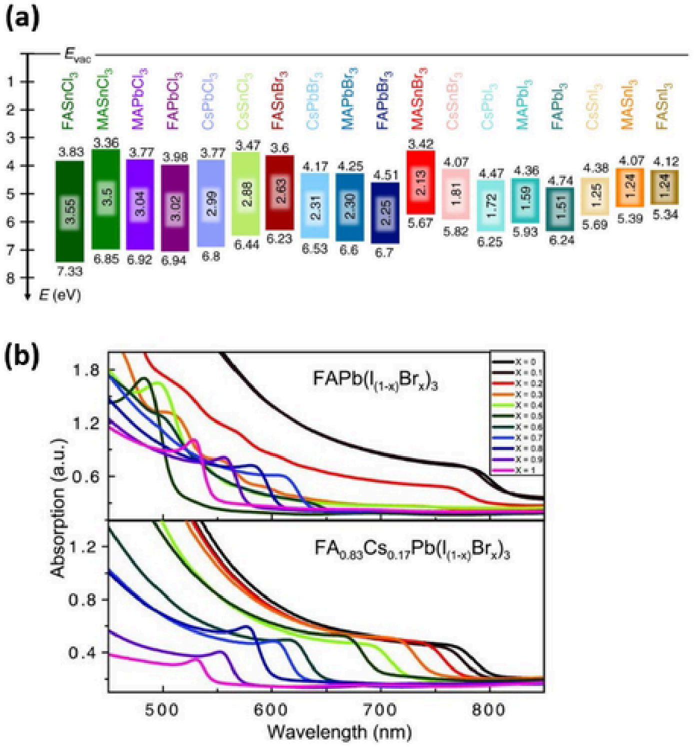

Figure 2: (a) Schematic energy level diagram of representative metal halide perovskites, showing the tunable bandgap range through compositional engineering 6 and (b) UU-Vis absorbance spectra of $FAPb[I_{1-x}Br_x]_3$ and $FA_{0.83}Cs_{0.17}Pb[I_{1-x}Br_x]_3$, demonstrating halide dependent bandgap tunability in mixed halide perovskites. [7]

Challenges and Limitations

Despite their remarkable advantages, PSCs face several critical challenges that must be resolved before they can mature from promising lab prototypes to durable, large scale commercial products. The most pressing issue is long-term stability. Unlike silicon PV modules, which routinely deliver reliable performance for 25-30 years, early PSCs degraded within days if exposed to air and moisture. Although significant progress has extended laboratory lifetimes to thousands of hours, real world durability under sunlight, humidity, heat, and mechanical stress remains a concern. Intrinsically, perovskite materials can undergo phase changes, ion migration, or thermal decomposition. Externally, moisture, oxygen, UV light, and thermal cycling accelerate degradation and can lead to layer delamination or rapid efficiency loss. Encapsulation strategies and compositional engineering have improved resilience significantly, but matching the robust lifespan of silicon modules still requires further breakthroughs in both material chemistry and enginnering and protective packaging.

Another key concern is lead toxicity and its environmental impact. Most high efficiency perovskite absorbers rely on lead-based compounds such as lead halides, which pose contamination risks if a panel cracks or is improperly disposed of. While the absolute quantity of lead is small compared to older battery technologies, even trace leakage is unacceptable in a renewable energy technology expected to be deployed widely. Lead free perovskite alternatives like tin-based or bismuth-based absorbers have been investigated, but so far deliver lower efficiencies and face stability issues. As an interim solution, advanced encapsulation and lead isolating interlayers are being developed to prevent any lead release even if modules are damaged. In parallel, recycling strategies will be essential to recover lead safely at the end of life, ensuring PSCs meet environmental standards and public acceptance.

Finally, scaling up PSCs from lab-scale devices to industrial production introduces its own set of technical hurdles. High lab efficiencies are often achieved on tiny cells using methods like spin-coating, which do not translate easily to meter-scale modules. Uniform large-area deposition, robust transport layers, and stable contacts must be engineered for high-throughput manufacturing. Techniques such as blade coating, slot-die coating, and roll-to-roll printing are being refined, but require precise control to avoid defects that degrade performance. Moreover, sensitive perovskite layers must be quickly encapsulated during production to avoid moisture damage. Achieving high yield, fast production speeds, and long-term reliability at scale are intertwined challenges that demand innovation in equipment, materials, and process integration. Despite these obstacles, steady progress is evident: companies have launched pilot lines, and early commercial perovskite-silicon tandem panels are now shipping, proving that with sustained R&D, perovskites can be scaled up responsibly to play a pivotal role in the global renewable energy transition.

Summary

In summary, perovskite solar cells stand as one of the most promising innovations in clean energy today. They combine high power conversion efficiencies, cost-effective and scalable production, and unmatched material tunability that enables everything from ultra-efficient tandems to lightweight, flexible, and aesthetically integrated solar solutions. This unique blend of performance and adaptability makes PSCs a potential candidate for accelerating the global energy transition. While challenges remain, particularly ensuring long-term operational stability, addressing lead content responsibly, and scaling manufacturing while maintaining high yields, remarkable progress in the last decade inspires confidence that these hurdles are resolvable. With continued advances in material chemistry and engineering, encapsulation and industrial processing, perovskites are on track to become a mainstream, scalable, and commercially viable photovoltaic technology. If they deliver on this promise, they will help meet soaring global electricity demand with affordable, abundant, and low-carbon power, pushing photovoltaics well beyond the limits of silicon alone and into applications that transform buildings, vehicles, and entire urban landscapes into energy producers. The next decade will show whether PSCs truly become the “game changer” many expect, but their trajectory so far points clearly to a brighter, more sustainable energy future.

