RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

ESSAY

View Article Online
View Journal | View Issue

Check for updates

Cite this: *RSC Sustainability*, 2024, **2**, 3571

Atoms and photons: how chemical sciences can catalyze the development of sustainable solutions powered by light

Govind Nanda*

DOI: 10.1039/d4su90048k

rsc.li/rscsus

Chemical sciences have paved the way for the most ground-breaking scientific discoveries in the world, which in turn have led to mammoth anthropogenic impacts. From understanding the molecular chemistry behind the Haber process to synthesize ammonia, to the large-scale adoption and production of ammonia-based fertilizers, chemical science has found a way to translate nanoscale reactions into some of the most innovative processes critical for a growing and flourishing population. With a scientific field having such transformative potential, it is important to ensure its development is aligned with principles of sustainability to ensure a greener and cleaner environment. One of the most key elements of the planet's environment is light, as it serves as the primary source of energy for most processes that are critical for the existence of life on the planet. In fact, even the upper limit of the highest attainable speed in the universe is limited by how fast light can travel! Concepts sprouting out of chemical sciences can pave the way for creating powerful tools which can allow for direct utilization of light for both producing clean energy and decarbonizing the current energy economy.

However, even with the most modern methods of manipulating light, use of novel photonic techniques towards decarbonizing the production of energy and increasing energy efficiency remains untapped. Many novel ideas can enable us to explore its untapped potential, but there are intricate scientific issues that come in the way of their execution. These technical challenges can be successfully addressed by viewing them from the lens of chemistry. Moreover, combining the knowledge of photonics and chemical sciences can also lead to instrumental changes towards the large-scale deployment of these technologies and can lead to enormous reductions in greenhouse gas emissions globally.

Garnering sunlight for generating electricity using solar cells has been one of the most effective strategies in decarbonizing the production of energy, with the world recently exceeding 1 TW in solar power capacity.[1] 97% of the current market for solar cells is dominated by silicon as a base layer,[2] as it can absorb the visible and near infra-red wavelengths of sunlight effectively. However, as shown in Fig. 1a, it falls short in

Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada. E-mail: g.nanda@mail.utoronto.ca

Govind Nanda

Govind Nanda is a research professional specializing in the fields of photovoltaics, thin film coatings and semiconductor physics. He received his undergraduate degree in Engineering Physics from IIT Delhi, followed by an M.A.Sc in photonics from the electrical and computer engineering department at the University of Toronto. Currently, Govind works at 3E Nano (dba NxLite) – a spinoff from the University of Toronto pioneering innovative technology and integrations to transform windows into high performance transparent façade elements. Passionate about sustainability, his vision is to use his technical expertise in developing green technologies, while making them more economically viable to adapt.

