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Photonic solutions help fight climate crisis

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The mitigation of climate change requires major transformations in the ways we generate energy and operate technologies that release carbon dioxide. Photonic concepts and novel light-driven technologies provide many potential solutions, transforming our current modes of energy use into more effective and sustainable ones.

Photonic processes lie at the heart of climate change. The temperature rise of the Earth is fundamentally due to an alteration in the radiative flux balance of the planet between sunlight absorption and thermal radiative emission to space, resulting from rising levels of carbon dioxide (CO_2) and other greenhouse gases, as shown in Fig. 1.

Every day we release large amounts of CO_2 into the atmosphere by our use of diverse energy forms, such as electricity, heat and fuels, to support complex industrial processes that fabricate our goods, to create and control our built environment, to sustain our food production and to transport raw materials as well as final goods (Fig. 1). We need dramatic technological changes in all these sectors to reduce the generation of CO_2 and avoid further global warming. In this Comment we discuss how photonic concepts and advanced light-driven technologies can be pivotal in this transformation by enhancing the performance of energy generation devices, developing novel energy storage solutions, and reducing consumption in energy-intense applications.

Photovoltaics

The world's largest CO_2 emitter is the energy generation sector that uses mainly coal, oil and gas (Fig. 1). To solve this problem, photovoltaic (PV) panels, which directly generate electricity from sunlight, are being installed at a very high rate worldwide. They have the potential to sustainably create half of the world's electricity needs by 2040; the rest will come from wind, hydropower and other renewable energy sources. The expansion of PV will accelerate if the cost of PV can be reduced further to <0.15 € W_p^{-1} for PV panels; if the power conversion efficiency can be increased from 25% to 40%, thereby reducing the area needed for PV systems; and if new lightweight and flexible forms of PV systems that can be better integrated in our environment become available.

Photonics facilitates all these developments (Fig. 2). The incorporation of nanostructures with precisely engineered light scattering can enhance spectral splitting and conversion in multi-junction solar cell geometries to enhance their efficiency[1]. Light scattering geometries can enhance light in-coupling and trapping, thereby enabling a reduction in PV absorber layer thickness, materials use and costs[2]. Photonic principles can also create PVs with coloured appearances and other aesthetically appealing features that make them easier to invisibly embed in our environment, thereby further speeding up the large-scale deployment of PVs. Some of these new technologies, such as the fabrication of flexible high-efficiency perovskite solar foils, may benefit from light-driven materials processing, as discussed below.

Light-driven chemical reactions

Among all industrial sectors, the chemical industry consumes the most energy and is the third-largest direct producer of CO_2 emissions[3]. Here, fossil fuels serve a dual role, powering production processes (fuels) and acting as feedstock. Additionally, we will not meet the net-zero emission targets for 2050 if we do not capture, transform and/or store the CO_2 emissions that we cannot eliminate in the near future. Examples include the CO_2 generated as an unavoidable by-product in the chemical industry, in cement production, and in air travel. Some of these CO_2 emissions can be captured and transformed into useful products, such as synthetic fuels and chemicals, which would close our carbon-cycle. Thus, comprehensive decarbonization solutions must tackle both sourcing greener feedstocks and ensuring sustainable process energy for driving chemical reactions.

A key strategy is to investigate the extent to which thermochemical processes, predominant in today's processes, can be electrified, for example by resistive heating of catalysts using renewable electricity, or benefit from the use of heat generated by burning liquid fuels or hydrogen that are fabricated in a sustainable way. Concurrently, photonics opens new opportunities for the direct use of light in thermochemical and photochemical transformations, realizing direct light energy storage into chemical bonds.

Plasmonic nanoparticles or nanostructured metasurfaces that concentrate light to molecular or nanoscale dimensions can be used to enhance the conversion efficiency at photocatalytic surfaces by minimizing non-radiative charge recombination and by locally providing heat to the catalytic active sites[4]. Spectrally narrow resonances are uniquely suited to the use of light-emitting diodes (LEDs) powered by renewable electricity, bypassing the difficulties of broadband solar light absorption[5]. In addition, resonant optical excitations of strong near fields and hot charge carriers in plasmonic nanostructures can provide additional non-thermal control to overcome photocatalytic reaction barriers, opening a completely new route for reaction pathway control and selectivity steering[4,6]. Several critical chemical transformations can benefit from these opportunities (Fig. 2).

