Technologies series

Photocatalysts

Harnessing the Sun's energy in the fight against runaway pollution and climate change

What it is

Another much needed but little-known ally

Photocatalysts (or sunlight-activated catalysts) are substances that absorb sunlight and accelerate chemical reactions that convert waste gas or water into industrial chemicals and fuel.[1] Photocatalysts, an intermediate technology, make a wide range of environmental applications feasible, and have the potential to revolutionise the chemical industry.[2]

How it works

There are different kinds of photocatalysts.[3] Most are a composites of one or more semiconductors and co-catalysts,[4] and work thus:

1. Under solar or artificial light irradiation, photogenerated charges are formed on the semiconductor.[5]
2. The co-catalysts extract the photo-generated charges from the semiconductor(s) and use them to perform 'redox' reactions that convert light to chemical energy.[6]

Applications

Costs at this stage are unavoidably uncertain, though doubtless they will fall over time. Photocatalysts have the potential to revolutionise, and pave the way to scale in, many industries:

- **Hydrogen (H_2).** Photocatalytic water splitting – often referred to as *artificial photosynthesis,*[7] outperforms the established ways of large-scale H_2 production by substituting sunlight for fossil fuels as the energy needed to 'split' water into H_2 and oxygen.[8] CO_2 fuels[9] could utilise 1 to 4.2 $GtCO_2$ per year from 2050, at breakeven costs[10] of CO_2 utilisation of $0 to $670 per tonne.[11]
- **Sun-powered chemistry.** Photocatalysts enable sunlight to directly power the production of chemicals[12] using waste carbon dioxide (CO_2),[13] potentially using 0.3 to 0.6 $GtCO_2$ a year from 2050. The interquartile range for the breakeven costs of CO_2 utilisation is -$80 to $300 per tonne of CO_2.[14] The next stage of sun-powered chemistry is utilisation and commercialisation.[15]
- **Construction.** Buildings, which account for some 40% of total energy use globally,[16] could be transformed into 'living' and 'breathing' organisms.[17] Photocatalysis can decompose pollutants and enhance the quality of the atmospheric air, as well as 'self-clean' roofs, facades, and glass.[18]
- **Plastic waste.** Through a process called photo-reforming, waste plastics, including PPE,[19] can be converted into hydrogen (H_2).[20] This process can also generate reactive oxygen species that can kill pathogens and viruses including SARS-CoV2.[21]
- **Water treatment and viral inactivation.** Photocatalytic processes destroy the shell or capsid of viruses. This photocatalytic process can be used for air purification[22] or water remediation,[23] helping to achieve sustainable development goals.[24] It is a promising alternative technology to using chemical disinfectants that produce harmful by-products.[25]
- **GHG removal.**[26] Photocatalysis of methane converts it to CO_2, effectively reducing its global warming potential (GWP) by at least 90%.[27] Nitrous oxide can also be reduced to nitrogen and oxygen, and CO_2 into methanol.[28]

Implications and issues

Energy storage. Solar energy can be stored indefinitely in chemical bonds, overcoming one of today's main challenges of achieving a sustainable supply of renewable energy: storing energy for a long time to meet daily demand cycles and seasonal fluctuations.[29]

The role of industries. CO_2 is captured from the air or at points during the industrial process, such that industries could become part of the solution to climate change rather than the cause.[30]

Little commercialisation so far. Solar chemical research is currently only at the early stages of development, occurring mainly in university laboratories.[31] However, given its rapid growth of potential applications, the photocatalysis industry is expected to experience strong growth over the coming 3 to 5 years.[32] ■

[1] See Photocatalystcoatings.com. n.d. *How It Works – Photocatalyst Coatings*. [online] Available at: https://photocatalystcoatings.com/how-it-works/ [Accessed 17 January 2021].

[2] Unlike extractive processes today, which use fossil fuels to manufacture most industrial chemicals, photocatalysts use the sun's energy and can convert emissions into value-added goods.

Although solar energy is in many ways the perfect source of renewable energy, it is currently weather-dependent, and requires considerable space. Furthermore, solar panels may perforce be placed a long way from where the energy is used. Unlike solar panels, photocatalysts convert solar energy into types of fuel that can be transported to where they are needed, and can be stored for a rainy day.

Photocatalysts enable the utilisation, transportation, and storage of the ~ 0.02% solar energy that is absorbed by Earth's surface annually, which is sufficient to meet the current global energy consumption.