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Designing the Future: Energy-Efficient Buildings for a Resilient World

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Rethinking Buildings: Global Models of Efficiency

The global perspective on architectural possibilities is being transformed by a variety of revolutionary structures, like The Edge in Amsterdam, which is one of the most intelligent office structures ever built, and Panyaden International School in Thailand, which manages classroom temperatures without air conditioning. The Bullitt Centre in Seattle operates without mechanical refrigeration, leading to an annual consumption of energy of zero. The IBN Centre in the Netherlands operates entirely off-grid, employing photovoltaics and thermal energy storage, while the Pixel Building in Melbourne integrates DALI-controlled lighting with carbon-neutral services. As demonstrated in Figure 1, these examples illustrate that buildings are not simply static structures; they are dynamic systems that respond, think, and breathe. Modern materials, strategic orientation, sophisticated mechanical systems, and efficient designs are all part of the new generation of high-performance structures. This article explores the exceptional efficiency of these structures, the future prospects, and the potential for countries like Sri Lanka to implement these concepts in order to create a resilient and energy-secure built environment.

Envelope and Material Innovations in Building Design

These buildings are built employing material strategy. In order to minimise operating energy, it's essential to minimise the transmission of heat via roofing, walls, windows, and floors. At The Edge, low-emissivity triple glass, automatic blinds and vacuum insulated panels (VIPs) modulate thermal conductivity and sun gain. The heating and cooling burdens decrease significantly when the envelope U-value decreases to below 0.8 W/m²·K. The Pixel Building's high-reflectivity facades and green roofs stabilise the inside temperature and alleviate peak heat burdens. The thermal mass of Panyaden School is significant and the embodied energy is minimal, thanks to the locally grown bamboo and rammed earth walls. In addition to insulation, these materials encourage circularity and bio-based construction, thereby reducing embodied and operational carbon. Passive solar control windows, phase change materials (PCMs), and cool roofing systems are becoming economically feasible, thereby facilitating intelligent thermal performance.

Popular energy efficient buildings


Panyaden International School, Chiang


Bullitt Center, Seattle

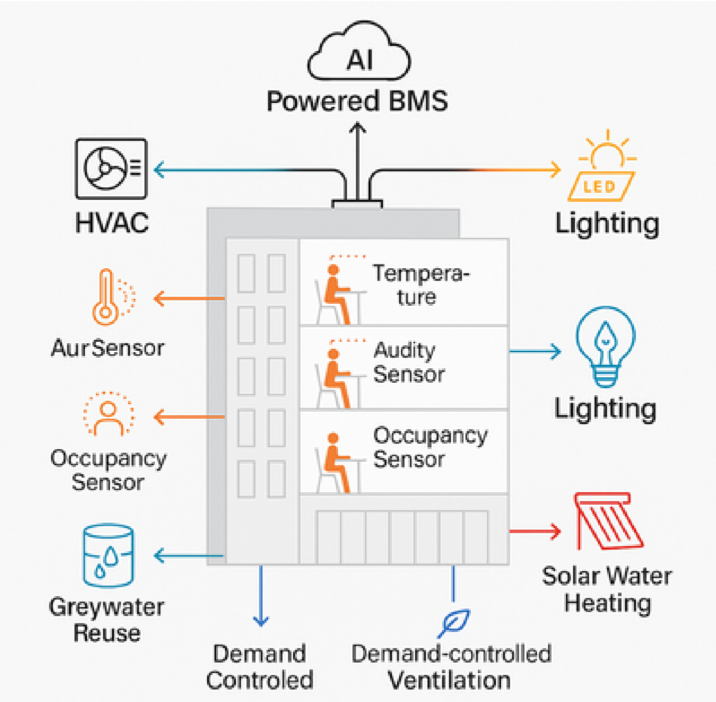
Spatial Configuration for Thermal Performance and Occupant Comfort

Nevertheless, material is just one component of the equation; spatial planning specifies the management of internal advantages and external conditions. The Edge's central atrium facilitates vertical air circulation, which improves passive cooling and daylight spread. The Bullitt Centre's slender floor plates optimise daylight infiltration and reduce reliance on artificial illumination during daylight hours, while educational environments in Panyaden are organised around open courtyards that facilitate cross ventilation. Passive performance necessitates spatial zoning. The used spaces are orientated to maximise lighting and natural ventilation, while essential sections such as stairwells, corridors, and storage rooms function as thermal buffers. During the design phase, engineers are able to optimise air change rates, thermal latency, and glare management by progressively evaluating these configurations using computational fluid dynamics (CFD) and daylight simulation technologies like Radiance. The integration of spatial configuration with digital modelling is now essential for performance-oriented design.

Thermal comfort strategies

Climatic Orientation and Solar Geometry in Building Form

The building's orientation in relation to the sun, breeze, and local microclimate is equally important. The Bullitt Centre is orientated due south and features extended overhangs that permit low-angle winter sunlight while obstructing high-angle summer beams. The BIPV façade of the IBN Centre in the Netherlands is orientated to monitor solar angles seasonally, thereby maximising energy yield. Wind exposure is also influenced by orientation; apertures are positioned to facilitate cross-flow ventilation, while shaded verandas or thermal chimneys facilitate buoyancy-driven stack ventilation. In tropical climates such as Sri Lanka, east-west facades are minimised to mitigate heat burden, while north-south alignments are complemented by shading devices such as vertical fins or pergolas. Solar path analysis and wind rose data are now employed by advanced buildings to simulate and optimise these variables, thereby ensuring that buildings are not merely positioned, but rather climatically tailored.