In particular, molecular hydrogen plays a key role in the energy transition as it has a very high energy density per unit mass and upon combustion produces heat and water without carbon emissions. However, the common methane–CO_2 reforming reaction to create H_2 has unfavourable thermodynamics and kinetics, requiring high temperatures and hence a large energy input. A potentially attractive alternative route to produce H_2 is through the electrolysis of water, which can be directly driven by sustainably generated electricity, mediated by a suitable catalyst. Photo-assisted catalysis provides an alternative technology with advantages in terms of scalability, simplicity and, potentially, cost[7]. High solar-to-hydrogen efficiencies (>19%) have already been reported by direct photocatalysis[8]. Key challenges lie in combining the desired attributes of high solar-to-hydrogen efficiency, durability and low cost into one architecture and materials platform.

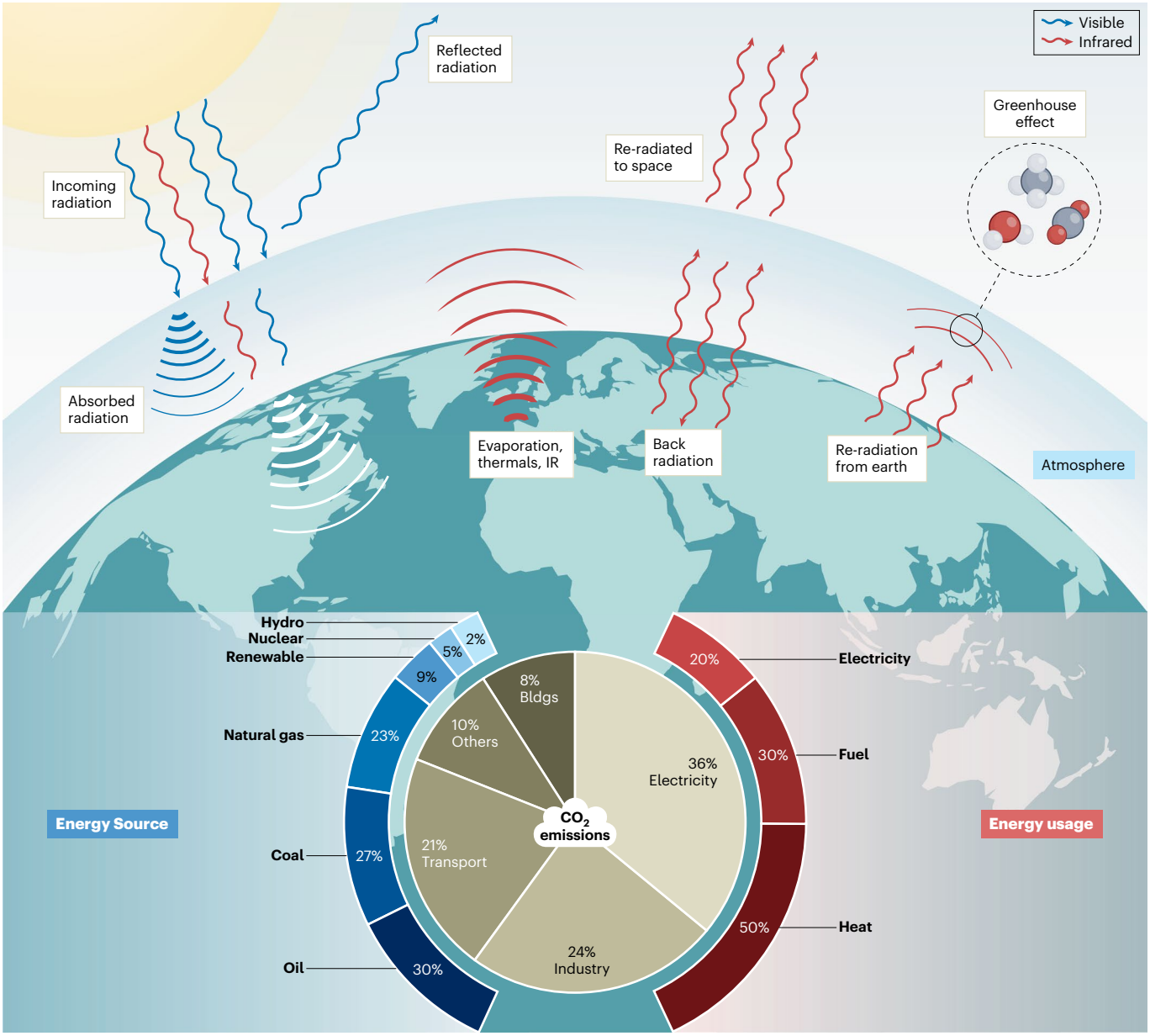

Fig. 1 | The climate change issues. Radiative energy balance of the Earth. Incoming sunlight radiation and outgoing infrared (IR) emissions (top). State of the art for energy sources, uses and CO_2 emissions globally (bottom). Data taken from IEA (2023)[17].

More broadly, fossil materials presently form the source of both hydrogen and carbon for producing many base chemicals like ethylene, propylene and ammonia. New technologies that use sustainable hydrogen production can substitute this non-renewable feedstock in chemical production. Alternatively, CO_2 capture and utilization can enable carbon-neutral feedstocks. However, CO_2 reduction reactions typically create a variety of reaction products, ranging from CO to hydrocarbons and alcohols, among other things, and high reaction selectivity is key to avoid energy-intensive and costly separation and purification steps[9]. In this regard, the production of high-molecular-weight carbon products (C_n, $n > 2$) — for which the high-energy C–C coupling step is required — relies on the use of Copper (Cu) as the only catalyst able to perform such transformation[10]. With Cu being an Earth-abundant and plasmonic material in the optical spectral range, this provides opportunities to optimize the C–C reaction efficiency and selectivity by using strong light–matter coupling conditions that are created by nanophotonic concepts[11]. The many CO_2-derived reactions and their key role in the net-zero energy scenario invite us to further explore catalysts to drive CO_2 conversion reactions efficiently and selectively with light.

Solar batteries

Chemical processes are also important for large-scale renewable energy storage, and photonics can further help these processes. Solar redox flow batteries, in which a photoelectrochemical cell is directly