See: Royal Society of Chemistry. n.d. *Fuel From Sunlight*. [online] Available at: https://www.rsc.org/news-events/journals-highlights/2019/feb/fuel-from-sunlight/ [Accessed 17 January 2021].

See also: Pokrant. 2020. *An almost perfectly efficient light-activated catalyst for producing hydrogen from water* Available at: <https://www.nature.com/articles/d41586-020-01455-w>

[3] Titanium dioxide is frequently used as a UV-induced photocatalyst due to its abundance, low cost, and chemical stability.

[4] See: Royal Society of Chemistry. 2020. *Recent advancements in g-C3N4-based photocatalysts for photocatalytic CO2 reduction: a mini review* [online] Available at: https://pubs.rsc.org/en/content/articlepdf/2020/ra/d0ra05779g [Accessed 20 January 2021].

[5] Kosco, J., Moruzzi, F., Willner, B. and McCulloch, I., 2020. *Photocatalysts Based On Organic Semiconductors With Tunable Energy Levels For Solar Fuel Applications*. [online] Onlinelibrary.wiley.com. Available at: <https://www.onlinelibrary.wiley.com/doi/epdf/10.1002/aenm.202001935> [Accessed 17 January 2021].

[6] Photocatalysts are able to break down specific organic or inorganic compounds such as bacteria, chemical gas, and viruses in the atmosphere or in water, into simple harmless oxidised compounds.

See: Photocatalystcoatings.com. n.d. *How It Works – Photocatalyst Coatings*. [online] Available at: https://photocatalystcoatings.com/how-it-works/ [Accessed 17 January 2021].

See aoso : Kosco, J., Moruzzi, F., Willner, B. and McCulloch, I., 2020. *Photocatalysts Based On Organic Semiconductors With Tunable Energy Levels For Solar Fuel Applications*. [online] Onlinelibrary.wiley.com. Available at: <https://www.onlinelibrary.wiley.com/doi/epdf/10.1002/aenm.202001935> [Accessed 17 January 2021].

[7] Royal Society of Chemistry. n.d. *Fuel From Sunlight*. [online] Available at: <https://www.rsc.org/news-events/journals-highlights/2019/feb/fuel-from-sunlight/> [Accessed 17 January 2021].

[8] Theoretically only water, light, and a photocatalyst are needed to drive this process.

Hydrogen, an alternative to burning fossil fuels, is a particular interest for industries. However molecular hydrogen is scarce. On the other hand, huge reservoirs of hydrogen are locked up in water.

Oxford University Innovation is currently seeking to license a technology that increases both rate and efficiencies in the production of hydrogen from photocatalytic splitting of water, for purposes of development and commercialisation. The method is the subject of a priority patent application.

See: Oxford University Innovation, 2021. *Solar-Powered Photocatalytic Production Of Hydrogen – Oxford University Innovation*. [online] Available at: https://innovation.ox.ac.uk/licence-details/solar-powered-photocatalytic-production-hydrogen/ [Accessed 17 January 2021].

Other methods use this sunlight-driven process via a photocatalyst material made from plants to produce renewable energy from untreated water and shows the potential to produce low-cost and sustainable hydrogen.

See Joh.cam.ac.uk. 2020. *Scientists Use Garden Plants To Make Hydrogen – The World's 'Most Promising' Renewable Fuel | Stjohns*. [online] Available at: https://www.joh.cam.ac.uk/scientists-use-garden-plants-make-hydrogen-worlds-most-promising-renewable-fuel [Accessed 17 January 2021].

See also Byrley, P., 2016. *Turning Water Into Hydrogen Isn't Easy. This Could Change That*. [online] World Economic Forum. Available at: <https://www.weforum.org/agenda/2016/09/turning-water-into-hydrogen-isnt-easy-this-could-change-that> [Accessed 17 January 2021].

"Production costs are consistent with the Department of Energy's targeted threshold cost of $2-$4 per kg H_2 for dispensed hydrogen, demonstrating that photoelectrochemical water splitting could be a viable route for hydrogen production in the future if material performance targets can be met." See: Pinaud, B., Benck, J., Seitz, L., Forman, A., Chen, Z., Deutsch, T., James, B., Baum,

K., Baum, G., Ardo, S., Wang, H., Miller, E. and Jaramillo, T., 2013. Technical and economic feasibility of centralized facilities for solar hydrogen production via photocatalysis and photoelectrochemistry. *Energy & Environmental Science*, 6(7), p. 1983.

