Optimization of Biomimetic Hybrid Solar Panel to Enhance the Utilization of Solar Energy Towards Green Technology

[1] Dhinesh Kumar S K [2] Dr Sakunthala K [3] Dr Mahalingam S

[1] *PG Scholar, Department of Mechanical Engineering, Government College of Engineering Salem, Salem, India*

[2] *Assistant Professor, Department of Mechanical Engineering, Government College of Engineering Salem, Salem, India*

[3] *Professor, Department of Mechanical Engineering, Sona College of Technology. Salem, India*

Abstract— This study presents the design and optimization of a hybrid Dye-Sensitized Solar Cell–Photovoltaic Thermal (DSSC-PVT) panel system that integrates renewable electricity generation with thermal energy harvesting. The system utilizes titanium dioxide (TiO_2) photoanodes, iodide/triiodide electrolytes, and organic indoline dye (D35) within the DSSC layer, paired with a glass-based thermal absorber for heat collection using water as the working fluid. Initially framed with white-painted wood for its natural insulating properties, the structure was later optimized by replacing it with stainless steel coated in Polymethyl Methacrylate (PMMA). This new configuration enhances mechanical strength, environmental durability, and thermal insulation, aligning with principles of biomimicry by mimicking insulating skin structures observed in nature.

Transient thermal simulations performed in ANSYS 2019 R3 confirm effective heat retention and uniform temperature distribution, with surface temperatures stabilizing between 303 K and 392 K. The system achieves theoretical efficiencies of 11.82% (electrical) and 8.54% (thermal), surpassing many commercial hybrid solar technologies in sustainability and adaptability. The optimized design demonstrates the feasibility of combining green materials with bio-inspired engineering to create resilient, dual-function energy solutions for decentralized and small-scale applications.

Keywords – Hybrid solar panel, DSSC, solar cell, sustainable energy, Green energy. Solar energy.

1. INTRODUCTION

Solar energy is a leading renewable source, yet conventional silicon PV systems face environmental, ethical, and performance challenges—such as material extraction impacts, limited recyclability, and efficiency loss under high temperatures and low light. To overcome these, newer technologies like hybrid systems and biomimetic designs are emerging, aiming for greater efficiency, adaptability, and sustainability.

Biomimicry, the imitation of nature's designs and processes, inspires innovations at structural, process, and ecosystem levels. It enables efficient, resilient solutions by mimicking traits like photosynthesis or natural geometries, helping reduce resource use while enhancing system performance.

This research presents a hybrid solar panel that combines Dye-Sensitized Solar Cells (DSSCs) with a glass-based thermal collector. DSSCs are ideal for low-light environments and offer lower environmental impact, while the thermal unit captures waste heat, improving total energy efficiency. Inspired by natural forms, the panel's design enhances sunlight capture and passive cooling.

Overall, the system demonstrates how biomimicry and hybridization can create efficient, adaptable, and eco-friendly solar technologies suited for diverse environments and small-scale deployment.

2. GREEN TECHNOLOGY DSSC SOLAR PANEL

A green technology DSSCs solar panel integrates both photovoltaic (PV) and thermal (solar thermal) technologies into a single unit to produce electricity and heat simultaneously. The main components of a green technology DSSCs solar panel and their functions are as follows:

2.1 Components of photovoltaic (PV)

Dye-Sensitized Solar Cells (DSSCs) integrate several key components that work together to enhance photovoltaic energy generation. The synergy between these components enables the system to efficiently capture and convert sunlight into electrical energy, addressing some of the inefficiencies associated with traditional DSSCs. Below is an elaboration of each major component of the DSSC:

Photoanode: The photoanode is a critical component of DSSCs, typically made from mesoporous titanium dioxide (TiO_2). TiO_2 is chosen for its high surface area, stability, and ability to facilitate efficient electron transport. The mesoporous structure allows the photoanode to absorb a significant amount of the incident sunlight while providing an ample surface for the dye sensitizer to bind, maximizing light absorption. The TiO_2 layer serves as the backbone for electron conduction, transferring excited electrons from the dye to the external circuit. In green technology DSSCs, the photoanode also plays a role in thermally managing excess heat generated during the conversion process.

