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DSC-PEC Tandem H_2 Production System

Harvesting Indoor Light for Green H_2 Production

Presented By:
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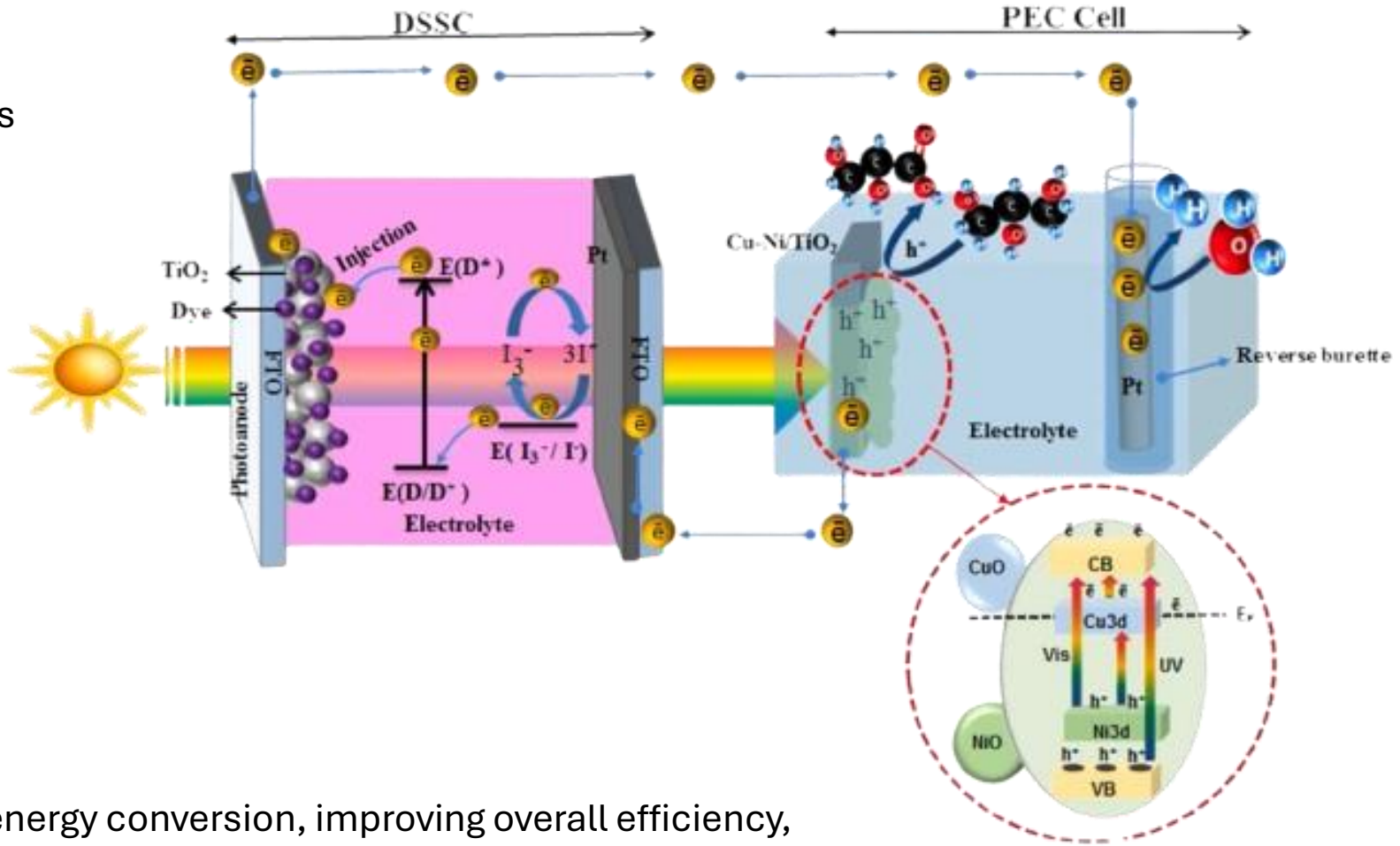
PEC-DSC Tandem Solar H_2 Production

What is it?

- The DSC-PEC (Dye Solar Cell - Photoelectrochemical) tandem system is a hybrid setup where a DSC is combined with a PEC cell, working together to produce hydrogen using solar energy.

How it works:

- **DSC** generates electricity by converting light into electrical energy using dye molecules.
- **PEC** uses that electricity to split water into hydrogen and oxygen, leveraging sunlight for both power generation and the electrochemical reaction.



Why a tandem system?

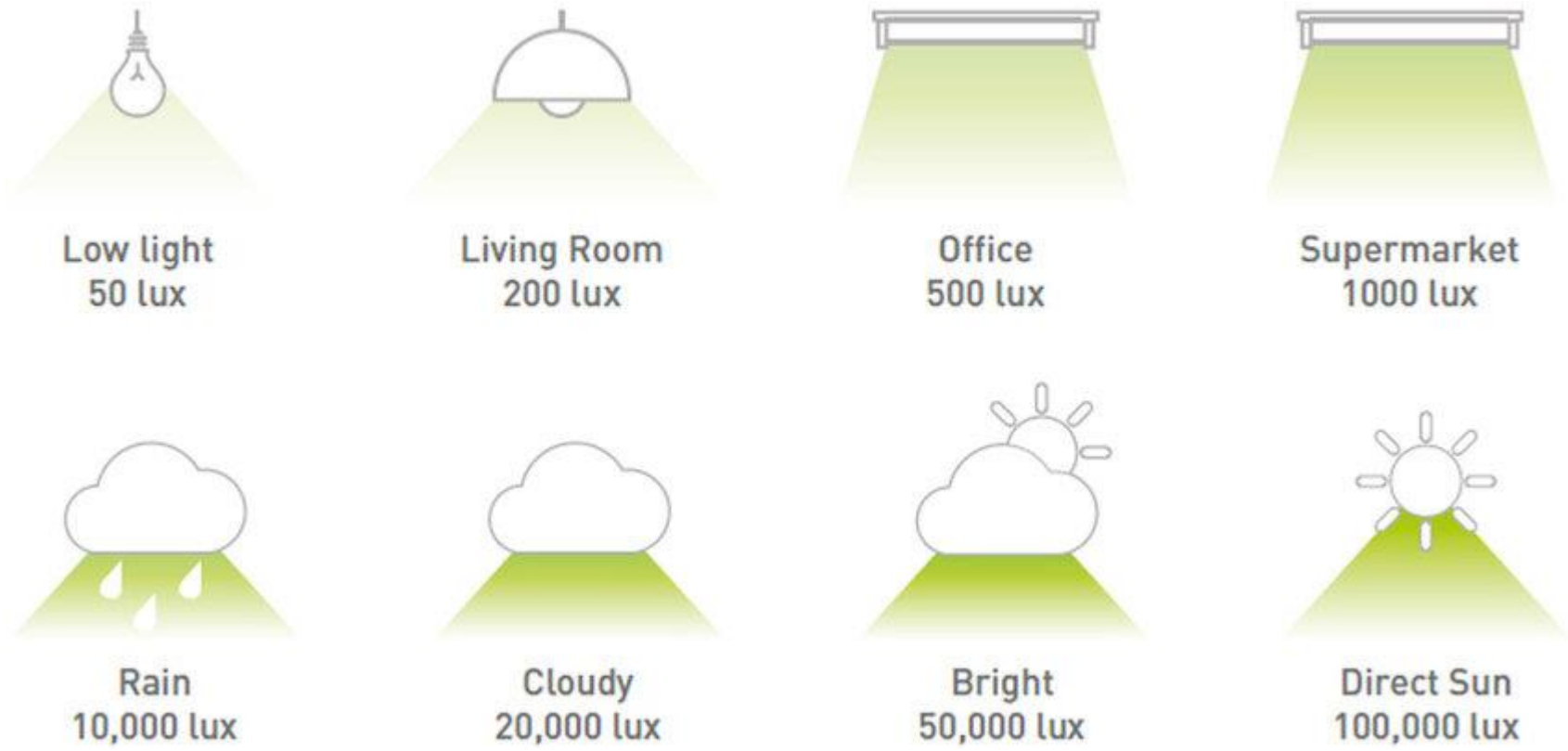
- Tandem systems combine two types of energy conversion, improving overall efficiency, especially in suboptimal light conditions like indoor environments.