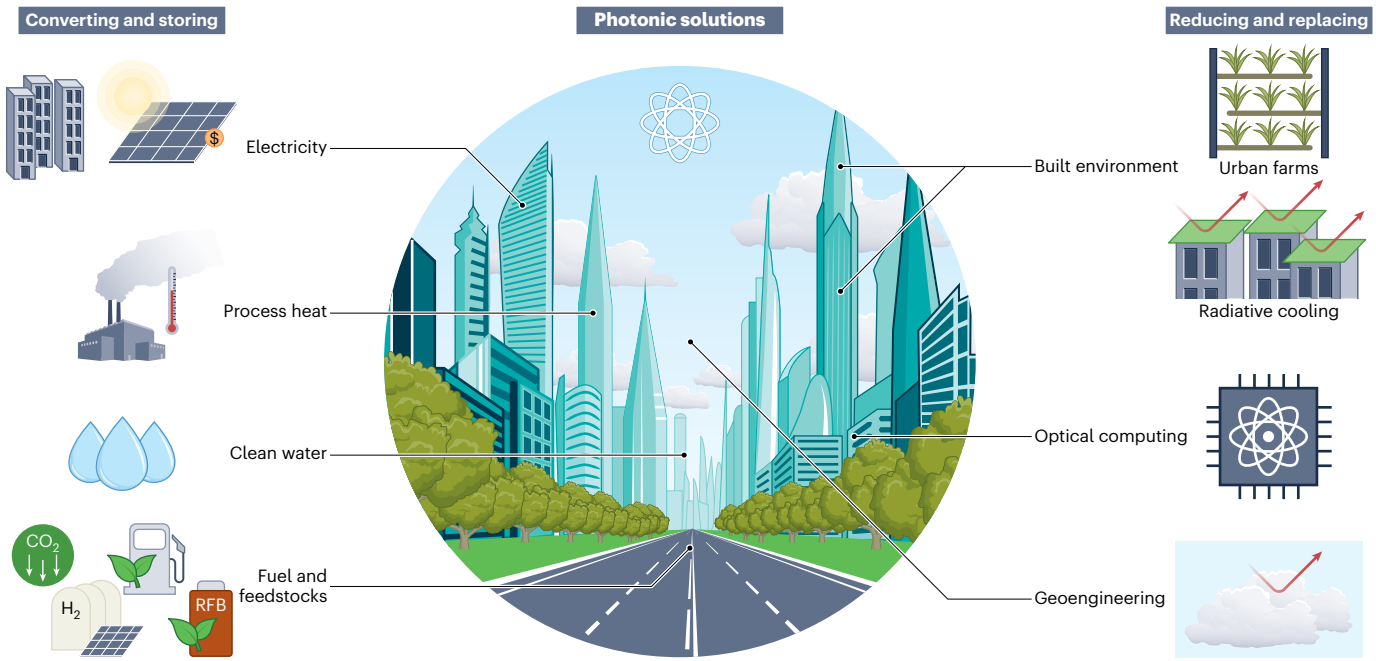

Fig. 2 | The solutions. Photonic approaches to address climate change for the city of the future.

integrated with a redox flow battery, can provide large-scale direct solar energy storage[12]. Sunlight-to-electrical efficiencies of up to 20% were reported thanks to the monolithic coupling of multi-junction solar-cells with the redox-flow battery part[13]. Yet, major challenges remain in the design of single photoelectrode systems based on scalable and low-cost materials and of geometries that simultaneously optimize light harnessing and charge transfer in these devices[14].

Overall, the use of light to drive chemical reactions inspires entirely new ways to design chemical reactors in which the guiding and concentration of light is optimally integrated with the flow of chemicals, both in liquid and gaseous forms. Photonic design of photoelectrode and catalyst metasurfaces with optimized morphology and integrated with nano- and microfluidic geometries provides unique new ways to stimulate chemical reactions by the control of thermal gradients and optical hotspots. Chemical fluids integrated with light-absorbing resonant nanoparticles can also provide new opportunities to couple light to chemical reaction spots. The development of large-scale photoreactor systems is still in its infancy but has potential for significant developments in the future.

Reducing energy consumption

In addition to the major technological transformations that must take place in our energy and chemical industries, there are many more smaller-scale uses of energy in our society that can be modified such that the cumulative effect of the initiatives has a disruptive impact. The innovation space is nearly unlimited, and we here mention only a few of the major examples (Fig. 2).

Much energy use can be avoided by optimizing heat management in our built environment. Optical metasurfaces can enable efficient passive radiative cooling systems by enhancing emission of (far-)infrared light. Radiative cooling powers as high as 270 W m^{-2} have been demonstrated for bifacial radiative coolers while simultaneously harnessing solar irradiation for hot water production[15]. Widespread adoption of this technology can significantly reduce the energy expenditures for indoor cooling. Computing, combined with the boom of artificial intelligence (AI) technologies, is using rapidly growing amounts of electricity. Passive optical computing technologies that use light as information carriers and perform analogue (pre-)processing of data can reduce future energy use and sustain the widespread deployment of AI tools[16].

Photonic solutions can also help reduce the thermal needs of industrial processes. For example, plastics recycling and paper production are major CO_2-emitting industries owing to the large amounts of heat needed for the pyrolysis of plastics waste and the evaporation of water from paper pulp, respectively[17]. Photocatalytic approaches could open low-temperature pathways in plastic recycling while photonically engineered structures for light-driven interfacial evaporation could reduce thermal loads and losses in paper production[18]. Photonic-assisted evaporation concepts can also be used for efficient water desalination technologies, which are urgently needed to supply potable water to a large population worldwide[19]. Photothermal effects also open a completely different pathway for the realization of moisture harvesting from the atmosphere. The combination of water evaporation technologies with electrokinetic (hydrovoltaic) devices can realize combined water-energy production for off-grid applications[20]. In all these systems, an optimal photo-thermal design of the light-absorber and the condenser is critical for enhancing productivity. Finally, we mention the use of photonics in agriculture, where LEDs, powered by renewable energy, create colours that selectively stimulate crop growth and enable new ways to create urban farms.