[9] Not exclusively Hydrogen.

[10] Cost estimates are breakeven costs i.e. they take revenue into account.

[11] The prices are in 2015 US$ per tonne CO_2 utilised. The wide variation in the estimated potential for the scale of CO_2 utilisation in fuels reflects uncertainties in potential market penetration. There is currently a CO_2-to-methanol plant in Iceland. However, this could be a special case as they can exploit geographic advantages, such as the availability of cheap geothermal energy.

See Ritcher, A., 2018. *Turning CO2 into renewable methanol at a geothermal plant in Iceland*. [online] Available at: <https://www.thinkgeoenergy.com/turning-co2-into-renewable-methanol-at-a-geothermal-plant-in-iceland/> [Accessed 17 February 2021].

See also: Richter, A., 2018. *Geothermal energy provides Icelandic households the cheapest rates for house heating in the Nordic countries, nearly one fifth of the comparable cost for heating in Finland's capital of Helsinki*. [online] Available at: https://www.thinkgeoenergy.com/geothermal-energy-giving-iceland-lowest-heating-costs-in-the-nordics/ [Accessed 17 February 2021].

[12] Such as methanol, formaldehyde, formic acid, alcohols, hydrocarbons etc.

See: European Chemical Sciences (EUCheMS). 2016. *Solar Driven Chemistry - A Vision For Sustainable Chemistry Production*. [online] Available at: <https://www.euchems.eu/wp-content/uploads/2016/10/161012-Solar-Driven-Chemistry.pdf> [Accessed 18 January 2021].

[13] Sun powered chemistry relies on using photocatalysts to break the resistant double bond between carbon and oxygen. Adoption of sun-powered chemistry will move the chemistry sector a step closer to becoming part of a true, waste-free, circular economy, as well as helping to make the goal of generating negative emissions a reality.

See Martinez, J., 2020. *Sun-Powered Chemistry Can Turn Carbon Dioxide Into Common Materials*. [online] Scientific American. Available at: <https://www.scientificamerican.com/article/sun-powered-chemistry-can-turn-carbon-dioxide-into-common-materials/> [Accessed 17 January 2021].

See also: Ozin, G., 2021. *CO2 Photocatalysis Sees The Light Of Day - Advanced Science News*. [online] Advanced Science News. Available at: <https://www.advancedsciencenews.com/co2-photocatalysis-sees-the-light-of-day/> [Accessed 17 January 2021].

[14] The prices are in 2015 US$ per tonne CO_2 utilised.

In 2019, emissions were around 33 gigatonnes (Gt) See: 2020. Llewellyn, J., Llewellyn, P., Sepping, S., *Llewellyn Consulting - Climate change: let the numbers speak*

The competitive cost per tonne of CO_2 ranges from USD $40-80. See also: S&P Global. 2020. *What is Carbon Pricing?*. [online] Available at: <https://www.spglobal.com/en/research-insights/articles/what-is-carbon-pricing> [Accessed 17 February 2021].

Sun powered chemistry reduces emissions in 2 ways: 1) using unwanted gas 2) using sunlight as a source of energy instead of fossil fuels. The ability to more easily store the Sun's energy for electricity generation will have major implications for climate change, through reduced fossil fuel dependence.

See: Ozin, G., 2021. *CO2 Photocatalysis Sees The Light Of Day - Advanced Science News*. [online] Advanced Science News. Available at: <https://www.advancedsciencenews.com/co2-photocatalysis-sees-the-light-of-day/> [Accessed 17 January 2021].

For cost comparisons see: Adlen, E., Hepburn, C., Mylenka, T., Korteweg, H. and Dongre, S., 2019. 10 Carbon Capture Methods Compared: Costs, Scalability, Permanence, Cleanness - Energy Post. [online] Energy Post. Available at: https://energypost.eu/10-carbon-capture-methods-compared-costs-scalability-permanence-cleanness/ [Accessed 20 January 2021].

[15] Sun powered chemistry research is currently at the experimental phase mainly occurring in academic laboratories. Only some chemicals are commercialised such as the production of urea and polyurethane. The breakeven costs per tonne of CO_2 show these two markets are currently profitable. See: Langanke, J., Wolf, A., Hofmann, J., Böhm, K., Subhani, M., Müller, T., Leitner, W. and Gürtler, C., 2014. Carbon dioxide (CO2) as sustainable feedstock for polyurethane production. *Green Chem.*, 16(4), pp.1865-1870.