Harvesting the Indoor Light

- **Indoor light is ubiquitous:**
  Natural and artificial indoor light sources are abundant but underutilized. By tapping into indoor light, you create an untapped market for hydrogen production systems that can be integrated into homes, offices, and commercial spaces.

- **Energy efficiency:**
  Utilizing indoor light can contribute to energy efficiency in smart buildings, making use of light that would otherwise be wasted.

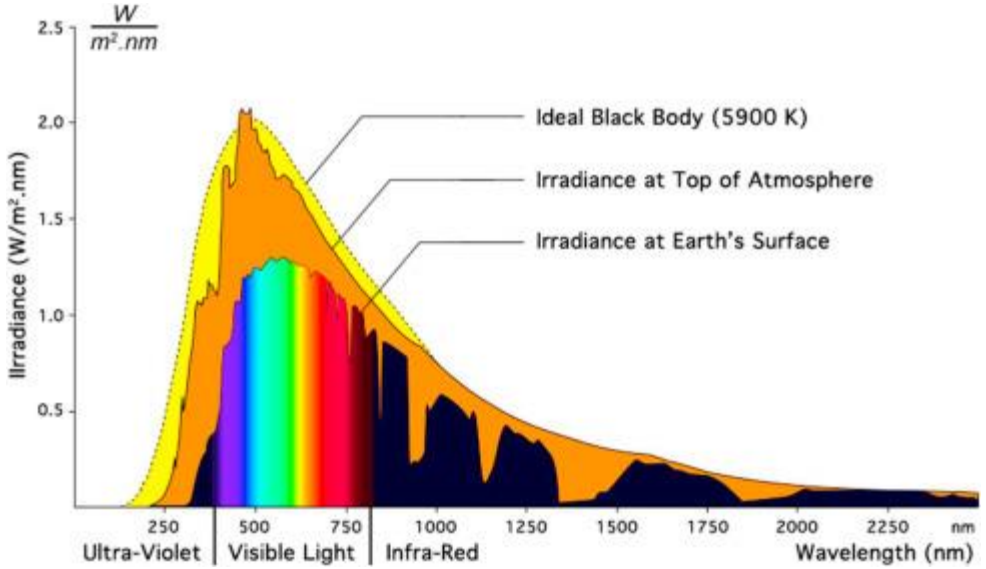
- **Low-intensity light efficiency:**
  Traditional PV cells underperform in diffuse, low-intensity indoor light. DSC and PEC can be tailored to these conditions, improving efficiency in real-world applications where natural sunlight is scarce.



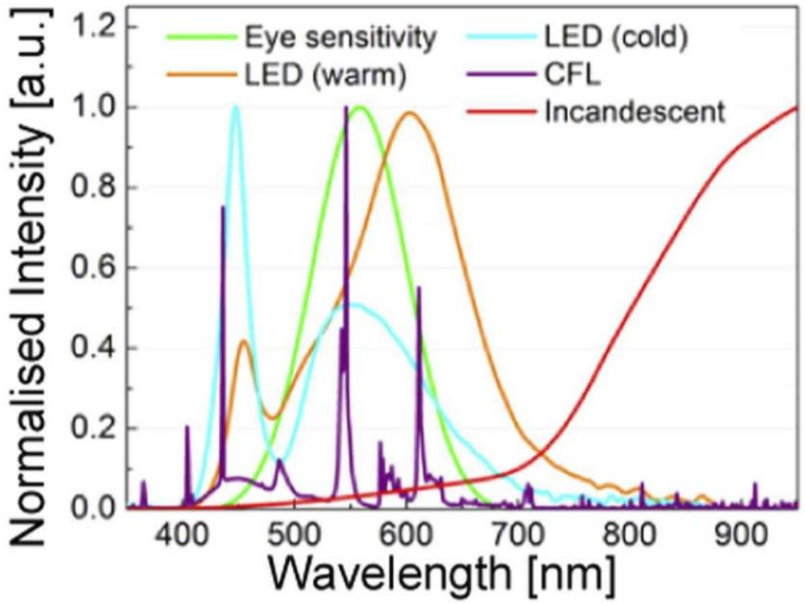
The Challenges: Photovoltaic

- **Efficiency under indoor light:**
  Most conventional PV cells (like silicon) are optimized for direct sunlight, not diffuse indoor light. Indoor lighting often lacks the full spectrum of sunlight, particularly in the UV and IR regions

- **Cost and scalability:**
  High-cost materials like silicon also make it difficult to create a cost-effective solution for smaller-scale indoor installations.