Radiative flux balancing: photonics and geo-engineering

One way to directly affect global warming is to exploit photonic engineering of the visible and infrared scattering/absorption properties of clouds and aerosols, for example marine cloud brightening, offsetting

the uncontrolled geoengineering effects of anthropogenic CO_2 emissions[21]. Although highly controversial, this subject is seeing some public discussion because these approaches may be substantially less expensive than mitigating or removing CO_2 emissions and could be implemented quickly. Yet, such technologies pose a 'moral hazard' argument: namely, that their implementation would dampen or postpone worldwide efforts to restrict greenhouse gas emissions and to remove CO_2 from the atmosphere. As a result, geoengineering should only be seen as a last resort.

Supply chain and novel approaches

Many of the photonic design concepts intimately connect challenges in chemistry, materials science and engineering, and hence a concerted effort by specialists in all research areas is required in order to analyse problems and find solutions. Such studies will also require novel spectroscopy and microscopy tools to probe and optimize processes, sometimes in operando conditions, and the development of these tools presents photonic challenges in themselves. New climate-change-mitigating photonic technologies also require an in-depth analysis of the societal effects of large-scale implementation, use of scarce materials, access to the entire supply chain of raw and processed materials and must include easy recyclability of materials and devices (circular design). Techno-economic analyses are essential to evaluating whether large-scale market penetration of the new photonic technologies is feasible.

Concluding thoughts

This Comment presents some photonic design principles that are at the heart of new technologies to fight the climate crisis. There are many potential solutions, some relatively simple to grasp, others very complex but with enormous potential impacts. We challenge the members of the photonics community to leverage their high-level knowledge of the behaviour of light in complex environments to help create solutions to mitigate climate change before it is too late.

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References

1. Cordaro, A. et al. *ACS Photonics* **10**, 4061–4070 (2023).
2. Atwater, H. A. & Polman, A. *Nat. Mater.* **9**, 205–213 (2010).
3. Cortés, E. *Nature* **614**, 230–232 (2023).
4. Cortés, E. et al. *ACS Nano* **14**, 16202–16219 (2020).
5. Schroeder, E. & Christopher, P. *ACS Energy Lett.* **7**, 880–884 (2022).
6. Kiani, F. et al. *ACS Energy Lett.* **8**, 4242–4250 (2023).
7. Andrei, V. et al. *Nature* **608**, 518–522 (2022).
8. Cheng, W.-H. et al. *ACS Energy Lett.* **3**, 1795–1800 (2018).
9. Atwater, H. A. *Physics Today* **76**, 32–39 (2023).
10. Nitopi, S. et al. *Chem. Rev.* **119**, 7610–7672 (2019).
11. DuChene, J. S. et al. *Nano Lett.* **20**, 2348–2358 (2020).
12. Feng, H. et al. *Adv. Energy Mater.* **12**, 2200469 (2022).
13. Li, W. et al. *Nat. Mater.* **19**, 1326–1331 (2020).
14. Ma, J., Oh, K. & Tagliabue, G. *J Phys. Chem. C* **127**, 11–21 (2023).
15. Zhou, L. et al. *Cell Rep. Phys. Sci.* **2**, 100338 (2021).
16. Cordaro, A. et al. *Nano Lett.* **19**, 8418–8423 (2019).
17. International Energy Agency. *World energy outlook 2023* https://www.iea.org/reports/world-energy-outlook-2023 (IEA, 2023).
18. Zhang, P., Wang, H., Wang, J., Ji, Z. & Qu, L. *Adv. Mater.* **36**, 2303976 (2024).
19. Alabastri, A. et al. *Energy & Environ. Sci.* **13**, 968–976 (2020).
20. Wang, X. et al. *Chem. Soc. Rev.* **51**, 4902–4927 (2022).
21. Feingold, G. et al. *Sci. Adv.* **10**, eadi8594 (2024).

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Competing interests

The authors declare no competing interests.