AI-powered building management system

Building Systems: Intelligence, Efficiency, and Adaptability

Services like HVAC, lighting, and control systems make a passive envelope adaptive. The Edge monitors air quality, temperature, lighting, and occupancy with over 28,000 IoT sensors as similar to Figure 3. An AI-controlled BMS controls heating, cooling, and lighting in real time using these sensors. Digitally controlled LEDs, solar water heaters, greywater reuse, and carbon dioxide-based demand-controlled ventilation are also used in the Pixel Building. IBN Centre stores summer heat underground for winter use using ground-source heat pumps and seasonal thermal energy storage (STES). These technologies decrease operating expenses, improve indoor air quality, and peak load shaving. COPs exceeding 4.0 and illumination power densities below 5 W/m² make these systems efficient, predictive, and self-optimizing. In corporate and educational buildings with dynamic energy demand, machine learning-enabled HVAC and adaptable lighting are becoming standard.

Onsite Energy Generation and Net-Zero Building Integration

One of the most significant leaps in building performance comes from onsite energy generation, allowing buildings not only to reduce dependence on external grids but also to become net-zero—or even net-positive—energy producers. In conjunction with occupancy-driven controls and high-efficiency systems, rooftop photovoltaic (PV) arrays at The Edge in Amsterdam provide a significant portion of the building's electricity requirements. The IBN Centre in the Netherlands is a net-positive energy building that generates more energy annually than it consumes, thereby going one step further. Simultaneously, the Pixel Building in Melbourne serves as an illustration of hybrid generation, as it converts organic refuse into usable energy through the use of anaerobic digesters, solar PV panels, and rooftop wind turbines. The integration of these systems with battery storage and real-time energy monitoring platforms enables net metering, which enables the recirculation of excess electricity into the grid. EnergyPlus and TRNSYS are potent simulation tools that are used to design such energy strategies. These tools simulate thermal loads, system efficiencies, and user behaviour under dynamic conditions. Therefore, these strategies are not arbitrary. Energy Use Intensity (EUI) values below 70 kWh/m²·yr are achieved by these buildings, which frequently exceed and meet global net-zero energy benchmarks.

Emerging Global Trends in Energy-Efficient Building Design

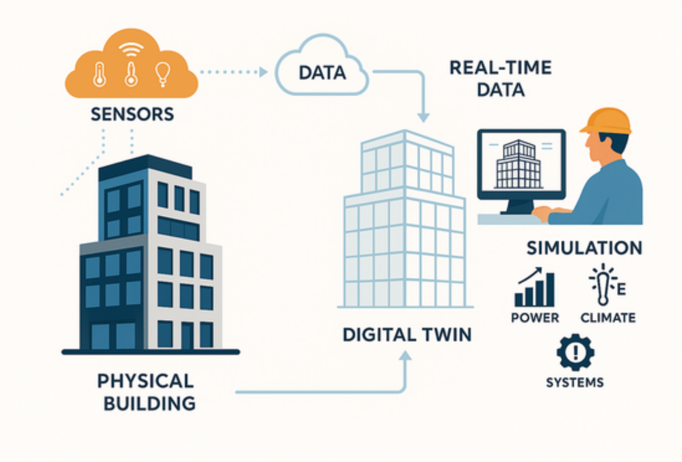
Future energy-efficient buildings will use digital intelligence, prefabrication, renewable integration, and occupant-centric systems. Digital twins as shown in Figure 4—live data-driven virtual duplicates of buildings that imitate performance, detect faults, and optimise energy use—are a major trend. These twins construct self-correcting settings using BIM, sensor data, and AI-based analytics. Prefabricated passive buildings with incorporated insulation, airtight joints, and service conduits ensure performance consistency and reduce construction waste. Electrical and thermal energy storage will help balance intermittent renewables and load demand. Hempcrete, mycelium insulation, and printed earthen walls will become popular. Finally, buildings will integrate sensors for light quality, air purity, and circadian rhythm to promote human well-being from energy-efficient to health-responsive.

Sri Lankan Success Stories in Building Efficiency

This transition is currently being led by specific structures in Sri Lanka. The carbon-neutral garment manufacturing facility in Thulhiriya, MAS Thulhiriya, has achieved a 40% reduction in energy consumption by utilising passive refrigeration, solar photovoltaic systems, and rainwater collection. Dialog's Colombo headquarters utilises energy-efficient lighting, intelligent glass, and HVAC systems that are operated by building management systems. The Sri Lanka Institute of Nanotechnology (SLINTEC) structure is equipped with natural ventilation, greywater reclamation, and solar control mechanisms. The NIBM green campus in Pitipana is equipped with renewable energy sources, natural lighting, and verdant roofs. These examples illustrate that the foundation has been established; the challenge is to expand and integrate it into the mainstream.

Conclusion: Constructing a Regenerative Future

In summary, the global blueprint for energy-efficient buildings is well-established, and its adaptation to Sri Lanka is both feasible and imperative. Sri Lanka can convert its construction sector from a carbon source to a carbon sink by integrating renewable energy, smart technologies, climate-aware design, and advanced material science. The climate imperative is evident, the case studies are validated, and the instruments are accessible. What remains is the determination—across academia, industry, and policy—to construct a future that is not only energy-efficient but also regenerative, resilient, and proudly Sri Lankan.



