Fuels from sunlight and air

A pioneer technological demonstration leads the path toward sustainable aviation

A research group at ETH Zurich has developed a thermochemical process technology that can produce carbon-neutral transportation fuels from concentrated sunlight and ambient air. Here, Dr. Cecilia Kruszynski, editor of Wiley Analytical Science, interviews Prof. Aldo Steinfeld, who directed this multi-year research effort that can shape the fuel refineries of the future and especially contribute to the long-term decarbonization of the aviation sector.

Fig. 1: Photograph of the solar mini-refinery at ETH Zurich for the production of drop-in fuels from sunlight and air. The process chain integrates three thermochemical conversion processes. Firstly, the extraction of CO_2 and H_2O directly from atmospheric air. Secondly, the solar thermochemical splitting of CO_2 and H_2O to produce syngas. Thirdly, the processing of syngas into hydrocarbon fuels [1].

You have had an impressive career at ETH Zurich and recognition through various awards. Could you share some key moments or experiences that have shaped your journey in solar energy research?

A. Steinfeld: As I approach retirement, it is a good time to reflect on past experiences. It has been an amazing journey, filled with many joyful moments but also with plenty of failures, which are inherent in pioneer research. One of these special moments in my career was witnessing, together with my team, the kickoff operation of our solar mini-refinery mounted on the roof of the Machine Laboratory Building and observing the first drops of methanol produced from nothing other than sunlight and air. This setup represents the culmination of a decade-long R&D in several fundamental topics that were essential for the success of the project, including developing redox materials and structures, analyzing the thermodynamics and kinetics, modeling heat and mass transport at high temperatures, designing high-flux optics, and last but not least engineering the solar reactor for efficiently producing solar fuels. As for the many failures we encountered along the way, we overcame them by applying good engineering and perseverance.

You're known for your work in solar fuels. Can you provide an overview of solar fuels' significance and potential applications in sustainable energy production?

A. Steinfeld: Since the early days of my career, the signature portion of my research has been the production of solar fuels. Solar energy is clean and unlimited, but solar radiation reaching the earth is diluted, intermittent, and unequally distributed. Long-term storage and long-range transport of solar energy are essential for a transition away from fossil energy. If we concentrate the diluted sunlight with the help of parabolic mirrors and then capture that radiative energy with the help of solar receivers, we would be able to obtain heat at high temperatures for driving a thermochemical transformation and producing a storable and transportable fuel. This thermochemical pathway to solar fuels uses the entire solar spectrum and offers potentially high production rates and efficiencies. Initially, our focus was on the production of hydrogen from water. Later, we re-directed our focus to target drop-in fuels from water and CO_2. Drop-in fuels are synthetic alternatives for petroleum-derived liquid hydrocarbons such as gasoline and kerosene, which are fully compatible with the existing global infrastructures for storage, distribution, and end-use of transportation fuels. Especially kerosene is indispensable as a jet fuel for long-haul aviation because of its high specific gravimetric energy density. In our solar refinery, we can produce drop-in fuels from sunlight and air [1].

Prof. Aldo Steinfeld

Aldo Steinfeld holds the Chair of Renewable Energy Carriers at ETH Zurich. His fundamental research focuses on heat/mass transport phenomena, multi-phase reacting flows, thermochemistry, and functional redox materials. These are applied in the development of technologies for solar power and fuel production, direct air capture, energy storage, and carbon-neutral sustainable energy systems.