Spectrum of sunlight

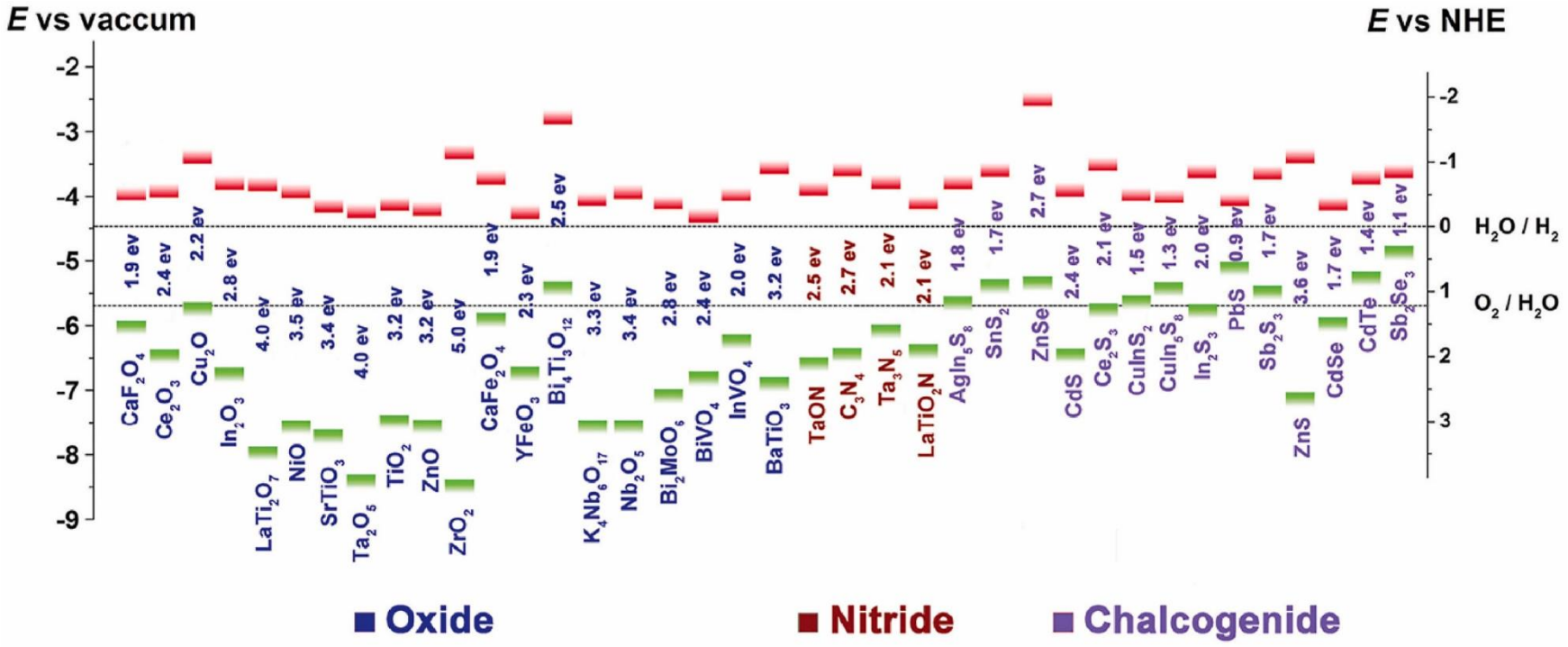


Characteristics of indoor lighting conditions. a) Normalized spectra of the CIE 1931 standard human eye response (green), and of warm white light-emitting diode (LED, orange), cool white LED (cyan), compact fluorescent light (CFL, violet) and incandescent (red) commercial lamps measured with an ILT950 spectroradiometer.

Elsevier, 2017, Pages 147-186, ISBN 9781785481499
https://doi.org/10.1016/B978-1-78548-149-9.50004-3

The Challenges: Photoanodes

- **Material stability and light absorption:**
  - Photoanodes need to be stable in water and have a wide absorption range, but many materials degrade under operational conditions or fail to perform well under weak indoor light.

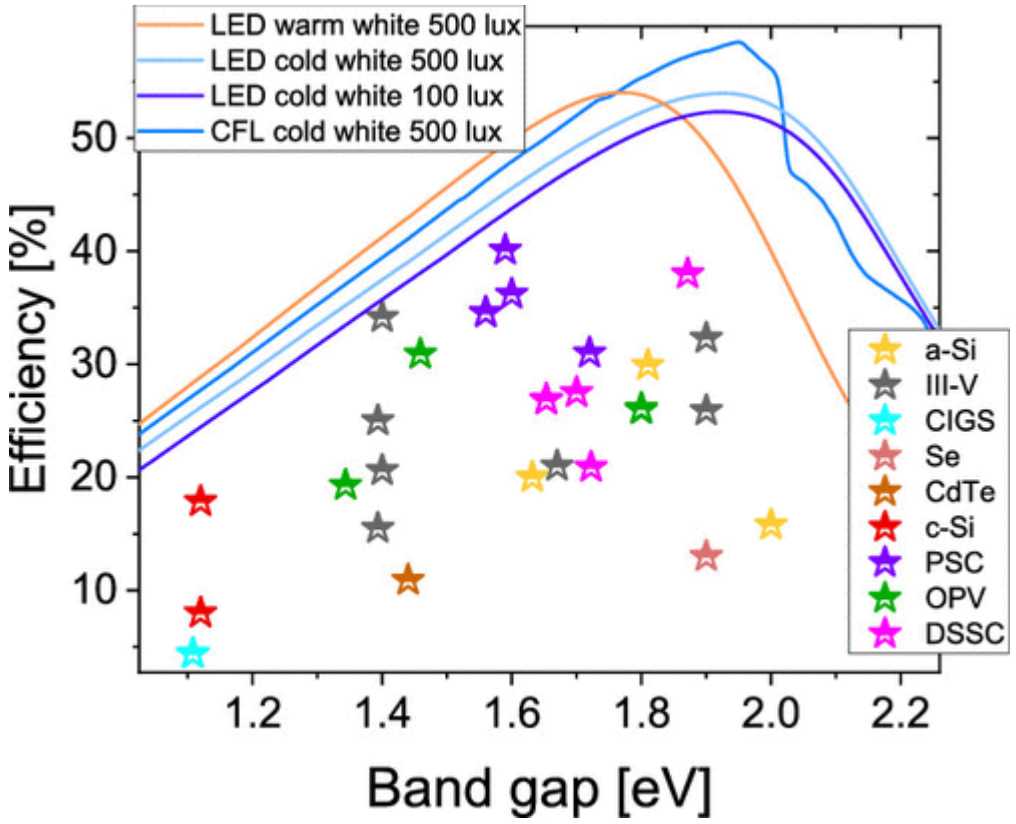


Bandgap and band edge positions of various semiconductors with respect to the vacuum level and normal hydrogen electrode (NHE)

Int. J. of Hydrogen Energy, 65, pp.779-803
https://doi.org/10.1016/j.ijhydene.2024.03.378

- Not only the bandgap energy should be in the range of **1.8–2.2 eV** (corresponds to wavelengths of approximately 560 to 700 nm), but the band edges should best fit the water redox potentials.
- No material met ideal bandgap and resistance to corrosion

DSC as Potential Indoor PV



Reported performance as a function of the band gap for several PV technologies measured under artificial indoor light between 50 and 3,000 lx