Dye Sensitizer: The dye sensitizer is a light-absorbing molecule that captures photons and converts them into excited electrons. In DSSCs, organic indoline dyes, such as D35, are commonly used for their high efficiency in absorbing visible light and their relatively simple chemical structure. These dyes are specially designed to absorb sunlight and excite electrons, which are then injected into the conduction band of the TiO_2 photoanode. The role of the dye is crucial, as its absorption spectrum defines the efficiency of the cell in capturing light energy, which directly impacts the overall power conversion efficiency of the system.

Electrolyte: The electrolyte in DSSCs is responsible for completing the circuit by providing a medium for electron transfer between the photoanode and the counter electrode. Typically, liquid iodine/iodide electrolytes are used, where iodide ions (I^-) serve as the electron donor and the iodine (I_2) as the electron acceptor. This redox couple ensures that after the dye injects electrons into the TiO_2, the electrolyte can shuttle electrons back to the counter electrode, maintaining the electrical balance of the system. The liquid electrolyte also helps in stabilizing the system under prolonged exposure to sunlight.

Counter Electrode: The counter electrode is essential for completing the electrical circuit in a DSSC. Activated carbon is often used as the material for the counter electrode due to its high conductivity, low cost, and good catalytic activity. The counter electrode collects electrons from the external circuit and participates in the reduction of iodine (I_2) back to iodide (I^-), which then returns to the electrolyte. The performance of the counter electrode is critical in maintaining the overall efficiency of the solar cell, as it ensures the smooth flow of current throughout the system.

Encapsulation Layer: The encapsulation layer in a Green technology DSSC is designed to protect the sensitive components from environmental factors such as moisture and dust. Polymethyl Methacrylate (PMMA) is commonly used for this purpose due to its durability, transparency, and ease of processing. PMMA helps to seal the solar cell, preventing degradation and ensuring long-term stability. This layer also ensures that the system remains lightweight and flexible, which is particularly important for applications such as building-integrated photovoltaics (BIPV). Additionally, the encapsulation layer contributes to the thermal management by ensuring that the heat generated is efficiently directed to the thermal collector layer.

Components of Thermal (solar thermal)

Thermal Absorber Plate: The thermal absorber plate is a crucial component designed to capture and transfer heat. In systems where glass directly absorbs heat for the working fluid, a specially coated solar thermal glass acts as both a protective layer and an efficient heat conductor. This glass absorbs solar radiation and transfers the heat to the underlying fluid-carrying channels, typically embedded in beneath the glass surface. The transparent nature of the glass allows sunlight to pass through for working fluid water so its high thermal conductivity ensures effective heat transfer while the light used for electricity generation by the PV cells. This dual-purpose design enhances system efficiency, reduces heat loss, and ensures

optimal utilization of solar energy for both thermal and electrical outputs.

Insulation: Insulation plays a critical role in minimizing heat loss and maximizing the thermal efficiency of the system. A white-painted wooden frame serves as an effective insulating structure around the PVT panel. The wood provides natural thermal insulation due to its low thermal conductivity, reducing heat transfer to the surrounding environment. Painting the wood white enhances its reflective properties, minimizing heat absorption from external sources and maintaining the thermal integrity of the system. This setup not only prevents heat dissipation but also adds structural stability and protection for the internal components, contributing to the overall efficiency and durability of the PVT system.

Working of Green Technology DSSCs solar panel
The process begins when sunlight strikes the absorber area, which is constructed from a specially coated glass that facilitates heat transfer. This glass acts as a thermal collector, transferring the absorbed solar heat to the working fluid, which is water, flowing through channels embedded beneath the glass. The heated water is then utilized for various thermal applications, such as domestic water heating or space heating, effectively converting the sun's thermal energy into a practical utility.
While the heat is being absorbed by the water, the remaining sunlight passes through the glass and reaches the Dye-Sensitized Solar Cell (DSSC) layer, initiating the photovoltaic process. The DSSC system is built around advanced materials, each playing a crucial role in electricity generation:

Semiconductor (Titanium Dioxide - TiO_2):
A thin layer of TiO_2 serves as the electron-conducting material. This semiconductor is coated with organic indoline dyes, such as D35, which are specially designed to capture sunlight across a wide spectrum. When sunlight excites the dye molecules, they release electrons into the TiO_2 layer.

