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CONCENTRATED SOLAR ENERGY FOR THE DEVELOPMENT OF FUNCTIONAL, HIGH-ENTROPY, AND MXENE-BASED MATERIALS: THE EXPERIENCE OF UZBEKISTAN

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Abstract. This paper presents an overview of Uzbekistan's Big Solar Furnace (BSF) in Uzbekistan, one of only two megawatt-class solar furnaces worldwide, and its role in the synthesis of functional ceramics, high-entropy alloys (HEAs), and MXene-based electrodes for hydrogen production. The BSF, with a thermal capacity of 1 MW and maximum temperatures exceeding 3,000 °C, enables clean and scalable experiments in advanced materials science. We discuss experimental achievements in oxide ceramics, antireflective coatings, molten alumina, and smart greenhouse films. In addition, MXene/NF and MXene–GO–CB/NF electrodes have shown promising results for water electrolysis, with low overpotentials, large electrochemically active surface areas, and high thermodynamic efficiencies (82–88%). The integration of solar-driven materials processing and MXene-based electrocatalysts underlines Uzbekistan's growing role in advancing sustainable, low-carbon technologies.

Keywords:

Concentrated Solar Energy, Big Solar Furnace, Smart Materials, Functional Ceramics, High-Entropy Alloys, MXenes, Hydrogen Production.

Introduction. The increasing demand for advanced functional materials such as ceramics, high-entropy alloys (HEAs), and MXenes has created a need for sustainable and energy-efficient synthesis techniques. The Big Solar Furnace (BSF) of Uzbekistan, located in Parkent, provides a unique opportunity to explore solar-driven processing at extreme conditions. Constructed in the 1980s, it remains the largest solar research facility in Asia. The geographic advantages of the Tien Shan foothills, with more than 280 sunny days per year, make the BSF an ideal platform for solar materials research [1].

Facility Overview

The Megawatt Solar Furnace (MWSF) is a sophisticated optical-mechanical complex equipped with automated control systems. It comprises a heliostat field and a large paraboloid solar concentrator, designed to focus high-density solar radiation onto a focal zone located on a central technological tower.

The technical specifications and performance parameters of the MWSF have been widely reported in the scientific literature [2, 3]. The key design features and optical-energy characteristics of the furnace are summarized below.

The heliostat field comprises 62 identical heliostats arranged in a checkerboard pattern across eight terraced levels on a gentle mountain slope (inclination ~13°). Each heliostat has a reflective surface area of 7.5 × 6.5 m, composed of 195 square mirror facets, each measuring 0.5 × 0.5 m with a thickness of 6 mm.

The solar concentrator is a rectangular section derived from a rotational paraboloid with a focal length of 18 meters. It has a height of 42 m and a width of 54 m. The total midsection area of the concentrator's reflective surface is 1906 m². A general schematic of the installation is presented in Figure 1.