Digital twin construction

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Hydrogen Fuel Challenges: Atomistic Insights into Material Degradation

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The adoption of hydrogen as an alternative fuel has led to the development of hydrogen infrastructure, which includes storage, transportation, and distribution systems. However, existing storage or transportation is expensive, as low-cost structural materials are prone to hydrogen degradation known as hydrogen embrittlement (HE). Steel is widely considered a viable material for hydrogen storage and transport; however, HE remains a major limitation, with delayed fracture representing a particularly serious concern1). Delayed fracture is characterized by abrupt failure after extended exposure to sustained stress in a hydrogen-containing environment. This behavior cannot be fully explained on the basis of hydrogen concentration, as hydrogen diffuses rapidly and readily reaches thermal equilibrium in bcc Fe2). HE effects on the mechanical properties of structural metals has been recognized for more than a century and often results in premature failure. As a result, HE remains a critical concern, particularly in steels, owing to the high mobility of H in Fe. Despite extensive experimental efforts, a complete mechanistic understanding remains challenging because H occurs at low concentrations, diffuses rapidly, and interacts with defects across multiple length and time scales. Atomistic studies, including molecular dynamics and first-principles calculations, therefore provide an effective approach to probe the underlying mechanisms and complement experiments. To elucidate the underlying mechanisms, three primary questions must be addressed: (i) by what pathway can vacancies be transported to stress singularities (i.e., grain boundaries) at the high concentrations implicated in failure, given that monovacancy diffusion is too slow; (ii) what is the nature of the interaction between hydrogen and vacancies at grain boundaries (GBs); and (iii) by which mechanism do GBs lose cohesion.

Hydrogen facilitates the formation of monovacancies and small vacancy clusters (VCs), increasing the concentration of vacancy–hydrogen complexes and promoting the growth of larger VCs (Refer Fig. 1(a)①). As the cluster size increases, the migration activation barrier increases and the effective mobility decreases; correspondingly, H atoms trapped within the cluster are less likely to migrate between neighboring vacancies. In this regime, H transport proceeds predominantly by dissociation, in which H atoms detach from the complex, diffuse through the lattice, and are subsequently re-trapped at other defects. When a planar VC reaches a critical size, the elastic attraction between opposing Fe atoms on the top and bottom inner surfaces induces an out-of-plane collapse, forming a vacancy-type prismatic dislocation loop (PDL) (Fig. 1(a)). Consistent with this mechanism, recent studies report that VCs can transform into PDLs3-4).

Under compressive strain, smaller VCs are predicted to be thermodynamically favored in the PDL configuration3) (Refer Fig. 1(b)), reflecting the stabilizing influence of hydrostatic compression on PDL nucleation and growth. Furthermore, a PDL containing approximately 37 vacancies exhibits mobility many orders of magnitude higher than that of monovacancies, indicating a rapid vacancy-transport pathway in bcc Fe mediated by PDLs5). Under tensile stress, PDLs are unstable and revert to VCs; the reverse transformation is accessible at room temperature for two-dimensional VCs and requires slightly elevated temperatures for three-dimensional VCs3-4). Taken together, these results provide a mechanistic basis for achieving high vacancy concentrations at stress singularities, clarify the stress-state dependence of H trapping and release, and thereby address the first question.

Further, another recent study shows that hydrogen interacts with vacancies at GBs, forming stable vacancy–hydrogen (V–H) complexes and driving co-segregation to interfacial sites with excess free volume. Vacancies lower the local hydrogen solution energy, which enhances trapping. Moreover, hydrogen, in turn, stabilizes vacancies and small vacancy clusters by reducing their effective formation energies and promoting their retention at GB sites. This synergistic interaction produces vacancy-induced hydrogen segregation that increases the hydrogen concentration by up to 117 % relative to the vacancy-free case, at a vacancy density of 7.49 1/nm^2 in tilted GBs of α-Fe.

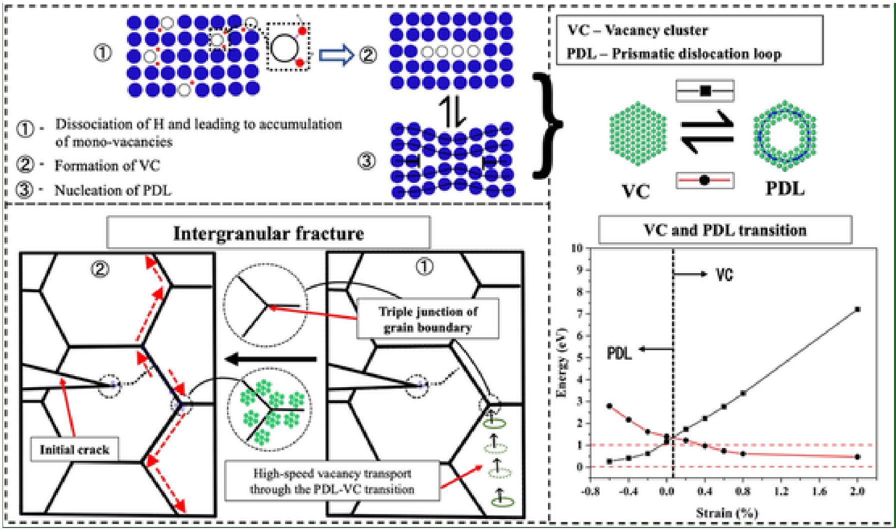

Figure Illustrates the formation of VC and the nucleation of PDL, focusing on considering the stability of PDLs and vacancies under different strains, (b) explains the transition between these defects under applied strain, aiming to identify the stable state at stress singularities and understand the delicate balance between VC and PDL near GBs, and (c) describes the mechanism, elucidating the high concentration of vacancies near GB. This mechanism involves the transportation of high-density vacancies by diffusion of PDLs, which weakens the GB cohesive strength, ultimately leading to IG-like failure.