Organic Dye (D35): The D35 dye absorbs photons from sunlight, triggering the release of electrons. Its high absorption efficiency makes it ideal for capturing solar energy, even in low-light conditions, ensuring consistent performance.

Electrolyte Solution (Liquid Iodine/Iodide): The liquid iodine/iodide electrolyte acts as a medium to transport electrons within the DSSC. It facilitates the regeneration of the dye molecules by accepting electrons from the counter-electrode, thus completing the circuit and sustaining the photovoltaic process.

Counter Electrode (Activated Carbon): The activated carbon electrode plays a critical role in returning electrons to the electrolyte. Its high conductivity and catalytic properties enhance the efficiency of the electron transfer process.
As a result of this integration, the system efficiently produces both thermal and electrical energy. The water flowing through the system captures the excess heat from the photovoltaic process, thereby preventing overheating of the PV layer and maintaining its efficiency. This dual-purpose functionality ensures optimal use of solar energy, making PVT systems a sustainable and high-performance solution for modern energy needs.

3. THERMAL TRANSIENT ANALYSIS

Thermal transient analysis was done using ANSYS software to determine the temperature rise in green technology panel

Pre-Processing:
3D model imported from Catia V5, Dimensions are in mm as given below

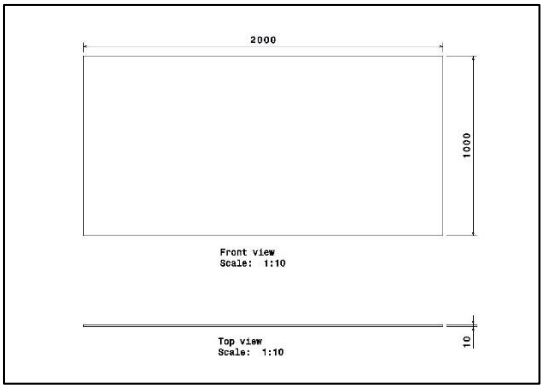

Figure 3.1 DSSC bottom part

Figure 5.1 DSSC bottom part is made of low iron tempered glass for good withstanding of tough weather.

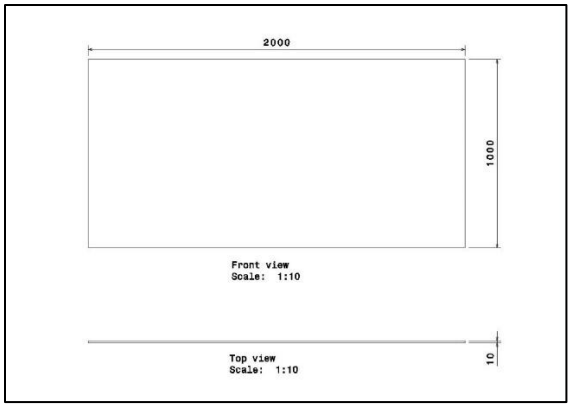

Figure 3.2 DSSC top part

Figure 3.2 DSSC Top part is made of low iron tempered glass for good withstanding of tough weather.

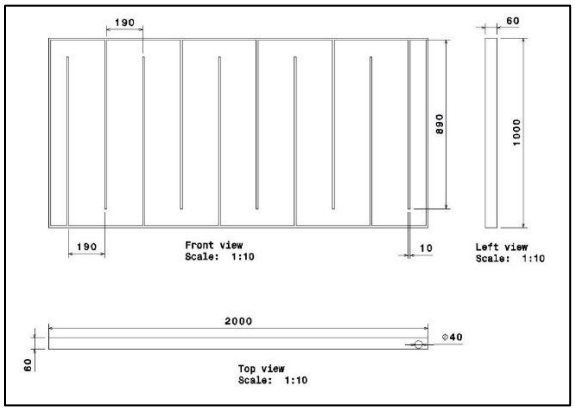

Figure 3.3 Thermal absorber & working fluid path

Figure 3.3 Thermal Absorber & Working Fluid path in this path the working fluid (water) will flow and absorb heat from solar