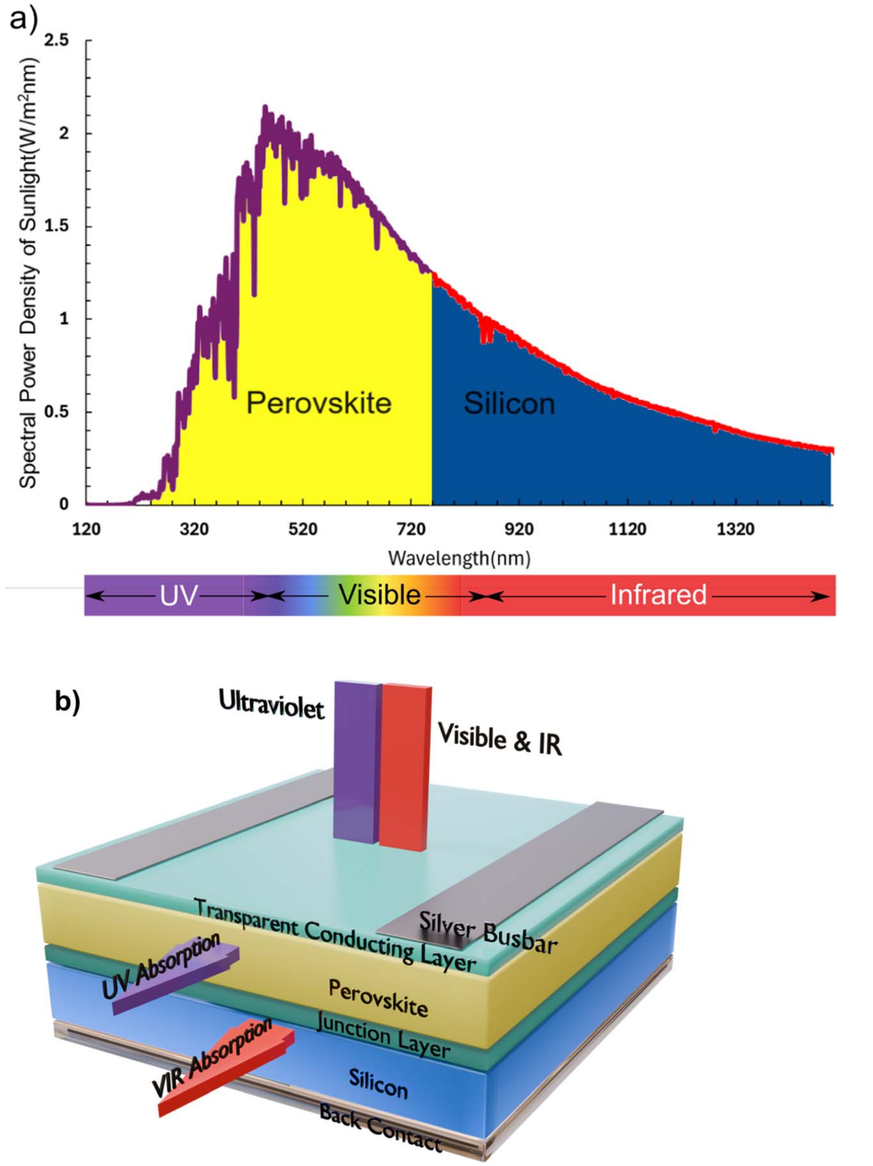

Fig. 1 Concepts that allow tandem solar cells to capture the full power of sunlight. (a) The graph illustrates how perovskites and silicon absorb UV and visible wavelengths of light respectively. (b) The diagram shows the microscopic structure of a perovskite–silicon based tandem solar cell.

absorbing sunlight in the visible and UV range, which theoretically limits silicon solar cells to a highest achievable efficiency of 30%.[3] Unlocking the capability of harvesting the full spectrum of sunlight can plummet the prices of solar energy and help in making significant progress towards achieving the world's renewable energy generation goals. Traditionally, solar cells are known to have only one absorber layer, but more recently, tandem solar cells, as described in Fig. 1b, are being introduced which use multiple absorber layers to capture the full spectrum of solar radiation.[4] Interfacial engineering,[5] which is rooted in the chemical sciences, will play a critical role in making efficient charge transport layers which can help in effective compounding of the voltages achieved by both the bottom sub cell (*i.e.* silicon) and the top sub cell (*i.e.* perovskite).

As high efficiencies enable solar energy to move from gigawatt to terawatt scale adoption, a bottleneck that emerges in production of these devices are the critical elements in use which are integral to solar cell design for minimal electrical losses. It is predicted that with the current solar cell designs, adding a global production of 380 GW per year would require using up to 20% of the yearly global silver supply![6,7] Calculations also suggest that to reach the global energy demand of 3 TW, the silver consumption per watt of energy produced needs to be reduced from the current range of 15–25 mg W^{-1} to 5 mg W^{-1}.[7] Efforts can be made in the direction of either reducing the silver consumption or developing alternative solutions using metals like copper and aluminum to reduce the pressure of silver demand and make solar energy more sustainable from a critical materials perspective. Moreover, an overlooked perspective on solar energy is the challenge of recycling the materials out of end-of-life solar cells. It has been forecasted that the solar photovoltaic waste produced in the state of New South Wales, Australia would range from 3–10 kilotons in 2025, and will rise exponentially to about 34–63 kilotons in 2035.[8] Therefore, along with achieving high efficiencies, it is becoming increasingly more important to address the critical material shortages and recycling issues.

While it is critical to decarbonize the production of energy, it is equally as important to reduce emissions produced by the existing infrastructure. According to the IEA, operations of buildings account for 26% of global energy-related emissions, out of which 18% are emissions as a result of the electricity and heating requirements.[9] The weakest links in the building envelope in terms of thermal insulation are windows. Windows are a great source of natural light and reduce reliance on artificial lighting, however, they also make the indoors warm up and cool down much faster which in turn increases cooling and heating costs, respectively.