Materials	Efficiency (%)	Measurement conditions	Reference
a-Si:H	21%	1000 lux white LED	Renewable Energy, 36(2), pp. 642-647, 2011
DSSC: XY1b + Y123 dye	32%	1000 lux warm white, fluorescent tube	Joule, Volume 2, pp. 1108-1117, 2018
III-V: $Al_{0.2}Ga_{0.8}As$	21%	580 lux white LED	IEEE Transactions on Electron Devices, 62(7), pp. 2170-2175, 2015
III-V: GaAs	19%	580 lux white LED	IEEE Trans Electron Devices, 63(7), pp. 2820-2825, 2017
OPV: BTR	28%	1000 lux fluorescent lamp	Journal of Materials Chemistry A, 6(14), pp. 5618-5626, 2018
Perovskite: $CsPbI_2Br$	34%	200 lux indoor illumination	Advanced Functional Materials, 31(42), 2021

ACS Appl. Energy Mater. 2023, 6, 20, 10404−10414
https://doi.org/10.1021/acsaem.3c01274

DSC as Potential Indoor PV

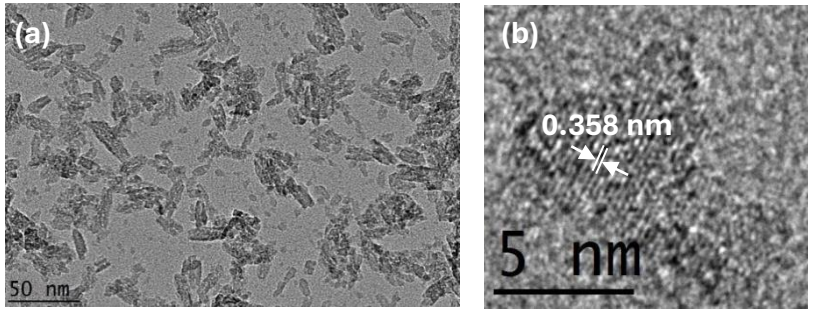


Fig. 1: TEM images of synthesized nanoparticles TiO_2 at magnification of (a) 88 kX, (b) 530 kX

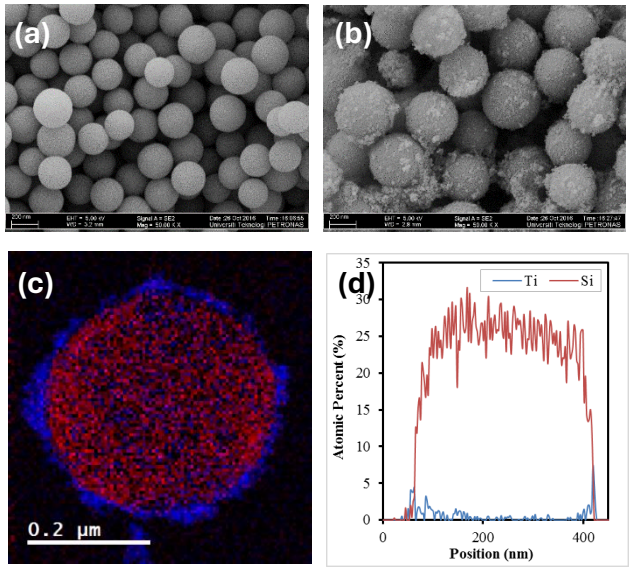


Fig. 2: The (a) and (b) FESEM images of synthesized SiO_2 sphere, and SiO_2 coated with TiO_2, (e) EELS dot mapping and (d) EDX line scan of single SiO_2-TiO_2 core shell sphere

Nanomaterials 12 (18), 3128
https://doi.org/10.3390/nano12183128

Optimizing Photoelectrode DSC

- Highest I_{sc} due to:
  - presence of large surface area (3X bigger than commercial)
  - Effective light scattering by the micron-size STCS thus extend travel distance of light [4, 45]
  - Multiple light refraction of the incidence light passing through the structure of different refractive index [46]
- High value of R_{br}/R_t
  - Ease the electron movement within photoelectrode network
  - Reduce rate of recombination (1/3 compared to Dyesol and 1/2 compared to commercial sample)
  - Leads to longer electron lifetime

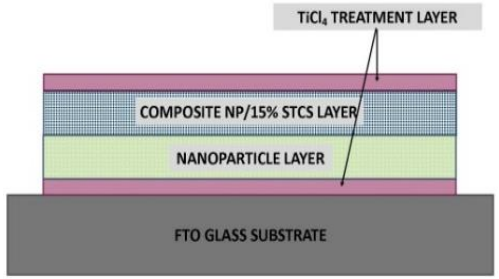


Fig. 3: Optimized configuration

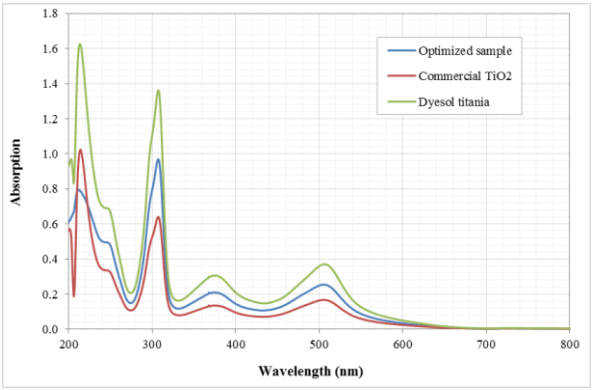


Fig. 4: UV-Vis of desorbed dye solution

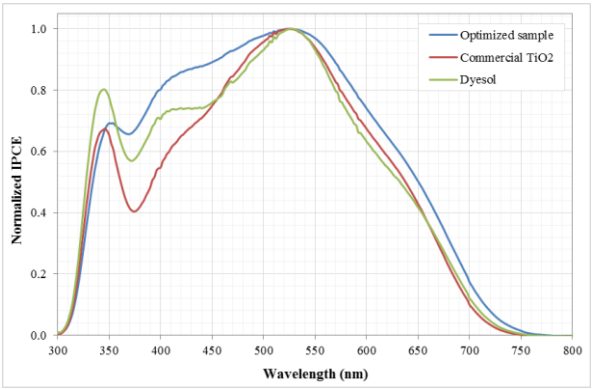


Fig. 5: IPCE analysis of fabricated DSC

Table 1: Electrochemical and photovoltaic properties of optimized, commercial and Dyesol sample

Sample	R_t (Ω)	R_{br} (Ω)	R_{br}/R_t	C_μ (F)	τ_n (s)	k (s^{-1})	D_n (cm^2s^{-1})	n_s (cm^{-3})	I_{sc} (mA)	V_{oc} (V)	FF	η (%)
Optimized sample	1.20	39.93	33.3	5.39×10^{-3}	0.215	4.650	1.55×10^{-6}	10.80×10^{17}	15.399	0.747	0.605	6.964
Commercial TiO_2	3.66	93.80	25.6	1.10×10^{-3}	0.103	9.718	2.49×10^{-6}	1.53×10^{17}	10.080	0.793	0.634	5.065
Dyesol paste	4.78	35.25	7.4	2.34×10^{-3}	0.082	12.133	0.89×10^{-6}	3.26×10^{17}	13.782	0.753	0.651	6.753