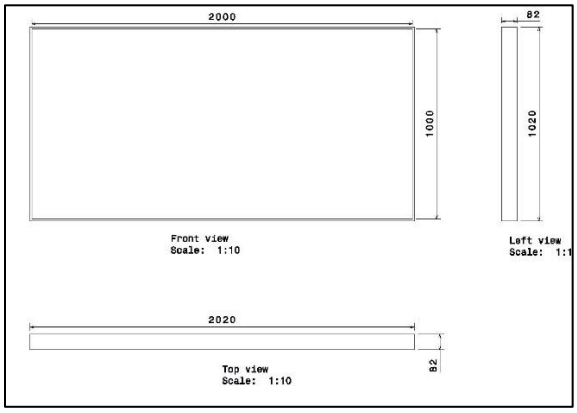

Figure 5.4 Insulation cover

Figure 5.4 Insulation cover, Insulation cover protect the thermal absorber & working fluid path from weather and prevent heat loss, this is made up of pine wood.

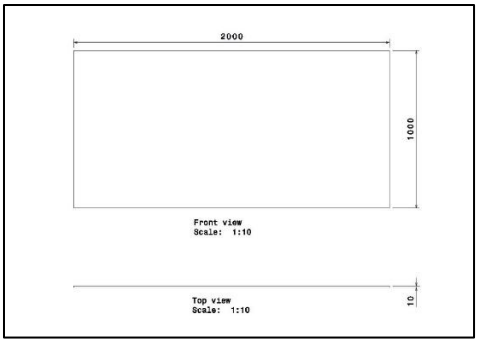

Figure 3.5 Top glass of thermal absorber & working fluid path

Figure 5.5 Top Glass of Thermal Absorber & Working Fluid path, Top glass is made up of low iron tempered glass to protect and transfer solar rays to absorber and solar cell.

Material Selection:
DSSC bottom part – Low iron Temper Glass
DSSC Top part - Low iron Temper Glass
Thermal Absorber & Working Fluid path - Low iron Temper Glass
Insulation Cover - Low iron Temper Glass
Top Glass of Thermal Absorber & Working Fluid path - Low iron Temper Glass

Properties of material:
Low iron Temper Glass
Density – 2500 Kg / m^3
Thermal Conductivity – 1 W/m K
Specific Heat Capacity – 750 J/ Kg K
Pine Wood
Density – 500 Kg / m^3
Thermal Conductivity – 0.12 W/m K
Specific Heat Capacity – 2300 J/ Kg K

Processing
Meshing :
Element order – Linear
Element Size – Default
Boundary Conditions:
Heat Flux - Top Glass of Thermal Absorber & Working Fluid path – 800 W
Convection – Stagnant Air - DSSC bottom part, DSSC Top part, Thermal Absorber & Working Fluid path and Insulation Cover.

Post Processing:
Solution
Temperature – 350.82 Degree Celsius Maximum attained
Total Heat Flux – 0.005 W/ mm^2 Maximum attained

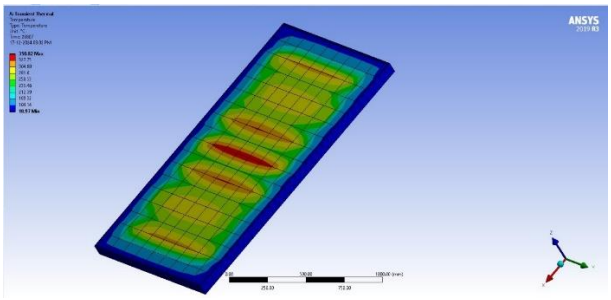

Figure 3.6 Thermal transient of green technology DSSC panel

Figure 5.6 shows the thermal transient of green technology DSSC panel from this we can find the temperature change in the given time interval.