This synergistic H–vacancy interplay was quantified at GBs under zero and 2% tensile strain. The key findings are that vacancy diffusion to GBs drives vacancy-induced H segregation, markedly elevating hydrogen concentration across almost all boundaries and dominating the loss of cohesion. At a vacancy mentioned above, the cohesive strength loss reaches 80% at zero strain and 95% at 2% strain, whereas in the vacancy-free case the decrease is only 35%. Low-angle GBs show little sensitivity to tensile loading, but most other GBs are strain-sensitive, and vacancy segregation amplifies the effect of strain. Stress-assisted vacancy redistribution produces nanovoids on the GB plane, providing a mechanistic link to intergranular decohesion and delayed fracture.

Furthermore, the vacancy-induced hydrogen segregation and the associated loss of GB cohesion directly address questions (ii) and (iii). Nevertheless, additional work is required to validate this mechanism in alloyed steels. In parallel, there is a pressing need to refine interatomic potentials so they accurately represent hydrogen interactions with alloying elements in steel. Particularly, Fe–H–C–Ni–Cr–Mo–X (X = other relevant solutes) potentials should reproduce first-principles benchmarks for H solution energies, migration barriers, vacancy/solute binding, segregation thermodynamics at GBs, and cohesive energies under strain. Accordingly, this atomistic understanding of the failure mechanism can be extended to experimental validation. This will enable the development of low-cost structural materials to realize hydrogen as an affordable alternative energy source.

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Performances of a medium-scale anaerobic digester converting biogas to electricity at University of Jaffna, Kilinochchi premises: A way towards sustainability

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Biogas production for carbon neutrality

The term “Carbon neutrality” or “net-zero emission” is often used in climate change related communications. The carbon neutrality implies that the carbon emissions are balanced by the carbon sequestration, thus there is no net increase in atmospheric CO_2. Driven by this global climate change challenge, Sri Lanka has revised its nationally determined contributions (NDCs) to achieve carbon neutrality by 2050. In an effort to mitigate the climate change impacts and decarbonizing at least 80% of the economy, Sri Lanka is keen on developing and deploying renewable energy resources. Especially, the past decade has seen a renewed importance in exploring local and foreign investment in wind, solar and green hydrogen related sectors. While establishment of most of these sectors require expensive materials and complex infrastructure, biogas to energy conversion has still been a promising technology mainly due its technical, economic viability and adherence to circular economy model.

Biogas is produced by anaerobic digestion of organic matter in an oxygen free environment. The composition of biogas predominantly includes methane and carbon dioxide and small quantities of other gases such as nitrogen, hydrogen sulfide and oxygen. As an energy carrier, lower heating value (LHV) of biogas ranging from 16 – 28 MJ/m^3 depending on its methane content (typically 40 – 70 %). Conventional biogas to energy technologies in Sri Lanka have only focused on converting biogas for heating and cooking purposes while utilizing the effluent from digester as fertilizer. In the meantime, several small to medium scale anaerobic digesters in Sri Lanka have been abandoned due to operational issues and poor biogas production. Apparently, there is still a considerable controversy surrounding widespread acceptability of anaerobic digesters as a model for circular economy and carbon neutral energy production. In this context, this article discusses the operation and key performances of an anaerobic digester at University of Jaffna Kilinochchi premises. Especially, this sheds new light on how the conventional management of anaerobic digesters can be transformed towards sustainability.

Technical aspects

In anaerobic digestion, complex organics are converted into biogas by different groups of microorganisms. Thus, an oxygen free environment and appropriate physical-chemical conditions in the digesters are essential for ensuring optimum biogas production. In such conditions, uninterrupted supply of feedstock and balanced nutrients such as carbon, nitrogen, phosphorus and trace metals in the feedstock are adequate for continuous biogas production. However, sustainable operation of a biogas digester is only rationalized by finding an organic waste which is economically viable to be used as feedstock rather than utilizing it for other purposes. Also, conversion of complex organics into simpler organics and enhancing the activity of microorganisms responsible for anaerobic digestion require adequate moisture level/water content in the digester. When feedstock has low/moderate water content, it is crucial to supplement water into the digester externally. Thus, another important factor dictating the sustainable operation of digester is to maintain the adequate water intake in the digester using non-potable water. Considering all these factors, the biogas plant was constructed in an Animal farm premises where the digester can continuously receive the cow dung, cow urine and wash water originated from cattle shed and cattle manure storage area. Thus, the feedstock does not compete with any non-renewable resources. The biogas digester was constructed in compliance with SLS 1292: 2006. The reinforced concrete was used for the construction of most of the components while standard fiber molds were used for the construction of the walls. In general, sizing of the digester is dependent on the daily input of feedstock and the solid/hydraulic retention time (SRT/HRT) which is the average time that liquid/slurry spend in the digester. As such, the capacity of the digester was determined as $35m^3$ by considering the maximum feedstock input, estimated daily biogas generation and assuming a detention time of 40 days. As such, the plant is designed to treat 95 tons of waste annually.