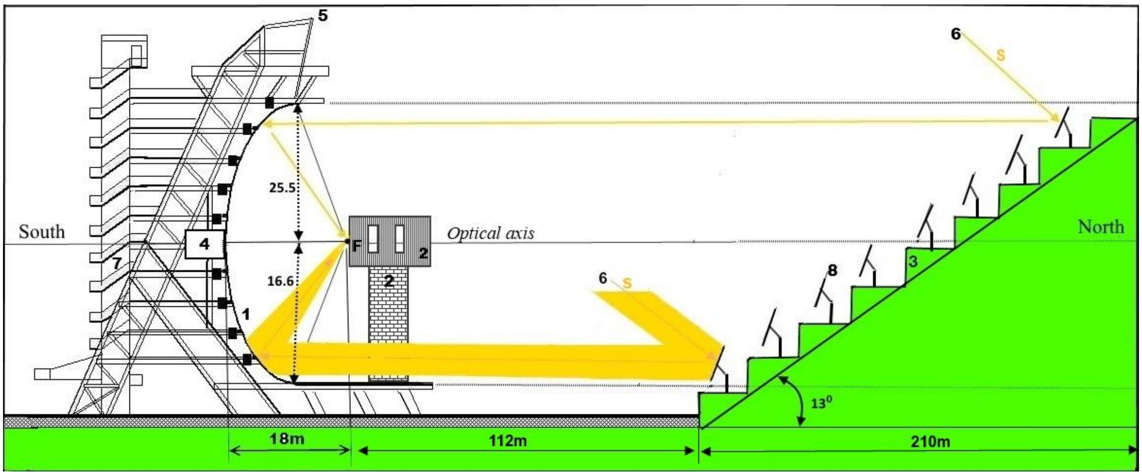

Figure 1. General Scheme of the MWSF in Parkent1. Concentrator, 2. Technological tower, 3. Heliofield, 4. Pyrometry room, 5. Autoreflection mark, 6. Sun rays, 7. Focus, 8. Heliostats

Research Achievements

Functional Ceramics

More than 150 oxide compositions were synthesized at the BSF, including corundum, spinel, aluminum titanate, calcium zirconate, and lithium aluminate. These ceramics demonstrate superior thermal shock resistance and optical performance, with potential applications in nuclear reactors, aerospace, and optics [3].

Over the past years, more than 150 unique oxide compositions have been developed and synthesized using the MWSF. Their thermophysical and application-specific characteristics have been extensively studied. The MWSF proves to be a versatile and indispensable tool for full-cycle research in high-temperature synthesis, heat treatment, and property evaluation.

Some notable materials synthesized for industrial applications include:

- $3Al_2O_3 \cdot 2SiO_2$, Al_2MgO_4 – Optical ceramics
- Al_2TiO_5, $CaZrO_3$ – Ceramics with low thermal expansion
- $AlGdO_3$, $LiAlO_2$ – Reactor-grade nuclear materials
- Li_2O–Al_2O_3–SiO_2 systems with (ZrO_2, HfO_2) – Transparent, low-CTE glass-ceramics
- $YBa_2Cu_3O_{7-x}$, $Bi_2Sr_2Ca_2Cu_3O_\gamma$ – High-temperature superconductors with *T_c* ≈ 90 K, $\Delta T \leq 1$ K

Antireflective Coatings

Studies were conducted on climatic tests of composite fluoride antireflective coatings deposited on glass substrates intended for use in optical systems of solar energy. The work examined how long-term exposure to atmospheric factors — solar radiation, temperature fluctuations, humidity, rain, and wind loads — affects the optical and physicochemical properties of such coatings. The coatings were multilayer systems based on fluorides of alkaline-earth and rare-earth elements, providing reduced reflection and increased light transmission.

The climatic tests revealed the following:

- Preservation of high optical transparency after long-term exposure to environmental conditions.
- Minimal increase in the reflection coefficient, indicating the structural stability of the coatings.
- No significant defects (microcracks, delamination, darkening) that could degrade performance.
- High adhesion stability of the coating to the glass substrate.

Solar-melted alumina samples revealed a three-zone structure, with large corundum crystals up to 5 mm. XRD confirmed the formation of pure α-Al_2O_3, demonstrating the BSF's ability to produce high-purity ceramics not achievable by arc furnaces.

Mullite-based Al_2O_3–SiO_2 coatings synthesized with solar flux reduced reflection to 2.2–3.9%, compared to 7.2–7.4% for commercial coatings. When applied to silicon wafers, these coatings improved solar cell efficiency by up to 6% [4].

The study demonstrated that the developed composite fluoride antireflective coatings possess excellent long-term durability and can be effectively used in solar energy systems — concentrators, lenses, protective windows, photovoltaic modules, and other optical components operating in outdoor climatic conditions.