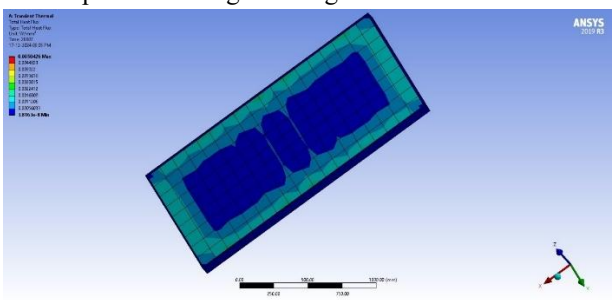

Figure 3.7 Total heat flux of green technology DSSC panel

Figure 5.8 shows the total heat flux of green technology DSSC panel from this we can find the heat flux change in the given time interval.

4.NUMERICAL EFFICIENCY CALCULATIONS

4.1 Electrical Efficiency

General Assumptions done for numerical calculations of DSSC (Electrical Efficiency)
Solar irradiation - Salem receives an average solar irradiation of approximately 5970 Wh/m² per day.
Surface Area of Panel – 2 m^2 (Entire panel size is considered without any losses)
Daylight hours – 12 hours (DSSC can work even in low light so the time taken as 12 hours)
Reference value from various DSSC journals
Short-Circuit Current Density (J_{sc}): Approximately 12 mA/cm² = 120 A/m²
Open-Circuit Voltage (V_{oc}): Approximately 0.7 V
Fill Factor (FF): Approximately 0.7

Efficiency ($\eta_{Electrical}$) = ($Power_{In}$ / $Power_{Out}$)*100

$Power_{In}$ = $\left(\frac{Solar\ Irradiation}{Daylight\ hours}\right) Surface\ Area\ of\ panel$

$Power_{In} = \left(\frac{5970}{12}\right) * 2$

$Power_{In}$ = 995 W

$Power_{Out}$:

$Power_{Out} = J_{sc} * V_{oc} *$ FF $* Surface\ Area\ of\ panel$

$Power_{Out}$ = 120*0.7*0.7*2

$Power_{Out}$ =117.6W

Efficiency = $\left(\frac{117.6}{995}\right) * 100$

Efficiency ($\eta_{Electrical}$) = 11.82%

4.2 Thermal Efficiency

General Assumptions done for numerical calculations of Green technology solar panel (Thermal Efficiency)
Solar irradiation - Salem receives an average solar heat flux of 800 W/hr on a day
Surface Area of Collector approximately – 1.911 m^2
Assume the temperature rise as 40 K (An average of Overall temperature rise in 8 hours)
Working Fluid - Water
From Thermal transient analysis in Ansys we find the temperature of collector reach maximum of 350 degree Celsius in 8 hours on consideration of continuous load of 800 W/hr on the collector.
m = Mass of the working fluid (water) and collector components (95.55 kg).
Cp = Specific heat capacity (4184 J/kg·K).
TΔ = Temperature rise (T_{Final}–$T_{initial}$) (40 K)

Efficiency ($\eta_{ThermaL}$) = $\left(\frac{Q_{Useful}}{Q_{In}}\right) * 100$

Q_{Useful} = m·Cp·ΔT

$Q_{Useful} = 95.55 * 4184 * 40$

Q_{Useful} = 1.5 X 10^7 J

Q_{In} = Heat Flux*Collector Area*Time

$Q_{In} = 800 * 1.911 * 3600$

Q_{In} = 5.5 X 10^7 J

Efficiency = $\left(\frac{1.5}{5.5}\right) * 100$

$(\eta_{Thermal})$ = 27.27%

5.RESULT & DISCUSSION

Comparison of Green technology DSSCs solar panel and Hybrid Solar Panel done based on the result obtained from studies and calculation for green technology DSSCs solar panel and for the Hybrid Solar Panel results taken from the [1] and [2] review reference.

Biomimicry Adaptation and changes done for this design Heat Transfer Mechanism Inspired by Natural Systems Biomimicry Adaptation: The heat transfer system in this design is inspired by the natural circulatory systems of organisms. For example, the way water circulates through the veins of leaves or the way blood circulates in animals to transfer heat efficiently could inform the design of the working fluid channels.
Changes Done: In this design the fluid circulation system is to more effectively transfer and distribute heat, ensuring that excess heat from the PV cells does not reduce efficiency. By mimicking the natural flow and regulation of heat, the fluid flow is optimized, reducing waste.