[16] UNEP - UN Environment Programme. 2019. *2019 Global Status Report For Buildings And Construction Sector*. [online] Available at: <https://www.unenvironment.org/resources/publication/2019-global-status-report-buildings-and-construction-sector> [Accessed 20 January 2021].

[17] McClelland, J., 2016. *How Science Is Helping To Bring Buildings To Life*. [online] World Economic Forum. Available at: <https://www.weforum.org/agenda/2016/05/how-science-is-helping-to-bring-buildings-to-life/> [Accessed 17 January 2021].

For more on how this application works:

GCCA. n.d. *Photocatalytic Concrete : GCCA*. [online] Available at: <https://gccassociation.org/photocatalytic-concrete/> [Accessed 17 January 2021].

[18] The use of photocatalysts for buildings is the most advanced and established application today however, it is still not in mainstream application.

Photocatalysts can also be added to concrete. This enables it to 'self-clean' as well as decompose most emissions from car exhaust and gases emitted from rainwater.

See: Photocatalystcoatings.com. n.d. *How It Works – Photocatalyst Coatings*. [online] Available at: <https://photocatalystcoatings.com/how-it-works/> [Accessed 17 January 2021].

See also: Build Up. 2017. *What Is Photocatalysis And How Does It Work?*. [online] Available at: <https://www.buildup.eu/en/learn/ask-the-experts/what-photocatalysis-and-how-does-it-work> [Accessed 20 January 2021].

Photocatalytic concrete decreased NOx levels by 25%, and by as much as 45% in ideal weather conditions. Theconstructionindex.co.uk. 2015. *Government Urged To Promote Photocatalysis In Clean Air Strategy*. [online] Available at: <https://www.theconstructionindex.co.uk/news/view/government-urged-to-promote-photocatalysis-in-pollution-strategy> [Accessed 20 January 2021].

[19] Personal Protective Equipment (PPE)

[20] Pubs.acs.org. 2019. *Photoreforming Of Nonrecyclable Plastic Waste Over A Carbon Nitride/Nickel Phosphide Catalyst*. [online] Available at: <https://pubs.acs.org/doi/10.1021/jacs.9b06872> [Accessed 20 January 2021].

[21] BBC News. 2020. *Covid: PPE 'Could Be Recycled' With Help Of Sunlight*. [online] Available at: <https://www.bbc.co.uk/news/uk-wales-55396511> [Accessed 20 January 2021].

[22] Prnewswire.com. 2020. *Huntkey's Business Partner Has Released The Photocatalyst Car Air Purifier In Japan*. [online] Available at: <https://www.prnewswire.com/news-releases/huntkeys-business-partner-has-released-the-photocatalyst-car-air-purifier-in-japan-301198955.html> [Accessed 20 January 2021].

[23] Over the past decade, the development of photocatalytic water disinfection and wastewater remediation has been ever increasing.

See: Zhang, C., Li, Y., Shuai, D., Shen, Y. and Wang, D., 2019. Progress and challenges in photocatalytic disinfection of waterborne Viruses: A review to fill current knowledge gaps. *Chemical Engineering Journal*, 355, pp.399-415.

[24] Ensuring the availability and sustainable management of water and sanitation for all is one of the United Nation's sustainable development goals.

Sdgs.un.org. n.d. *THE 17 GOALS | Sustainable Development*. [online] Available at: <https://sdgs.un.org/goals> [Accessed 22 January 2021].

For more on how advanced oxidation and reductive processes are able to remediate wastewaters see:

Cerrato, E., Gonçalves, N., Calza,P., Paganini, M., 2020. Comparison of the Photocatalytic Activity of ZnO/CeO2 and ZnO/Yb2O3 Mixed Systems in the Phenol Removal from Water: A Mechanistic Approach. *Photocatalysis and Environment* 10(10), 1222; https://doi.org/10.3390/catal10101222

[25] See: Zhang, C., Li, Y., Shuai, D., Shen, Y. and Wang, D., 2018. Progress and challenges in photocatalytic disinfection of waterborne Viruses: A review to fill current knowledge gaps. *Chemical Engineering Journal*, 355, pp.399-415.