DSC as Potential Indoor PV

- DSC shows better performance under low light condition
- Development of glass-based 100 mm x 180 mm bifacial W-design DSC module exhibit average V_{max} of 3.7 V, more than enough V required for PEC water splitting
- Other related development:
  - Development of graphene-embedded solid polymer membrane electrolyte
  - Graphene-supported PANI as counter electrode

Table 2: Photovoltaic properties of DSC tested under different light intensity

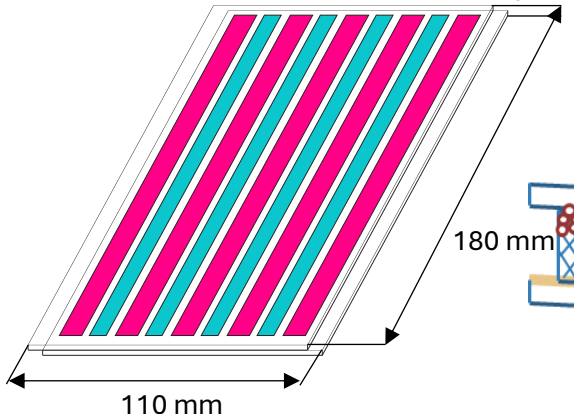
Light intensity (mW/cm²)	η (%)	FF (%)	V_{oc} (mV)	J_{sc} (mA/cm²)	V_{max} (mV)
0.8	4.3	65.7	580	0.09	480
33	0.78	58.6	628	0.7	460
100	0.63	42.9	597.8	2.47	340

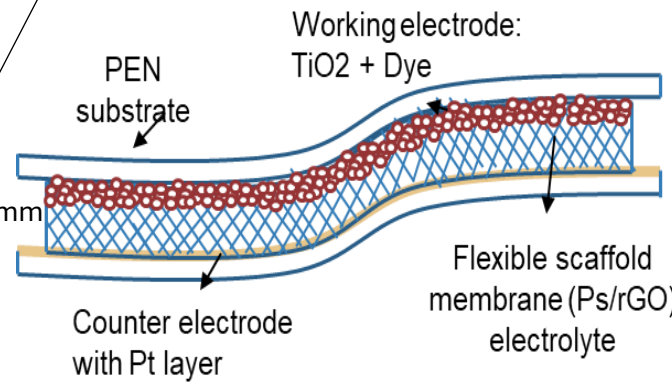
Table 3: Photovoltaic properties of bifacial W-design of 125 units Dye Solar Module

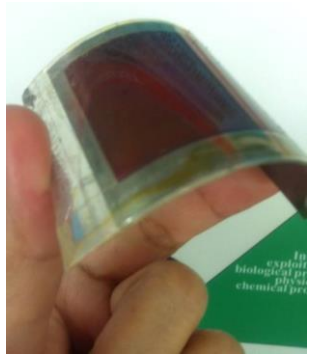
Parameter	Unit	Min Value	Max Value	Average Value
η	%	0.79	2.37	1.55
FF	%	28.6	56.7	44.6
V_{oc}	mV	4003.5	5790.5	5499
J_{sc}	mA/cm²	0.44	0.8	0.63
V_{max}	mV	2218.3	4536	3771
J_{max}	mA/cm²	0.26	0.59	0.42
I_{sc}	A	0.045958	0.083477	0.065160

DSC-based power generating window

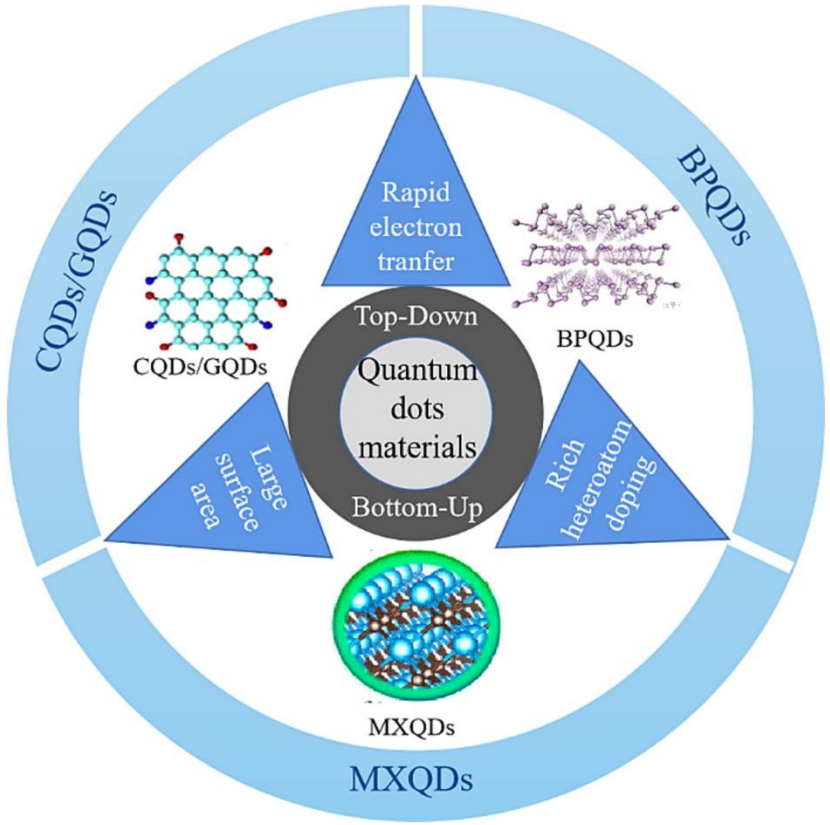
100 mm x 180 mm W-design bifacial DSC module







Quantum Dots as Potential Photoanodes



Multicolour luminescence of CQDs

- QD nanomaterials (2–10 nm in lateral size) show good electrocatalytic properties, such as C/GQDs (carbon and graphene quantum dots), BPQDs (black phosphorus quantum dots), MXQDs (MXenes quantum dots)
- Tunable absorption spectrum, large specific surface area, fast electron transfer rate, and abundant surface functional groups can improve the electrocatalytic performance of the composites
- Variety of synthesis methods also make the quantum dot-based electrocatalytic materials easily available