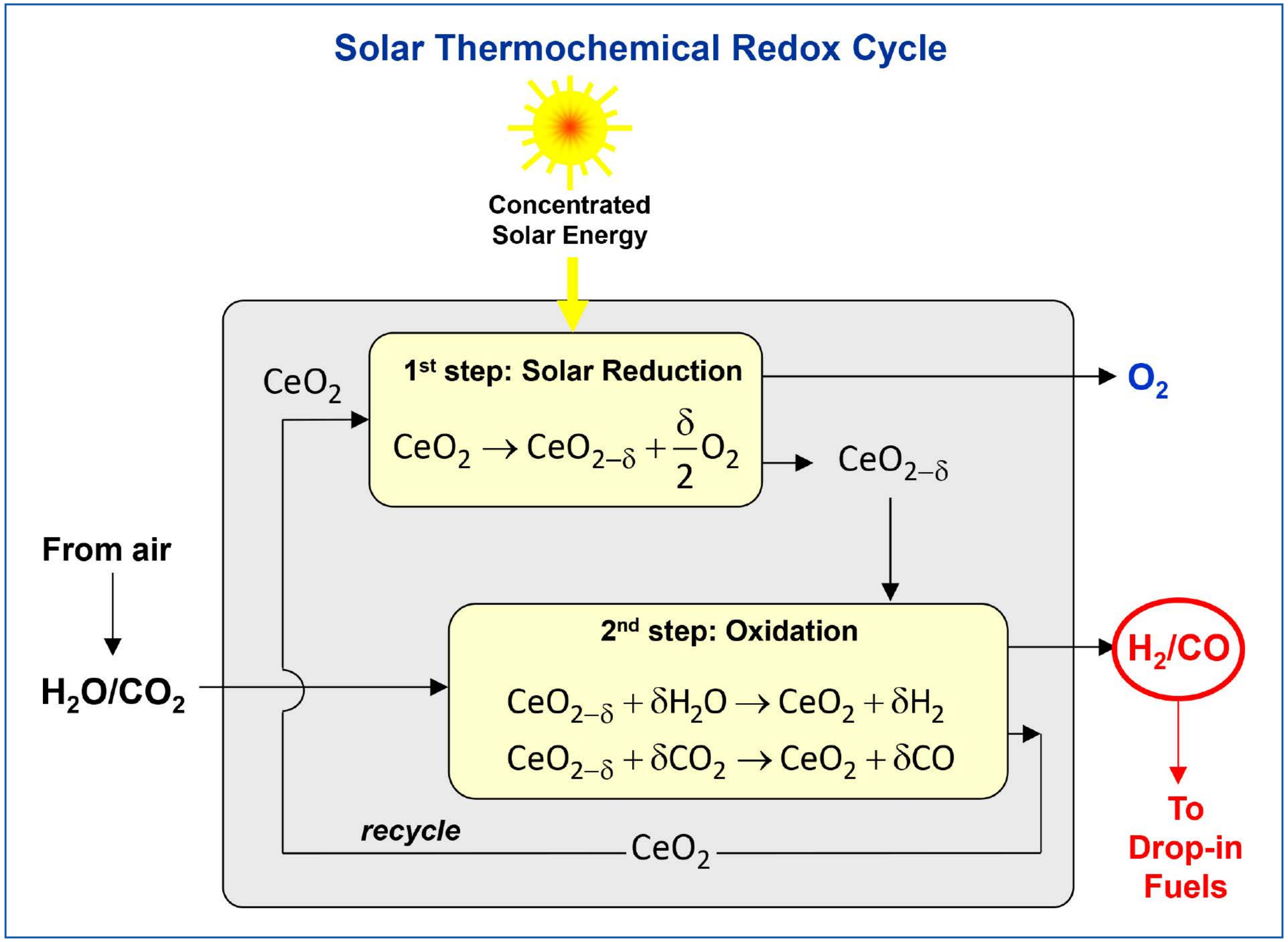

Fig. 2: Schematic of the 2-step thermochemical cycle for splitting CO_2/H_2O into separate streams of CO/H_2 and O_2 via reduction-oxidation (redox) reactions using non-stoichiometric ceria (CeO_2). In the first endothermic step, ceria is thermally reduced to generate O_2 using concentrated solar process heat. In the second exothermic step, the reduced ceria is re-oxidized with CO_2 and H_2O to generate CO and H_2 (syngas). δ denotes the nonstoichiometry – the measure of the redox extent and thereby the fuel yield per cycle.

How does this solar refinery function?

A. Steinfeld: Our solar refinery (Fig. 1) serially integrates three thermochemical conversion units. First, the direct air capture unit which co-extracts CO_2 and H_2O from ambient air via an absorption-desorption process using an amine-functionalized sorbent. Second, the solar redox unit converts CO_2 and H_2O into a tailored mixture of CO and H_2, so-called syngas, via a thermochemical redox cycle. And third, the gas-to-liquid unit which converts syngas to methanol or hydrocarbon fuels, such as kerosene.

Is this synthetic kerosene carbon neutral?

A. Steinfeld: Yes, it is truly a carbon-neutral fuel because solar energy is used for its production and because it releases only as much CO_2 during its combustion as was previously extracted from the air for its production. The solar fuel production chain's life-cycle assessment indicates 80% avoidance of greenhouse gas emissions with respect to fossil jet fuel and approaching zero emissions when construction materials, e.g., steel and glass, are manufactured using renewable energy [2].

One of your notable contributions is the development of the ceria-based thermochemical redox cycle for converting CO_2 and H_2O to syngas using solar energy. Can you explain how this process works?

A. Steinfeld: This thermochemical redox cycle (Fig. 2) is at the heart of the solar refinery. It comprises the endothermic reduction of ceria, followed by the exothermic oxidation of the reduced ceria with CO_2 and H_2O to generate a tailored mixture of CO and H_2. Ceria is thus not consumed and the net overall reactions are the co-splitting of CO_2 and H_2O:$CO_2 = CO+½O_2$ and $H_2O = H_2+½O_2$, but with the fuel and O_2 being generated in separate steps and thus avoiding the formation of explosive mixtures and obviating the need for high-temperature gas separation. The cycle is driven by concentrated solar energy.