The concept of low emissivity (low-ε) solar control coated windows has gained a lot of traction as a solution to reduce the energy consumption of buildings. This innovation uses a nano-thin layer of a metal, which is highly transparent owing to its incredibly low thickness. The metallic layer, being highly reflective to the infra-red wavelengths, blocks the heat and lets visible light pass through as

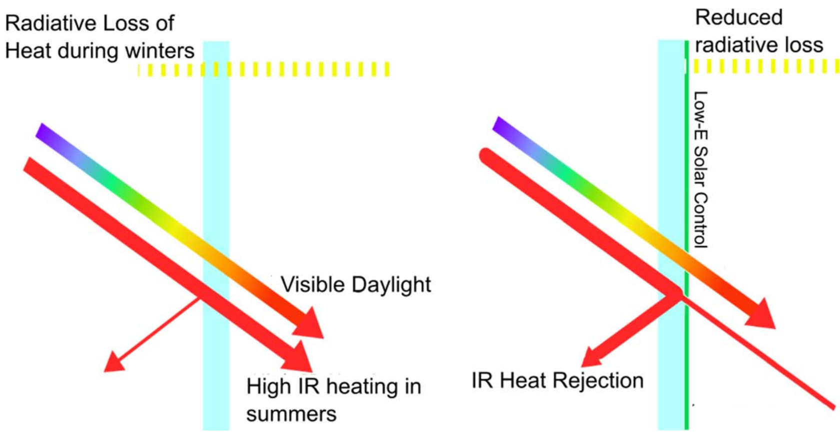

Fig. 2 Visual representation of the impact of applying low-ε solar control coatings. The left pane lacks any coating and allows IR heat in during the summer, and leads to high radiative loss of indoor heat during winters due to the highly emissive surface. The right pane has a low-ε solar control coating which reduces IR gain in summers and radiative loss in winters.

shown in Fig. 2.[10] Simultaneously, the low emissivity helps in reducing radiation losses of warmth from the building during cold weather, keeping the inside warmer for longer. One of the challenges to apply these techniques is the breadth of hot and cold climatic conditions that occur in various parts of the world. It is, thus, highly desirable to be able to tune solar control properties of windows to manipulate natural heating and cooling of indoor spaces.[11]

Phase transition materials like VO_2 are laying the pathway for smart windows, which may tune properties like emissivity and solar heat gain in response to real-time weather conditions which can drastically reduce the use of artificial heating and cooling needs of building envelopes.[12] However, even at these microscopic thicknesses, the materials being used in these coatings have the risk of corrosion when being subject to harsh weather and wide temperatures swings. Corrosion has been studied as a chemical phenomenon for decades, and the solutions posed by chemical sciences towards this issue have proven to be robust and durable. Techniques like alloying, encapsulating and sacrificial layering have proven to be successful for day-to-day metal applications, and need to be studied and applied furthermore in the nanoscopic regime so such novel technologies can thrive and contribute to the decarbonization of our existing infrastructure.[13]

As much as decarbonizing urban infrastructure can have a large impact on reducing CO_2 emissions around the world, it's crucial to not underestimate the impact of embodied emissions in the food we consume due to inefficiencies in the agricultural sector. Overuse of fertilizers and redundant irrigation decisions lead to unoptimized production in the agricultural sector, and lead to risks of soil contamination.[14] Even though governments regulate use of fertilizers which serves as a good preventive step to protect the environment, technology-driven solutions need to be employed to continually monitor the soil and environment to optimize resource use and maximize crop yield while ensuring minimal damage to the crops, soil and water resources.

Precision agriculture can assist farmers to gain information about moisture content, soil pH, nutrient levels, and crop health. Unmanned aerial vehicles can monitor large crop fields by using infra-red cameras, and single out sections of field which require fertilization or irrigation.[15] Since these decisions are based on chemical information, a high level of accuracy is required in collecting and interpreting the chemical signatures of the crop, soil, and water. This can be attained by using infra-red spectroscopy techniques where infra-red rays reflected from any crop can carry information about its precise chemical composition which can help in making more informed decisions about irrigation patterns and soil health.[16] A recent study employed mid-IR spectroscopy to determine the acidity of soils, which is useful information to selectively use lime to neutralize the soil to healthy pH.[17] Engineering such devices can result in large reductions in water and fertilizer use, drastically reducing the carbon footprint associated with agricultural practices.

The dynamic nature of physical and chemical processes that constitute life on planet Earth necessitates an adaptive approach towards sustainability. Emerging sustainable technologies bring along a plethora of complex challenges, and the chemical sciences can provide a strong foundation for finding innovative solutions. Increased performance of solar technologies needs to go in parallel with reducing critical element usage, and issues regarding the longevity and durability of light absorbing and reflecting technologies need to be addressed. Moreover, high precision spectroscopy along with faster chemical analysis techniques can help with making large improvements in the water and fertilizer consumption in the agricultural industry. Indeed, chemical sciences can illuminate the pathway to harnessing the full potential of photons and ensuring that the paradigm of sustainable thinking has a bright future ahead!

