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Recognizing the life and scientific contributions of a pioneer in solar thermochemistry: Prof. Aldo Steinfeld

A B S T R A C T

Professor Aldo Steinfeld's contributions to the fields of solar thermochemistry and energy conversion are extensive and impressive. His work has greatly contributed to the ongoing transition from fossil to renewable fuels. We, his former doctoral students and postdoctoral researchers, take a look back at his life and honor his contributions. His work has redefined the field and created a legacy that reverberates throughout the world. His impact is being realized through his tireless efforts towards developing cutting edge solar technologies, writing seminal papers, and his undying commitment to and leadership in the solar energy and renewable energy technology communities and beyond. This legacy has been recognized by numerous accolades and will continue after his retirement through his mentorship and guidance of the next generations of researchers dedicated to continuing his solar research.

A seminal paper (Fletcher and Moen, 1977) appeared in *Science* in 1977 outlining groundbreaking work aimed at harnessing the power of concentrated sunlight to split water into hydrogen and oxygen. This paper was published by Prof. Edward A. Fletcher from the University of Minnesota. Fletcher was called the "Father of Solar Thermochemistry". One of his doctoral students from South America took this foundational work and dramatically steepened its trajectory while broadening the applications.

Aldo Steinfeld was born and raised in Montevideo, Uruguay. His educational journey took him first to Israel where he completed his BSc in Aeronautical Engineering at the Technion and his MSc in Mechanical Engineering at Tel Aviv University in 1983 and 1986, respectively. He arrived as a young researcher at the University of Minnesota to work on his PhD thesis under Fletcher's supervision, investigating the solar-driven carbothermal reduction of metal oxides, which he completed in 1989. He furthered his scientific development as a postdoctoral fellow at the Weizmann Institute of Science, where he was exposed to solar tower technologies. While these experiences were the incubators for his version of solar thermochemistry, Switzerland became his base of operations for redefining the landscape of solar thermochemistry as he began to reimagine and develop his own brand of solar-driven processes and reactors. He joined the Paul Scherrer Institute (PSI) in 1991, where he later directed the Solar Technology Laboratory until 2014 in parallel with his faculty career at the Swiss Federal Institute of Technology in Zurich (ETH Zurich), where he has held the Chair of Renewable Energy Carriers since 1999. He applied his innovative spirit and keen intellect for over three decades along with a strong work ethic to develop solar energy solutions that address one of the most pressing challenges that modern society faces at the global scale: Securing a carbon–neutral sustainable future.

Steinfeld's research was marked by fundamental studies on the thermodynamics and transport phenomena of high-temperature thermochemical processes with applications in the development of novel technologies for concentrated solar power, fuels, and materials production. He began his in-depth investigations with systematic thermodynamic and kinetic analyses to determine equilibrium compositions and identify rate limiting mechanisms. His fundamental investigations were used to inform the designs of solar thermochemical reactors supported by heat and mass transfer modeling, which was followed with the fabrication and testing of solar reactor prototypes to evaluate performance and guide subsequent optimization and scale-up. Delivering concentrated solar process heat at elevated temperatures necessitated coupling solar receivers with high-flux solar optics, which became an integral part of the engineering development. Intensive research and development were also dedicated to identifying solutions for sensible, latent, and thermochemical heat storage to overcome the intermittency of sunlight. Steinfeld's students and postdoctoral researchers greatly benefitted from state-of-the-art experimental facilities, which served as unique platforms for performing innovative projects at solar fluxes exceeding 1000 suns, at temperatures exceeding 1000 °C, and at heating

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rates exceeding 1000 K/s.

Steinfeld's research covered a wide range of energy-relevant topics, but he is most renowned for his comprehensive and groundbreaking work on solar fuels. His strategy involved research on short- to mid-term pathways to solar fuels by reforming and gasification of carbonaceous feedstocks, and, in particular, the solar conversion of solid waste materials (*e.g.*, agricultural residues) into valuable fluid fuels with upgraded calorific contents. However, his long-term mission and ultimate objective was to produce solar fuels from only H_2O and CO_2 feedstocks.

Steinfeld's work on the science and technology for splitting H_2O and CO_2 became the signature portion of his research. His approach was to apply thermochemical redox cycles, encompassing the solar-driven reduction of a metal oxide followed by the oxidation of the reduced oxide with H_2O and CO_2 to generate H_2 and CO (syngas): the building blocks for a wide variety of synthetic drop-in fuels such a kerosene, diesel, gasoline, and methanol. He reimagined using CO_2 captured from air as a commodity to be transformed into a solar energy carrier, providing a viable alternative to CO_2 sequestration. In this, he proposed reversing the combustion process with sunlight to provide a sustainable course towards powering the transportation sector with carbon–neutral synthetic fuels that are compatible with transportation infrastructure. An impressive body of premier scientific papers was published by Steinfeld and his group on screening metal oxides with superior and stable redox performance, manufacturing porous ceramic structures with enhanced heat and mass transfer properties, and engineering solar reactors that yield syngas with high rate, selectivity, and efficiency.

One of his many breakthroughs was reported in a paper in *Science* in 2010 (Chueh et al., 2010), which involved the demonstration of a robust and scalable solar reactor concept for syngas production from water and CO_2 utilizing a ceria-based cycle. To close the anthropogenic carbon cycle, he and his students subsequently developed an adsorption–desorption process for the direct capture of CO_2 from atmospheric air. A recent paper in *Nature* in 2022 (Schäppi et al., 2022) reported on the operation of a fully-integrated, solar mini-refinery, which Steinfeld and his group mounted on the roof of ETH's Machine Laboratory for the production of drop-in fuels from sunlight and air. This pioneering achievement represents the culmination of his life-time research journey in the field of solar thermochemistry as he approaches retirement. Prospects are favorable for the industrial implementation of his research through the two successful ETH-spinoff companies: Climeworks and Synhelion, both founded by his former doctoral students.

While his scientific contributions and accolades are remarkable, the fields of solar thermochemistry and energy will continue to advance through his former students and postdoctoral researchers. Steinfeld has used his operational bases at PSI and ETH Zurich to deploy waves of researchers that have become ambassadors for his brand of solar thermochemistry throughout the world. Many of his student and postdoctoral researchers have followed in Steinfeld's footsteps and have become faculty members at top academic institutions that are situated throughout Asia, Europe, and North America, introducing his brand of solar research and using it as a foundation to reimagine the field in the 21st century and beyond. We, his former doctoral students and postdoctoral researchers, thank Prof. Steinfeld for maintaining high standards through his excellent teaching and admirable mentoring. He has shown us how to maintain high quality research and achieve groundbreaking results while treating our mentees - his academic grandchildren - with compassion and dignity. The future looks a lot brighter, sunnier if you will, because of Aldo Steinfeld.

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