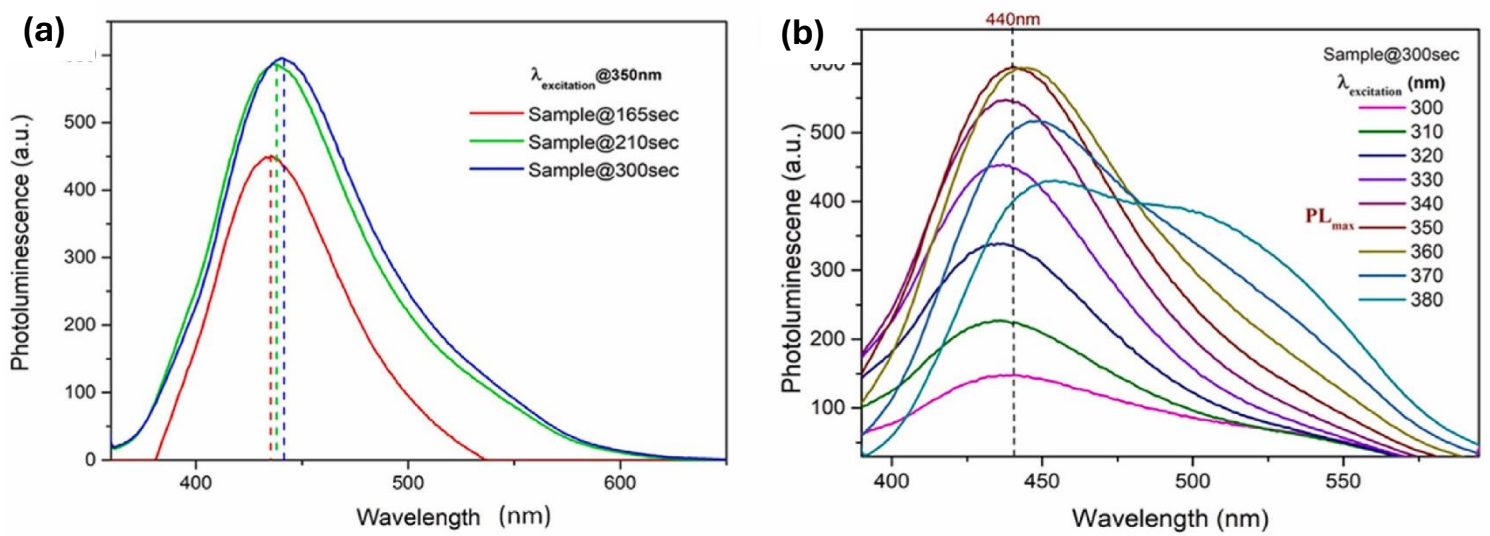


Fig. (a) PL emission spectra of samples 165, 210, and 300 s and (b) PL emission spectra of samples@300 s at different excitation wavelengths.

Mat. Sci. in Semiconductor Processing, 181, 2024, 108661
https://doi.org/10.1016/j.mssp.2024.108661

Quantum Dots as Potential Photoanodes

Development of GQD@TiO_2 (011) rutile Photoanode

- A green approach was undertaken to synthesize GQD through the hydrolysis of corn powder.
- Photoanodes synthesized via hydrothermal method exhibit vertically aligned TiO2 NRs with an average diameter of 141.7 and 233.4 nm for TiO_2 and GQD@TiO_2, respectively
- The UV–vis absorption the GQD had a prominent transition absorption peak near the 300 nm wavelength range, thus reduce the E_g and amplified absorption curve of GQD@TiO_2 (011) rutile.

Appl Surface Sci., vol. 576, Part B, 2022, 151871
https://doi.org/10.1016/j.apsusc.2021.151871

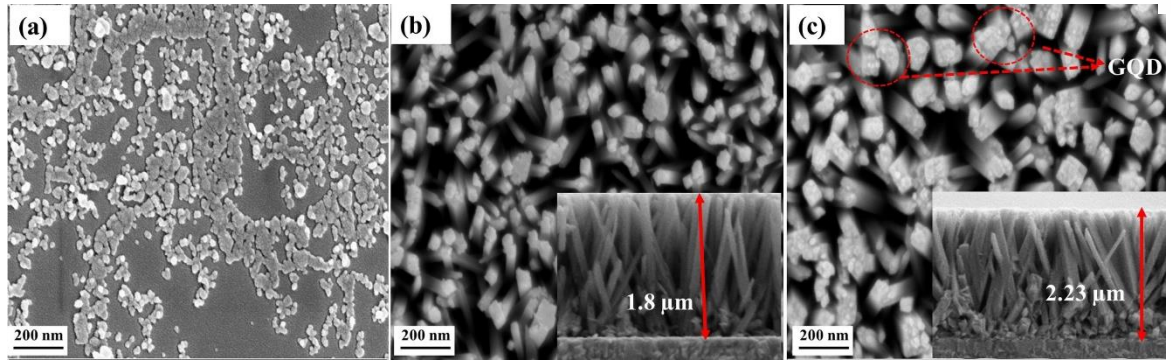


Fig. 6: FESEM image of (a) top-view GQDs on FTO substrate, (b and c) top-view and cross-sectional (inset) TiO_2, and GQD@TiO_2 composite, respectively.

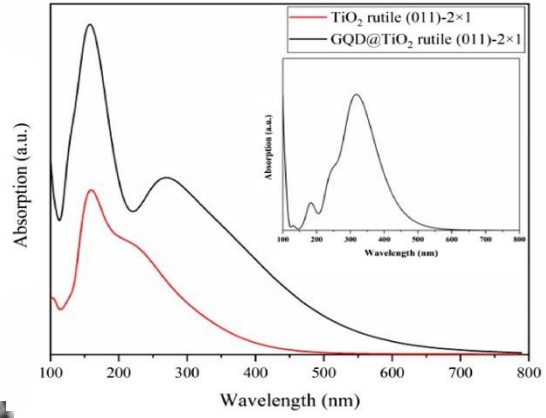
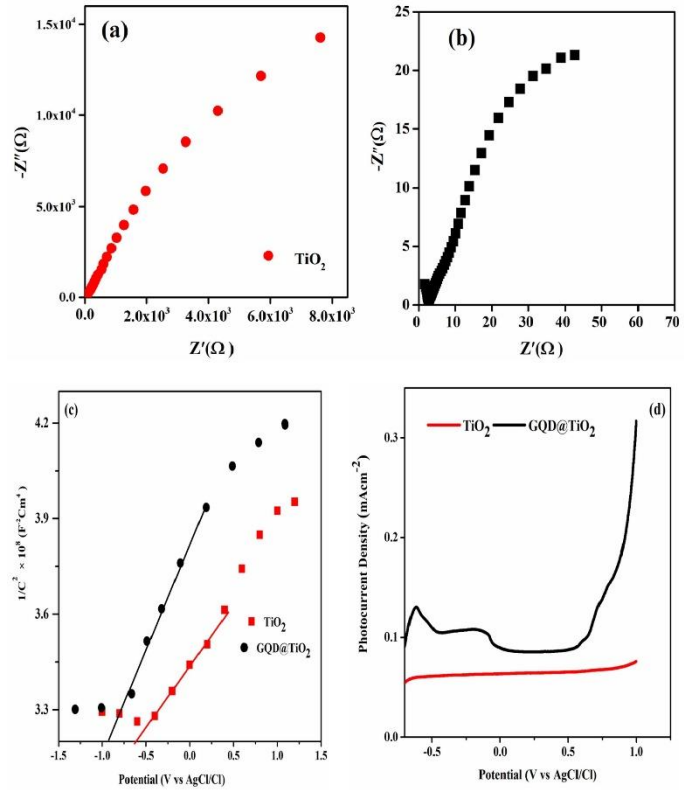


Fig. 7: The absorption display plot for the TiO_2 rutile (011) and GQD@TiO_2 rutile (011) (Inset represents UV–vis absorption for the GQD model).