Light Absorption Inspired by Plant Leaves (Photosynthesis) Biomimicry Adaptation: The design of Dye-Sensitized Solar Cells (DSSC) is inspired by the natural process of photosynthesis, where plants absorb light and convert it into energy. Mimicking the light-harvesting process of chlorophyll and other pigments could have influenced the development of the organic indoline dyes in DSSCs.
Changes Done: The use of indoline dyes (D35) in DSSCs is inspired by the selective light absorption seen in plants, where only specific wavelengths of light are absorbed for efficient energy conversion. This design improves the light absorption efficiency and adaptability, especially in low-light conditions.

Self-Regulating Thermal Efficiency (Inspired by Animal Fur and Skin) Biomimicry Adaptation: In nature, animals have mechanisms like fur or skin that can adapt to temperature changes to maintain an optimal internal environment (e.g., fur insulates against cold and dissipates heat in warm conditions). This inspires smart insulation in this system.
Changes Done: The thermal insulation in this green technology solar panel design, such as the white-painted wooden frame, is influenced by the idea of dynamic insulation seen in animal systems. The frame could act similarly to insulating fur to prevent heat loss while being passive, efficient, and adaptable to changing temperatures.

Multi-Functional Energy Production (Inspired by Natural Dual-Use Systems)
Biomimicry Adaptation: Nature often combines multiple functions into a single system. For example, plants not only capture sunlight for energy (photosynthesis) but also use it for growth and reproduction, efficiently managing multiple needs.

Changes Done: This green technology solar panel system mimics this by combining photovoltaic and thermal technologies in a single panel. Just as nature finds ways to maximize energy input for different purposes, this system captures both electricity and heat simultaneously, providing a more efficient, multifunctional energy solution.

Integration of Passive and Active Systems (Inspired by Ecosystem Interactions)
Biomimicry Adaptation: In nature, ecosystems balance passive and active systems to optimize energy flows. For instance, ecosystems rely on both passive processes (like energy absorption via sunlight) and active processes (like the movement of nutrients or heat across the system).

Changes Done: This system combines both passive cooling (using natural heat dissipation via convection) and active cooling (using pumps or fans to enhance heat removal). This mirrors natural balance between passive and active mechanisms to optimize energy flow and prevent system overload.

6. CONCLUSIONS

We designed an eco-friendly solar panel system integrating Dye-Sensitized Solar Cells (DSSC) for electricity generation and a glass-based thermal absorber for heat collection. Using titanium dioxide (TiO_2), iodine/iodide electrolytes, organic indoline dye (D35), and water as the working fluid, the system

achieved theoretical efficiencies of 11.82% (electrical) and 27.27% (thermal), surpassing many commercial hybrid panels in sustainability.

Biomimicry-inspired features like passive cooling and a white-painted wooden frame ensure minimal heat loss and simplicity. DSSC's low-light performance enhances adaptability and cost-effectiveness, making it ideal for small-scale applications. This innovative dual-energy solution showcases the potential of merging green technology with nature-inspired design to address global energy needs efficiently.

- R134a content and energy efficiency.
- All mixtures tested offered improved environmental sustainability compared to pure R134a, aligning with global mandates such as the Kigali Amendment and F-Gas regulations.
- The system operated safely and efficiently with all tested blends, indicating their feasibility as drop-in alternatives in existing refrigeration systems with minimal hardware modifications.