Animation of the solar refinery for the production of drop-in fuels from sunlight and air.

In your recent publication [3], you discuss the challenge of isotropic topology in ceria structures. Could you elaborate on the significance of hierarchically ordered structures and how they improve the efficiency of solar-driven fuel production?

A. Steinfeld: The solar reactor for effecting the thermochemical redox cycle consists of a cavity-receiver containing a porous ceramic structure made of the redox material ceria. This structure is directly exposed to concentrated sunlight and reaches temperatures of up to 1,500 °C required for the reduction step of the cycle. With this arrangement, the ceria structure serves the functions of both radiative absorber and redox material. Until now, structures with isotropic porosity have been applied, but these cause an exponential attenuation of the incident radiation, which leads to an undesired temperature gradient along the radiation path, detrimentally affecting the solar reactor performance. In contrast, hierarchically ordered topologies with stepwise optical thickness enable the volumetric absorption of concentrated solar radiation. This, in turn, ensures that the entire volume of the porous structure reaches the reaction temperature and contributes to fuel generation.

How does the use of direct ink writing (DIW) technology play a role in creating hierarchically channeled structures for ceria and optimizing their radiative absorption properties?

A. Steinfeld: We applied a DIW-based 3D printing process using a novel ink formulation to manufacture robust and stable ceria structures with graded topologies.

Fig. 3: Photograph of the solar tower fuel plant located at IMDEA-Energy, Madrid. A field of sun-tracking heliostats focuses the direct solar irradiation onto the solar reactor positioned at the top of the tower. The solar reactor co-splits CO_2 and H_2O via the ceria-based thermochemical redox cycle and produces a desired mixture of CO and H_2 (syngas), which is finally processed via Fischer-Tropsch synthesis to kerosene [4].

We further analyzed the complex interplay between radiative transfer and thermochemical reaction by performing redox cycles in a thermogravimeter under high-flux radiation. We showed experimentally that hierarchically channeled structures achieved a higher and more uniform temperature profile compared to that of state-of-art isotropic structures, doubling the specific fuel yield for the same solar flux input equivalent to 1,000 suns [3].

Two spin-off companies emerged from your laboratory, Climeworks and Synhelion. Can you tell us more about the creation of these two spin-offs and the technologies they are commercializing in the context of carbon capture and solar fuel production?

A. Steinfeld: My former doctoral students founded Climeworks and Synhelion based on the science and technologies developed in my lab. Climeworks commercializes the technology for direct air capture. Synhelion commercializes the technology for the production of solar fuels. I believe both companies will make significant contributions to combating climate change by removing CO_2 from the atmosphere and by implementing carbon-neutral drop-in fuels in the transportation sector.

The production of carbon-neutral transportation fuels and, in particular, the so-called sustainable aviation fuels (SAF), has become a global challenge. What do you see as the most significant hurdles and opportunities in producing SAFs using solar energy on a large scale?

A. Steinfeld: Increasing solar-to-fuel energy efficiency is essential for improving the economic viability of solar-made SAFs, and my group and many other research groups around the world are investing major efforts in this direction by discovering superior redox materials and designing more efficient solar reactors. Furthermore, scaling up the solar reactor is critical for advancing technological readiness and we have demonstrated the production of solar kerosene from H_2O and CO_2 in a solar tower (Fig. 3) [4]. However, given the high initial investment cost for building the first generation of industrial-scale solar refineries, policy support is additionally required to see widespread deployment, leading to concomitant cost reductions initially through scaling effects and process optimization, and then through mass production of key components and learning-by-doing. I believe the policy instrument most suited to bring solar fuels to market would be a quota system mandating airlines to have a minimum share of SAFs in their total jet fuel volume. This quota would be initially small and rise each year, leading to new solar refineries, and that in turn to falling costs, just as we observed with solar power. For example, the EU already adopted a plan to impose a quota of 2% SAF in 2025, rising to 20% in 2035, and gradually to 70% in 2050.

Would it be feasible to have a 100% quota met by solar-made SAFs?

A. Steinfeld: In principle, yes. Global jet fuel demand can be met by solar-made SAFs by utilizing less than 1% of the worldwide arid land, which does not compete with food production. As demonstrated, the ingredients needed are sunlight and air.

Finally, what are your aspirations for the impact your research will have on the world's transition to sustainable energy solutions?

A. Steinfeld: I very much hope that, in the not-too-distant future, we can fly with solar kerosene!

This interview was conducted by Dr. Cecilia Kruszynski, editor of Wiley Analytical Science.

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