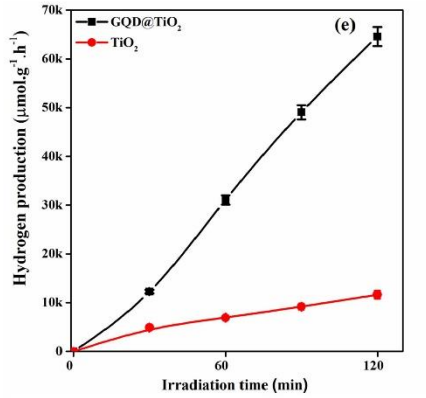


Fig. 8: (a) and (b) Nyquist, (c) Mott-Schottky, (d) photocurrent density, and (e) hydrogen production plots under visible light irradiation for TiO_2 and GQD@TiO_2 rutile.

Quantum Dots as Potential Photoanodes

- The hydrogen production rate over GQD@TiO_2 rutile (011) photoanode was 31063 µmol g^{-1} h^{-1}, nearly five times more efficient than the pristine TiO_2 rutile (011).

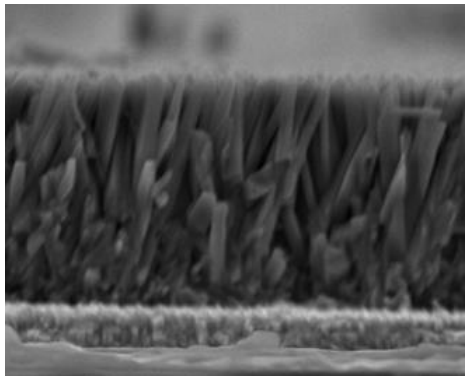
Table 4. Comparison of the photocatalytic hydrogen production results of GQD@TiO_2 (011) rutile with the other similar photocatalytic systems

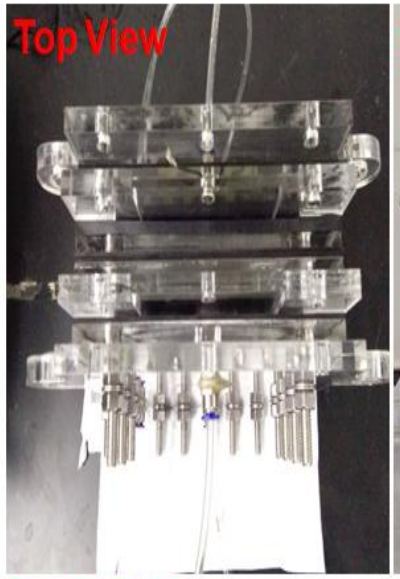
Photocatalysts	Experimental condition	Light source/Reaction system	hydrogen production (µmol/$h^{-1}g^{-1}$)	Reference
GQD@TiO_2	TiO_2 catalyst and a certain amount of GQDs were suspended in 20% (v/v) methanol solution	UV–Vis light/ batch	206.3	Superlattices Microstruct., 94 (2016), pp. 237-244
GQD@P-25(Commercial TiO_2)	a mixture of 5 vol% glycerol aqueous and	Direct sunlight/batch	29,548	Ind. Eng. Chem. Res., 59 (2020), pp. 13060-13068
GQD@TiO_2	The photocatalyst was dispersed in of 10% (v/v) ethanol solution	250 W high-pressure mercury lamp/ batch	8690	Appl. Surf. Sci., 396 (2017), pp. 1375-1382
GQD@TiO_2 (011) rutile	The fabricated thin film was immersed 5% in glycerol/KOH	500 W halogen lamp/PEC cell	31,063	This work

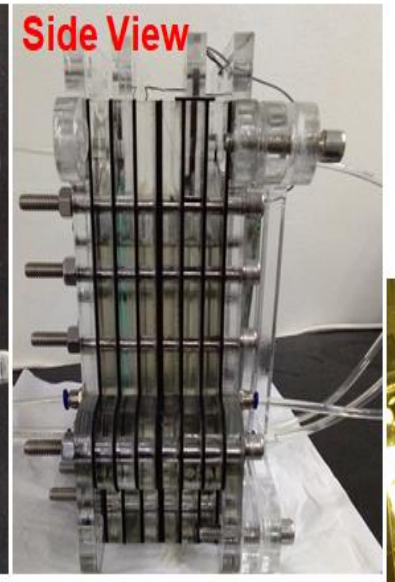
Appl Surface Sci., vol. 576, Part B, 2022, 151871
https://doi.org/10.1016/j.apsusc.2021.151871

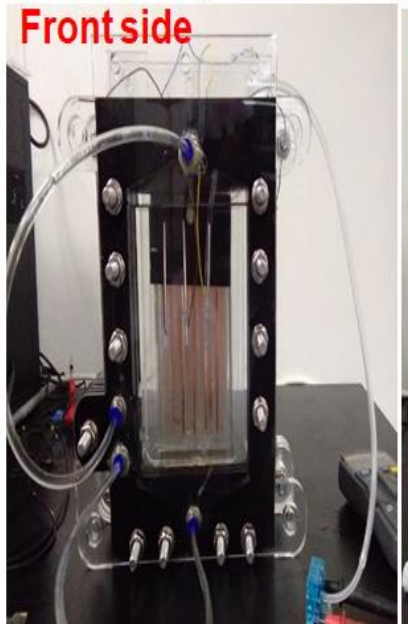
DSC-PEC Tandem Cell

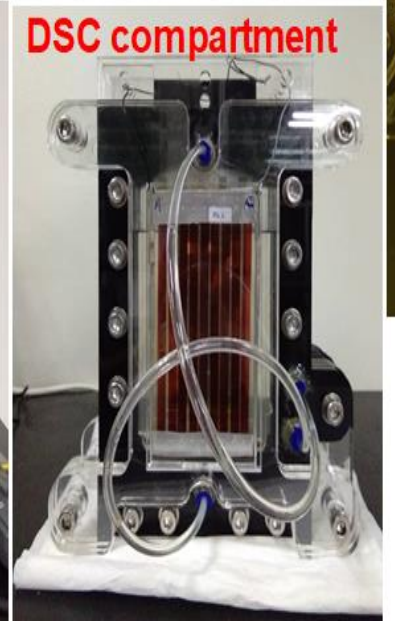
- Develop a new, highly efficient process of water splitting into hydrogen that combines a stable nanostructured bimetallic photocatalyst in Photo-Electrochemical Cell (PEC) with a highly efficient Dye Solar Cell (DSC), connected in series in a standalone solar panel.
- This developed standalone solar panel has potential for inexpensive large-scale production where the deployment can be double solar panels as glass walls of the building