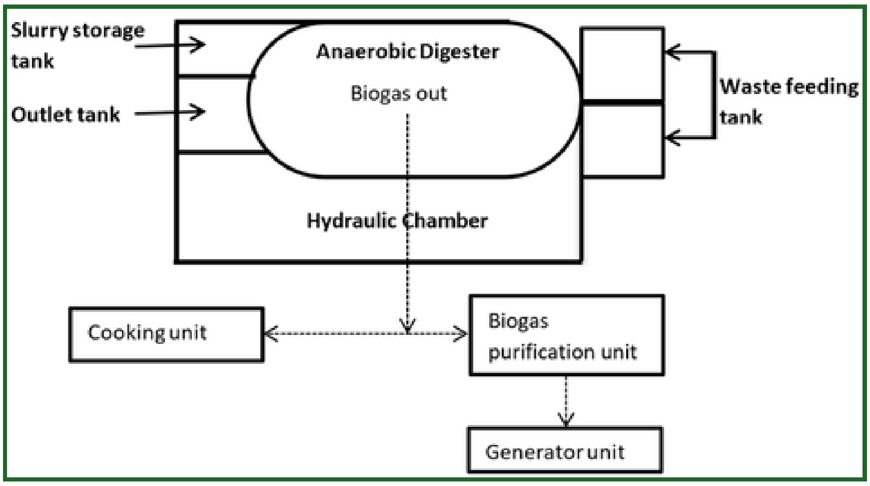

Figure 1: Schematic diagram of the anaerobic digester and its components

Figure 1 shows the schematic diagram of biogas to electricity plant located at University of Jaffna, Kilinochchi premises. As can be seen in Figure 1, the digester has two separate feeding tanks to admit the cow dung (and wash water) and food waste. In fact, food waste feeding tank is designed to mix the food waste with water and prevent oxygen from entering inside the digester. Unlike conventional digesters, this digester has a special compartment, hydraulic chamber to facilitate homogenous mixing of feedstock with the aid of valve system. A one-way valve system allows the mixture of feedstock and water to make a circulating path along the hydraulic chamber and digester unit, thus enhances the “hydrolysis” of complex organics. In anaerobic digestion, “hydrolysis” is often considered as a rate limiting step since complex organic polymers such as carbohydrates, proteins and lipids are broken down into soluble products such as sugars, amino acids and fatty acids. The “digestate”, effluent from the digester comes out when the internal pressure in the digester builds up and discharged in to the slurry storage tank (Figure 1).

The “digestate” which is enriched with Nitrogen (N), Phosphorus (P) and Potassium (K) and other micro nutrients can be collected manually or using a submerged pump to serve as the fertilizer for the crops in the agricultural farm. The digester also incorporates an outlet level that allows the excess gas to leave the system when the biogas level reaches its maximum level. This also serves as the safety mechanism to prevent the biogas unit from structural damage caused by gas pressure. As illustrated in Figure 1, the primary purpose of this digester is to convert the biogas into electricity via generator with 4 kW capacity. At present, the produced electricity is used for lighting the cow shed. In order to get rid of hydrogen sulfide and excessive moisture content in the biogas, a biogas purification unit which incorporates desulfurization and dehydration columns is installed. The estimated annual energy savings of the plant is about 6,500 kWh. Biogas digester is designed to store only a certain amount of biogas in the headspace of the digester. Thus, it is also crucial to have an alternative strategy to utilize the biogas for heating or cooking purposes in case of non-conversion of biogas into electricity. Thus, this biogas unit also has a provision for utilizing biogas for cooking and heating purposes if necessary.

▶ Potential challenges of operating anaerobic digesters

One of the key challenges associated with the digester operation is the process imbalances which lead to cessation of biogas production. Several small and medium scale biogas digesters in the country frequently face such challenges. In such cases, halt of biogas production is often associated with accumulation of volatile fatty acids (VFA) and sudden pH drop. In fact, transient buildups of VFAs are reversible in most cases and prolonged accumulation of VFAs and low pH level may lead to failure of the digester operation. One of the root causes for process imbalances in anaerobic digester is the inadequate or inconsistent supply of feedstock with appropriate quality and quantity. While optimum Carbon:Nitrogen (C:N) ratio for anaerobic digestion is between 20:1 to 30:1, inadequate C:N ratio may affect the activity of the consortium of microorganism which are responsible for the conversion of organic waste into biogas. Besides, lack of micronutrients including Phosphorus and trace metals such as Fe, Co, Ni, Zn and Mo may affect the biogas production. Introducing two or more different types of feedstocks or so called “co-digestion” is a simple and a feasible way to ensure the supply the feedstock with adequate nutrients. Thus, the digester (Figure 1) is designed to admit food waste, non-food crops and residues in addition to the cow dung. Also, it is essential to run the digester with steady quantity of feedstock to prevent shock loading of waste input which may cause process imbalances. The biogas produced in a digester must be systematically utilized without releasing residual gas to atmosphere to rationalize the environmental sustainability of digester operation. Another important factor dictating the sustainability of digester operation is the end use of digestate in both liquid and slurry form. At present, the digestate is utilized for agricultural purposes as organic fertilizer. An integrated approach is needed to utilize the digestate for its direct use in agriculture or supplement it with other organic fertilizer.