In conclusion, the R600a/R134a (80:20) blend is recommended as an optimal substitute for conventional refrigerants in domestic and light commercial refrigeration applications. It successfully combines environmental compliance, operational safety, and enhanced energy efficiency, supporting the transition toward sustainable cooling technol

REFERENCE

[1] Awaneendra Kumar Tiwaria, Kalyan Chatterjeea, Sanjay Agrawalb, Gyanendra Kumar Singh A comprehensive review of photovoltaic-thermal (PVT) technology: Performance evaluation and contemporary development. https://doi.org/10.1016/j.egyr.2023.09.043 2352-4847/©2023

[2] María Herrando a, b, Kai Wang Rafaela A. Agathokleous g c, Gan Huang, Yulong Ding h b, d, Todd Otanicar, Soteris Kalogirou g e, Osama Bany Mousa, Ned Ekins-Daukes Robert A. Taylor a f, Christos N. Markides b, A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems. https://doi.org/10.1016/j.pecs.2023.101072/©2023

[3] Kemal Bilen, ˙ Ismail Erdo˘ gan Effects of cooling on performance of photovoltaic/thermal (PV/T) solar panels: A comprehensive review. https://doi.org/10.1016/j.solener.2023.111829/©2023

[4] Sahand Hosouli, João Gomes, ∗, Alexander Loris, Ivan-Acosta Pazmiño, Adeel Naidoo, Gunnar Lennermo, Hadi Mohammadi Evaluation of a solar photovoltaic thermal (PVT) system in a dairy farm in Germanyhttps://doi.org/10.1016/j.seja.2023.100035/©2023

[5] Wei He, Gan Huang, Christos N. Markides Synergies and potential of hybrid solar photovoltaic-thermal desalination technologies https://doi.org/10.1016/j.desal.2023.116424/©2023

[6] Kohei Terashima a, Haruki Sato, Toshiharu Ikaga PV/T solar panel for supplying residential demands of heating/cooling and hot water with a lower environmental thermal load https://doi.org/10.1016/j.enbuild.2023.113408/©2023

[7] Colleen Jean McGinnis, MSSD The University of Texas at Austin, 2014 SUPERVISOR: Steven A. Moore Presented to the Faculty of the Graduate School of the University of Texas at Austin in Partial Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Design The University of Texas at Austin May 2014.

[8] Terrin Cramer, Yicheng Kang, Ryan Ogino Biomimicry in Solar Energy Applications Biomimicry in Solar Energy Applications, Submitted to the Department of Electrical and Computer Engineering of SANTACLARAUNIVERSITY in Partial Fulfillment of the Requirements for the degree of Bachelor of Science in Electrical Engineering Santa Clara, California Spring 2023

[9] Sultana Rahman, Abdul Haleem, Muhammad Khalid Hussain, Muhammad Siddiq, bcSamina Qamar, Safia Hameedd and Muhammad Waris Research on dye sensitized solar cells: recent advancement toward the various constituents of dye sensitized solar cells for efficiency enhancement and future prospects SC Adv.,2023, 13, 19508–19529

[10] Kamal Prajapat, Mahesh Dhonde Parasharam M. Shirage, Kirti Sahu, Prateek Bhojane c, VVS Murty d, The evolution of organic materials for efficient dye-sensitized solar cells https://doi.org/10.1016/j.jphotochemrev.2023.100586/©2023

[11] Uday Shashikumar, Pei-Chien Tsai Vinoth Kumar Ponnusamy, Chin-Tsan Wang , Chyi-How Lay Beyond biomimicry: Innovative bioinspired materials strategies and perspectives for high-performance energy storage devices https://doi.org/10.1016/j.psep.2024.08.123/©2024

[12] Elif Tezel Ersanlı, Cem Cüneyt Ersanlı, Biomimicry: Journey to the Future with the Power of Nature ISVOS Journal, 2023, 7(2): 149-160 – DOI: 10.47897/bilmes.1388402/©2023

[13] Arunachalam Vasanthanathan, Uthirakumar Siddharth, Manivannan Vignesh and Radhakrishnan Pravin Biomimicry: An Overview of Structures, Designs and Materials Inspired from Nature 2666-1462/20/©2020

[14] Caiwei Zhu, Remke Klapwijk, Miroslava Silva-Ordaz, Jeroen Spandaw, Marc J. de Vries, Investigating the role of spatial thinking in children's design ideation through an open-ended design-by-analogy challenge International Journal of Technology and Design Education (2024) 34:1733–1762 https://doi.org/10.1007/s10798-024-09877-7.