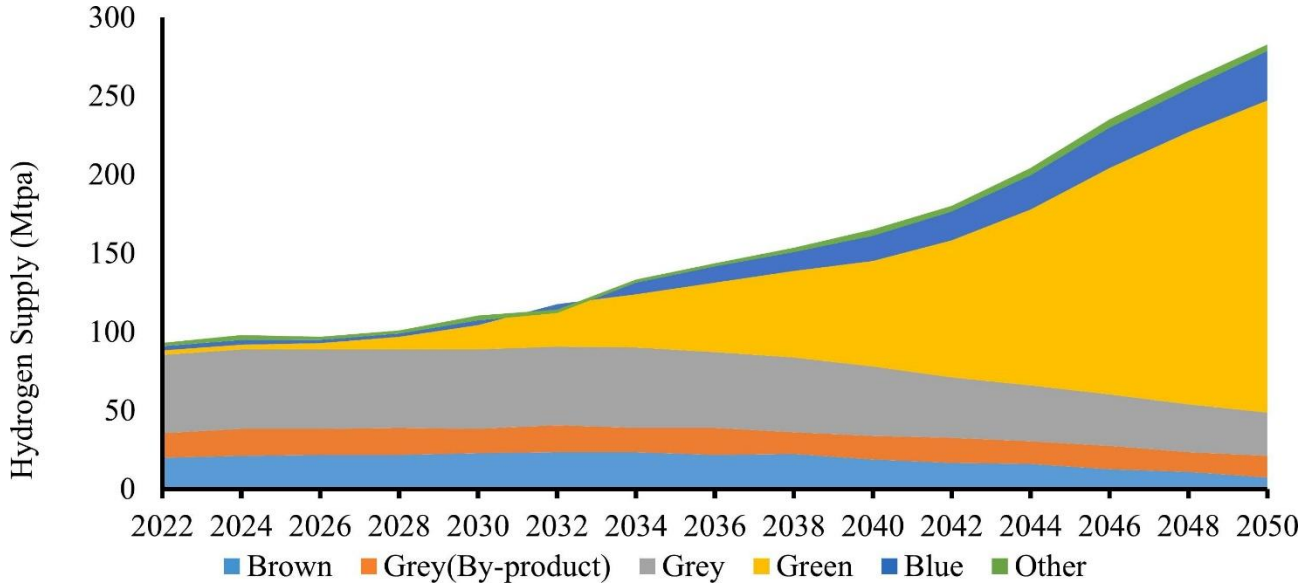






Potential Applications and Market Demand

- The green H_2 market was valued at USD 1.1 billion in 2023 and is projected to reach USD 30.6 billion by 2030, growing at 61.1% CAGR from 2023 to 2024.
- The green H_2 market is experiencing rapid growth, driven by global effort to reduce carbon emissions and advancements in electrolysis and renewables.
- The demand for decentralized, renewable energy solutions is growing.
- With the increasing shift towards green hydrogen, the DSC-PEC tandem system could address both residential and industrial needs, opening a multi-billion-dollar market in the near future.
- Indoor H_2 production systems could be seamlessly integrated into building architecture, such as windows or walls, producing clean hydrogen for energy use or storage.
- **Challenges:** Cost reduction and efficiency improvement are key challenges that need to be addressed to make green H_2 economically competitive with conventional H_2 production methods



The forecasted global H_2 production by color from 2022 to 2050. Information adapted from

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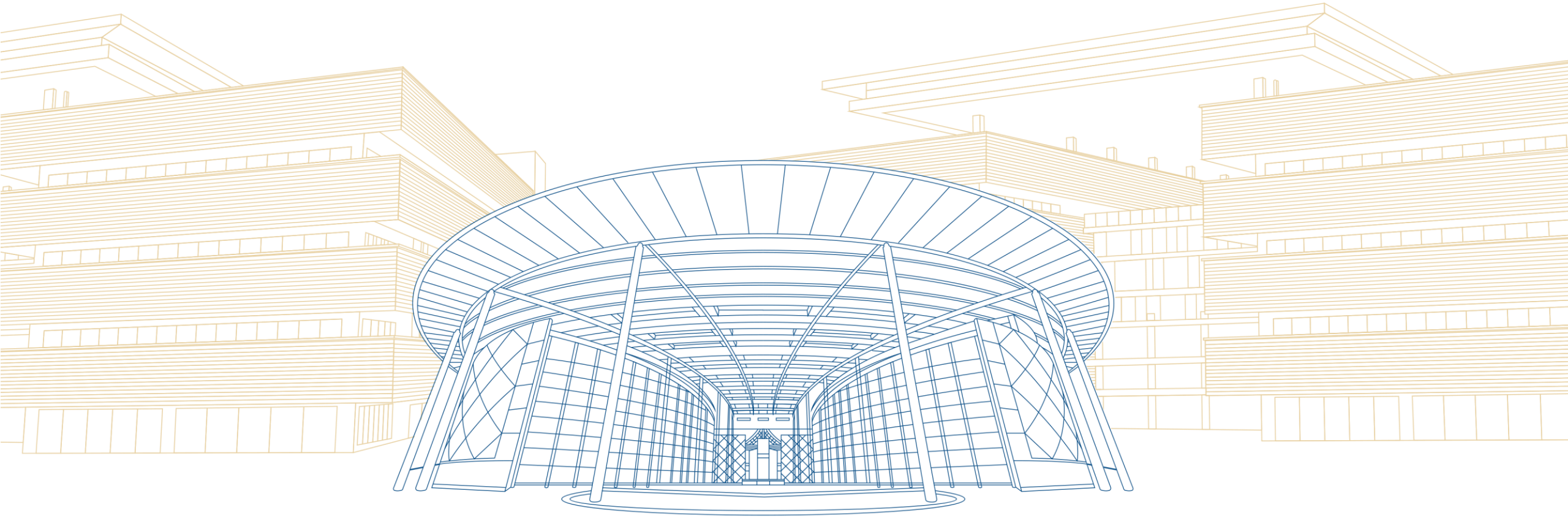

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