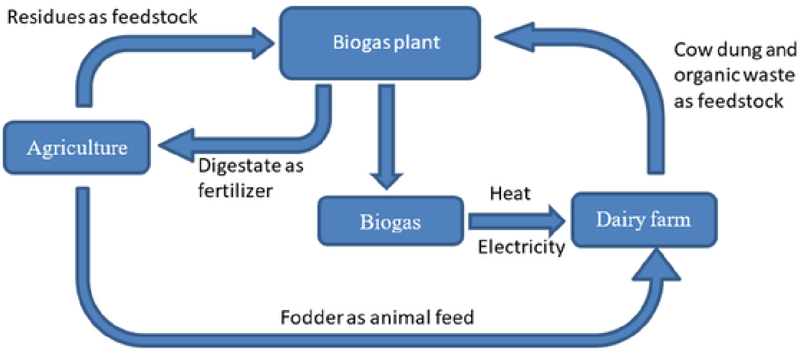

Figure 2: Application of circularity concept in the anaerobic digester

Unplanned release of digestate to the environment may lead to contamination of groundwater and eutrophication in surface water bodies as the digestate has elevated level of nutrients. The operation of the biogas digester requires minimum support of human resources for day-to-day operation and preventive maintenance. The supply and sorting of feedstock and handling of digestate require semi-skilled workers while skilled workers are necessary for the operation of biogas to electricity generation unit and carry out preventive regular maintenance. The Figure 2 illustrate the how the circularity concepts are incorporated in the operation of the digester as discussed in previous section.

▶ A way towards sustainability

Enhancing the biogas production and electricity generation through appropriate utilization of feedstock and process optimization would allow the dairy farm to reduce its energy dependency on national grid. On the other hand, substantial utilization of organic fraction of municipal waste will prevent the organic waste end up in the dumping sites and landfills. Meanwhile, the quality of the digestate can be improved by boosting its nutrient content (Nitrogen, Phosphorus and Potassium) with respect to Sri Lankan standards for organic fertilizer. Adding value to the digestate would not only enhance the crop productivity but also pave way for commercializing it as safe form of organic fertilizer. Ultimately, this would create more job opportunities in waste management, agriculture and integrated farm management. Although further studies are still required to rationalize the economic viability of such models for scale up and commercialization, an integrated approach for waste management and energy generation with the generation of value-added products would be a sustainable option for regional and national development.

From labs to headlines: How altmetrics reflect public attention and societal impact of hydrogen energy research

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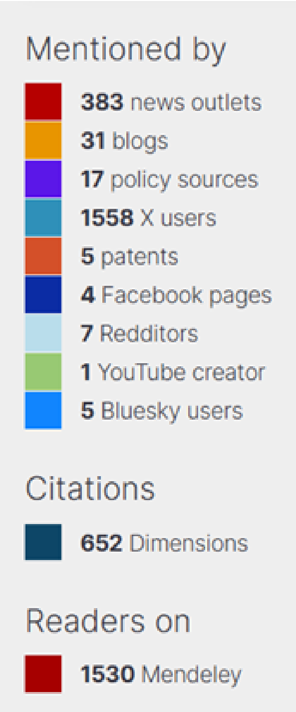
Hydrogen energy is gaining attention as a clean and sustainable alternative to fossil fuels, offering high energy density and eco-friendly attributes. Current production methods include water electrolysis and steam reforming, while storage options encompass compressed gas, liquid, and solid-state techniques. Applications range from fuel cells to hydrogen-powered engines, demonstrating potential for improved energy efficiency and reduced environmental impact (Cao et al., 2024). Research no longer lives only in journals. Every day, thousands of conversations about science take place online from social media posts to news stories and policy debates. Altmetrics track this digital attention, showing how research reaches far beyond traditional citations. In the fast-evolving field of hydrogen energy, research findings quickly spill over from labs into public conversations. Altmetrics capture this journey, revealing how studies on hydrogen are shared across social media, highlighted in the press, and even referenced in policy discussions offering a real-time view of societal engagement with science. Altmetrics are powerful because they reveal research impact in multiple layers (Gupta et al., 2025). These layers move beyond citations to capture how knowledge flows through different spheres:

1. Public attention: coverage in news stories, blogs, Wikipedia, or video platforms.
2. Social media visibility: discussions across X (Twitter), Facebook, LinkedIn, Reddit, and emerging platforms like Bluesky.
3. Academic engagement: readers on Mendeley, mentions in peer reviews, and appearances in teaching syllabi.
4. Societal and policy influence: references in policy documents, patents, or clinical guidelines that signal real-world application.

Public Attention

Altmetric data shows that some hydrogen research articles break through the confines of academia and become part of the public climate conversation. The clearest example is the 2021 article "How green is blue hydrogen?" published in Energy Science & Engineering by researchers from Cornell and Stanford. It received 604 news stories and 58 blog mentions, alongside an Altmetric Attention Score of A4272—the highest in the dataset.


Mentioned by

🟥 **383** news outlets
🟧 **31** blogs
🟪 **17** policy sources
🟦 **1558** X users
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🟦 **4** Facebook pages
🟦 **7** Redditors
🟩 **1** YouTube creator
🟦 **5** Bluesky users

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🟦 **652** Dimensions

Readers on

🟥 **1530** Mendeley

This paper did not just present technical findings; it sparked widespread media debate about whether blue hydrogen is a climate solution or a climate risk. Another strong example is a 2023 paper in Nature ("Structural basis for bacterial energy extraction"), which was covered in 202 news articles and discussed in 18 blogs. While more microbiological in focus, its implications for bioenergy positioned it within broader sustainability discussions. Public curiosity also extended to geo scientific discoveries. A 2018 article in the International Journal of Hydrogen Energy reporting the discovery of natural hydrogen accumulations drew 121 news mentions, showing how scientific breakthroughs can ignite interest in new energy frontiers. Similarly, studies like "On the climate impacts of blue hydrogen production" (2022, Sustainable Energy & Fuels) gained 77 news mentions, reinforcing the public appetite for research that challenges or refines energy transition narratives.

These patterns demonstrate that public attention clusters around two poles:

- Controversial debates (e.g., the climate credibility of blue hydrogen).
- Breakthrough discoveries (e.g., natural hydrogen reserves, production innovations).