Declaration on use of artificial intelligence

AI technologies were not used to write or edit the material in this essay, nor were they used to produce the images in the essay.

Conflicts of interest

There are no conflicts to declare.

References

1 Ember Climate, *Yearly Electricity Data*, 2024, available at: **https://ember-climate.org/data-catalogue/yearly-electricity-data/** (accessed March 5, 2024).
2 P. Bojek, *Solar – IEA (Technology Manufacturing)*, 2023, available at:

https://www.iea.org/energy-system/renewables/solar-pv (accessed March 7, 2024).
3 W. Shockley and H. J. Queisser, *J. Appl. Phys.*, 1961, **32**, 510–519, DOI: 10.1063/1.1736034.
4 A. Al-Ashouri, E. Köhnen, B. Li, A. Magomedov, H. Hempel, P. Caprioglio, J. A. Márquez, A. B. Morales Vilches, E. Kasparavicius, J. A. Smith, N. Phung, D. Menzel, M. Grischek, L. Kegelmann, D. Skroblin, C. Gollwitzer, T. Malinauskas, M. Jošt, G. Matič, B. Rech, R. Schlatmann, M. Topič, L. Korte, A. Abate, B. Stannowski, D. Neher, M. Stolterfoht, T. Unold, V. Getautis and S. Albrecht, *Science*, 2020, **370**, 1300–1309, DOI: 10.1126/science.abd4016.
5 S. Rafizadeh, K. Wienands, L. E. Mundt, A. J. Bett, P. S. C. Schulze, L. C. Andreani, M. Hermle, S. W. Glunz and J. C. Goldschmidt, *IEEE J. Photovoltaics*, 2019, **9**, 1428–1435, DOI: 10.1109/JPHOTOV.2019.2922388.
6 P. J. Verlinden, *J. Renewable Sustainable Energy*, 2020, **12**, 053505, DOI: 10.1063/5.0020380.
7 Y. Zhang, M. Kim, L. Wang, P. Verlinden and B. Hallam, *Energy Environ. Sci.*, 2021, **14**, 5587–5610, DOI: 10.1039/d1ee01814k.
8 N. Florin, R. Wakefield-Rann, E. Dominish, S. Dwyer, J. Gertsakis and N. Harford, *Scoping Study for Solar Panels and Battery System Reuse and Recycling in NSW*, Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, 2020, available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/grants/infrastructure-fund/isf-solar-pv-and-battery-recycling-report.pdf (accessed March 5, 2024).
9 C. Delmastro, O. Chen, F. d'Agrain, T. De Bienassis, C. Camarasa, J.-B. Le Marois and K. Petrichenko, *Buildings – Energy System – IEA*, 2023, https://www.iea.org/energy-system/buildings (accessed March 7, 2024).
10 B. P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey and R. Hart, *Sol. Energy Mater. Sol. Cells*, 2012, **96**, 1–28, DOI: 10.1016/j.solmat.2011.08.010.
11 S. D. Rezaei, S. Shannigrahi and S. Ramakrishna, *Sol. Energy Mater. Sol. Cells*, 2017, **159**, 26–51, DOI: 10.1016/j.solmat.2016.08.026.
12 Y. Cui, Y. Ke, C. Liu, Z. Chen, N. Wang, L. Zhang, Y. Zhou, S. Wang, Y. Gao and Y. Long, *Joule*, 2018, **2**, 1707–1746, DOI: 10.1016/j.joule.2018.06.018.
13 W. N. S. Wan Shamsuddin, K. Zuber, P. J. Murphy and M. L. Jane, *Sol. Energy Mater. Sol. Cells*, 2024, **266**, 112673, DOI: 10.1016/j.solmat.2023.112673.
14 C. Zheng, F. Ouyang, X. Liu, J. Ma, F. Zhao, Z. Ouyang and F. Ge, *Ecol. Evol.*, 2019, **9**, 11367–11378, DOI: 10.1002/ece3.5638.
15 C. Zhang and J. M. Kovacs, *Precis. Agric.*, 2012, **13**, 693–712, DOI: 10.1007/s11119-012-9274-5.
16 D. J. Mulla, *Biosyst. Eng.*, 2013, **114**, 358–371, DOI: 10.1016/j.biosystemseng.2012.08.009.
17 M. Leenen, G. Welp, R. Gebbers and S. Pätzold, *J. Plant Nutr. Soil Sci.*, 2019, **182**, 953–963, DOI: 10.1002/jpln.201800670.

