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Let the Sunshine In

In 1969, the vocal musical group The Fifth Dimension wrote a song about the coming of the Age of Aquarius, which would be filled with "harmony and understanding", an age filled with humanity, universal love, and light. Well, we might still be waiting for the emergence of the first few of these, but perhaps we are finally seeing the true dawn of the age of light. Los Angeles is set to ink a deal to build a solar farm that could provide 7% of the city's electricity at an astonishingly low cost of \$0.020/kWh with battery power at \$0.013/kWh to even out electricity provided to the grid. This new solar plant will create a 0.4 GW power plant, producing 876000 kWh of electricity annually, without the need to burn any fuel or consume any water. To put those numbers in perspective, electricity produced by natural gas is approximately \$0.04/kWh, with coal at \$0.05/kWh. Large fossil fuel and nuclear power plants typically produce 0.5 to 1 GW. This is a good start to nearly completely decarbonize the large electrical power needs of this city. It is amazingly economical and also desperately needed to slow climate change due to the release of CO_2 into the atmosphere from the combustion of fossil fuels.

What does this dawn of the "age of light" mean for future environmental technologies? One option long researched by environmental scientists is photocatalytic water treatment. However, decades of research have failed to produce impactful commercial processes. Given the importance of integrating solar power into our water infrastructure, however, it may be premature to give up on this general direction of research. The advent of inexpensive solar-produced electricity, combined with affordable storage, could enable more direct approaches by using solar electricity to drive electrochemical processes, particularly at decentralized or remote treatment locations, although there are many challenges for applications using these electrochemical technologies. The main problems are associated with side reactions produced with the different electrodes, and the low conductivity of drinking water. Mixed metal oxide electrodes (MMOs), also known as dimensionally stable anodes (DSAs), have been used for years for chlorine gas production in salt solutions, as these electrodes have low overpotentials for chloride ions, making them effective for producing disinfectants and oxidizing organic matter. Boron-doped diamond (BDD) electrodes have high oxygen overpotentials, making them better suited for direct oxidation of organic contaminants in water, and they can have a side benefit of producing ozone and hydrogen peroxide disinfectants. BDDs, however, are many times more expensive than MMOs, although prices for both electrodes could decrease with advances in materials and through mass manufacturing. In water treatment applications MMOs and BDDs unfortunately produce, to different extents, chlorates, perchlorates, bromates, Trihalomethanes, and other disinfection byproducts. The development of electrodes better targeted to drive specific reactions without these unwanted byproducts could help advance direct electrochemical applications in water treatment. The low conductivity of water is a particular concern for environmental engineers designing systems for water treatment, compared to industrial processes in which highly conductive electrolytes can be used. Such environmental electrochemistry and water treatment studies are therefore welcome topics for *ES&T* and *ES&T Letters*.

Most water treatment processes already use chemical disinfectants produced by electrochemical processes, such as chlorine, hydrogen peroxide, and ozone. Chlorine gas is produced using Pt catalysts and a cation exchange membrane made of Nafion, a polyperfluoroalkyl chemical, and NaCl brine solutions to generate Cl_2 at the anode and H_2 at the cathode. Hydrogen peroxide is produced using H_2 gas, a palladium catalyst, and a chemical mediator such as anthraquinone. Both of these disinfectants are generated off site and then transported on site for use. Methods that do not rely on precious metals and processes that could be implemented at the point of use could help enable more sustainable processes and improve safety by avoiding their transport over long distances. Ozone and ultraviolet light can be produced locally, so these processes could be more easily be integrated into a solar energy-drivenwater treatment process train.

Although it may seem improbable today, there may also be applications of electrochemical reactors for used water treatment. For many years, placing membranes into domestic wastewater was considered to be impractical, but today membrane bioreactors are common for used water treatment. Perhaps the same story will unfold for electrochemical systems such as microbial fuel cells or for ammonia recovery using electrochemical separation processes, which are currently nascent treatment processes that are not yet practial for commercial applications. One niche electrochemical treatment system that has reached commercial production is an advanced electrochemical reactor developed by researchers at the California Institute of Technology for complete recycling of water in latrines that are off grid. The energy demands for these systems are quite high at 35 Wh/L, compared to conventional complete wastewater treatment systems that operate at 0.6 Wh/L, but the need for only a few inexpensive solar power panels at each site makes the system feasible. These systems are not suitable for potable water uses, however, due in large part to the production of chlorinated byproducts.

Installed global solar power has already reached 0.5 TW, and it could double in just the next three or four years. Solar panels that float on water treatment plant ponds or sit on nearby land and produce the power more remotely are being installed and are already being integrated into treatment systems. Such solar arrays will reduce net electrical grid power consumption or provide additional inexpensive power to enable more effective or sustainable disinfection or chemical removals.

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Figuring out how to transform our water infrastructure in the coming age of light will certainly be a challenge, but it will be an enjoyable and needed adventure moving into our enlightened future.

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Notes

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