In both cases, news media and blogs act as bridges, translating complex scientific findings into public-facing narratives that influence how society perceives hydrogen's promise and pitfalls.

Social Media Visibility

Hydrogen research also sparks dynamic conversations across digital platforms, where debates and discoveries are amplified in real time. Unsurprisingly, "How green is blue hydrogen?" again leads, with over 2,145 mentions on X (Twitter), alongside seven Reddit discussions and activity on newer platforms such as Bluesky (5 mentions). The controversy around blue hydrogen's climate footprint made it a flashpoint online, mobilizing climate activists, energy professionals, and journalists into heated threads and reposts.

A 2024 article in the International Journal of Hydrogen Energy ("Origin of the distinct site occupations of H atoms in metal hydrides") generated 1,556 mentions on X and an impressive 328 Bluesky mentions, showing how technical, materials-focused work can resonate in fast-growing scientific communities online. Similarly, the 2023 Nature paper ("Structural basis for bacterial energy extraction") drew 1,785 X mentions and active Reddit engagement, demonstrating the reach of bioenergy-related discoveries across both scientific and public-facing spaces.

Infrastructure-focused studies also found traction. For instance, "A review of challenges with using the natural gas grid for hydrogen" (2024, Energy Science & Engineering) accumulated nearly 500 total social media mentions, as experts and policymakers debated practical pathways to scale hydrogen within existing energy systems. A Joule article from the same year (Green hydrogen pathways, energy efficiencies, and deployment challenges) attracted 421 X mentions and 10 Bluesky mentions, indicating a growing appetite for policy-relevant, systems-level discussions in the online energy community.

What emerges from these patterns is a layered picture:

- X (Twitter) remains the dominant arena for rapid-fire debate and dissemination.
- Reddit offers spaces for in-depth technical explanations and community-driven exploration.
- Bluesky is quickly emerging as a hub for early adopters and scientific dialogue, especially on cutting-edge hydrogen topics.

Together, these platforms illustrate how hydrogen energy research circulates in the digital commons, influencing not just scientists but also investors, activists, and the broader public.

Academic engagement

While public and social media attention shine light on controversy and discovery, academic engagement reveals how deeply hydrogen research is embedded within scholarly ecosystems. Altmetric captures this through Mendeley readers, Dimensions citations, peer review mentions, syllabi mentions, and F1000 endorsements.The data highlights a set of influential review and technical articles that have become intellectual anchors for the field:

A 2019 article in Materials Science for Energy Technologies on PEM water electrolysis attracted over 5,000 Mendeley readers and 1,860 citations, showing how methodological rigor and practical relevance cement a paper's scholarly footprint.

A 2017 review in Renewable & Sustainable Energy Reviews on hydrogen production pathways reached 5,012 Mendeley readers and 2,611 citations, positioning it as a go-to reference in both teaching and research.

A 2019 paper in Energy & Environmental Science on the role of hydrogen and fuel cells accumulated 3,971 Mendeley readers and 3,166 citations, underlining the centrality of policy and systems-level perspectives in academic discussions. Interestingly, while these papers dominate in readership and citations, peer review and syllabi mentions remain rare, suggesting that hydrogen scholarship—though widely read—has yet to fully permeate teaching curricula or formal post-publication evaluations. This points to a lag between research breakthroughs and their integration into classroom and pedagogical practice.

Taken together, these patterns suggest that hydrogen energy research is not only fueling debates in public and social spaces but also shaping the intellectual architecture of energy studies. The high readership counts show how early-career researchers and graduate students are engaging with hydrogen as a cornerstone of future energy systems. Meanwhile, citation counts confirm that these works are actively informing the next wave of research, policy modeling, and technological development.

Societal and policy influence

Perhaps the most powerful evidence of research impact is when studies leave the academic sphere entirely and enter the world of governance and industry (Adie & Roe, 2013). Hydrogen energy research increasingly appears in policy documents, from national hydrogen strategies in Europe to climate adaptation plans in Asia. For example, reports analyzing hydrogen's role in decarbonizing heavy industries have been cited in parliamentary briefings and international energy roadmaps, bridging the gap between lab findings and national agendas. Hydrogen related research received nearly 2122 policy mentions all around the world. The article "How green is Blue Hydrogen" was mentioned in 35 different policy documents few are, Mobilising the future, by the publication Office of the European Union, 2025, A Practical Guide to 1.5OC Scenarios for Financial Users by the United Nations Environment Program Financial Initiative, 2025, Why batteries trump hydrogen for buses by The Australia Institute, 2024 which is one of the country's most influential public policy think tanks.

Patents referencing hydrogen research also underscore its industrial relevance. Innovations in storage materials or electrolysis efficiency often draw directly on academic work, accelerating the path from theory to commercialization. Altmetrics illuminate these connections by showing how ideas migrate into the infrastructures and laws that will define our energy future. The article titled "Radiation characteristics of Chlamydomonas reinhardtii CC125 and its truncated chlorophyll antenna transformants tla1, tlaX and tla1-CW+" received 72 patent citation, which is the highest number of patent citation received among the hydrogen related articles.

Conclusion

Altmetrics reveal that hydrogen energy research is no longer confined to academic circles but actively shapes public debates, online conversations, and policy agendas. From sparking controversies about blue hydrogen to inspiring breakthroughs in storage and production, hydrogen studies are influencing how societies imagine a clean energy future. The interplay between public attention, scholarly engagement, and policy uptake highlights the multidimensional impact of this field. Ultimately, hydrogen research exemplifies how science can move from labs to headlines, accelerating both knowledge creation and real-world energy transitions.

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