Also see: Habibi-Yangjeh, A., Asadzadeh-Khaneghah, S., Feizpoor, S. and Rouhi, A., 2020. Review on heterogeneous photocatalytic disinfection of waterborne, airborne, and foodborne viruses: Can we win against pathogenic viruses?. *Journal of Colloid and Interface Science*, 580, pp.503-514.

[26] Photocatalysis would transform CH4 into equimolar quantities of CO_2. Thus, global warming potential (GWP) values for methane are effectively reduced by a factor of 2.75 leading to modified values in the range 10–30 approximately.

de_Richter, R., Ming, T., Davies, P., Liu, W. and Caillol, S., 2017. Removal of non-CO 2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science*, 60, pp.68-96.

[27] de_Richter, R., Ming, T., Davies, P., Liu, W. and Caillol, S., 2017. Removal of non-CO 2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science*, 60, pp.68-96.

[28] Tjandra, A. and Huang, J., 2018. Photocatalytic carbon dioxide reduction by photocatalyst innovation. *Chinese Chemical Letters*, 29(6), pp.734-746.

There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost and sustainability impacts is lacking to date.

Ipcc.ch. 2019. *Chapter 2 — Global Warming of 1.5 ºC*. [online] Available at: <https://www.ipcc.ch/sr15/chapter/chapter-2/> [Accessed 3 February 2021].

[29] The storage density of batteries is far below that of fuels with respect to both weight and volume. This is particularly important for developing countries where the costs of setting a solar grid in remote areas is not economically feasible. Further, sun-powered catalysts provide space efficiency.

See Euchems.eu, 2016. [online] Available at: <https://www.euchems.eu/wp-content/uploads/2016/10/161012-Solar-Driven-Chemistry.pdf> [Accessed 3 February 2021].

[30] Dimensional Energy. n.d. *Dimensional Energy*. [online] Available at: <https://dimensionalenergy.com/> [Accessed 3 February 2021].

[31] Ultraviolet (UV) light is both scarce and harmful. UV represents just 5% of sunlight. The development of new catalysts that work under more abundant and benign visible light has therefore been a major objective.

Martinez, J., 2020. *Sun-Powered Chemistry Can Turn Carbon Dioxide into Common Materials*. [online] Scientific American. Available at: <https://www.scientificamerican.com/article/sun-powered-chemistry-can-turn-carbon-dioxide-into-common-materials/> [Accessed 3 February 2021].To successfully achieve an industrial scale-up, benchmarking and standardisation should be developed so that different approaches are more easily comparable.

See Euchems.eu, 2016. [online] Available at: <https://www.euchems.eu/wp-content/uploads/2016/10/161012-Solar-Driven-Chemistry.pdf> [Accessed 3 February 2021].Current photocatalysts are costly and inefficient therefore not suitable for large-scale applications.

See also : World Economic Forum. 2016. *Turning water into hydrogen isn't easy. This could change that*. [online] Available at: <https://www.weforum.org/agenda/2016/09/turning-water-into-hydrogen-isnt-easy-this-could-change-that> [Accessed 3 February 2021].

See also: Oxford University Innovation. n.d. *Solar-powered photocatalytic production of hydrogen - Oxford University Innovation*. [online] Available at: <https://innovation.ox.ac.uk/licence-details/solar-powered-photocatalytic-production-hydrogen/> [Accessed 3 February 2021].

[32] See: Fotocatalisis.org. n.d. *How does photocatalysis change our lives?* [online] Available at: <http://www.fotocatalisis.org/assets/photocatalyse_plaquette5.pdf> [Accessed 3 February 2021]. Increasing consumer needs for air and water purification due to growing awareness towards hygiene because of COVID-19 are going to propel demand soon.

See also: Persistence Market Research,. 2019. *Global Market Study on Photocatalyst: Increasing Applicability in Air Purification Favoring Demand Growth*. [online] Available at: <https://www.persistencemarketresearch.com/market-research/photocatalysts-market.asp> [Accessed 3 February 2021], and Prnewswire.com. 2019. *Photocatalyst Market to Reach $5.23 Billion by 2027 | CAGR: 11.2% | Reports And Data*. [online] Available at: https://www.prnewswire.com/news-releases/photocatalyst-market-to-reach-5-23-billion-by-2027--cagr11-2--reports-and-data-301073775.html [Accessed 3 February 2021].