High-Entropy Alloys

The synthesis of high-entropy alloys (HEAs) using a big solar furnace (BSF) represents a promising direction that combines advanced materials with renewable high-temperature technologies. The BSF provides concentrated solar radiation with heat fluxes sufficient to melt even refractory systems—up to alloys based on Nb, Mo, Ta, and W. This addresses one of the key technological challenges in HEA production: the need for extremely high temperatures with minimal contamination and without electrode contact, unlike arc or induction melting. Rapid heating, steep thermal gradients, and the possibility of directed quenching enable the formation of homogeneous FCC/BCC solid solutions and controlled grain structures without relying on energy-intensive electrical equipment.

With proper process design (inert atmosphere, graphite crucibles, suppression of volatile-element evaporation, and high-speed cooling), the BSF can be used to produce both classical HEAs such as CoCrFeMnNi and refractory systems like NbMoTaW or TiZrHfNb, which are in demand under high-temperature and high-heat-flux conditions. An additional advantage is ecological and energy efficiency: solar-driven synthesis reduces the carbon footprint and makes HEA production attractive for concentrated solar power applications, aerospace structures, and thermal-barrier materials [5].

Thus, the BSF becomes not just an alternative heat source but a unique platform for developing new HEAs with controlled microstructure and reduced production cost. This field is largely unexplored and opens opportunities for publications, patents, and the creation of a new "solar-powered metallurgy" technology line.

MXene-Based Materials for Hydrogen Production

Synthesis of MAX phases using a Big solar furnace (BSF) represents a realistic and forward-looking pathway for producing high-quality precursors to MXenes. Concentrated solar radiation provides extremely high heat fluxes and rapid heating rates, easily reaching the 1200–1500 °C range required for the formation of Ti_3AlC_2, Ti_2AlC, Ti_3SiC_2 and related MAX ceramics. Compared to conventional furnace sintering, solar-driven heating accelerates solid-state reactions, shortens processing times and can yield finer, more uniform microstructures that are advantageous for subsequent selective etching into 2D MXene sheets. With proper process control—use of graphite or BN crucibles, inert atmosphere, protection of volatile A-elements (Al, Si) and optimized heating profiles—LSF-based synthesis can reliably produce phase-pure MAX materials suitable for scalable MXene manufacturing. MXenes themselves are a highly promising class of two-dimensional transition-metal carbides and nitrides known for their high conductivity, tunable surface chemistry and strong electrochemical activity. Recent developments in Uzbekistan demonstrate the potential impact of solar-enabled MAX-phase synthesis on next-generation energy materials: MXene/NF and MXene–GO–CB/NF electrodes showed excellent catalytic activity for both oxygen and hydrogen evolution reactions, achieving overpotentials of 290 mV (OER) and 200 mV (HER) at 10 mA cm^{-2}, and exceptionally large electrochemically active surface areas of 518 and 729 cm^2. These electrodes reached thermodynamic efficiencies of 82–88%, indicating a cost-effective route toward green hydrogen production [6]. Together, these advances highlight the strategic potential of combining solar-driven MAX-phase fabrication with high-performance MXene electrocatalysts, opening a largely unexplored technological direction in solar-powered synthesis of advanced 2D materials for sustainable hydrogen energy.

Solar Metallurgy and Waste Recycling

To study the prospects of using concentrated solar radiation for processing technogenic wastes containing non-ferrous and rare metals, a series of experiments was carried out at the Big Solar Furnace. It should be noted that traditional pyrometallurgical methods are characterized by high energy consumption, the need for fossil fuels, and significant emissions of harmful substances. In contrast, concentrated solar energy provides an environmentally friendly, high-temperature, and localized heat source [7].

The experiments demonstrated that under the action of concentrated solar radiation, effective phase separation occurs, resulting in the formation of a metallic concentrate and slags with reduced content of valuable components. A high rate of heat transfers and minimal thermal losses were established due to the directed focusing of the solar flux.

According to a performed analysis, technogenic wastes produced by the JSC Almalyk Mining and Metallurgical Combine (Almalyk MMC) contain a total of 31 metals and elements, including iron (30.3 wt%), silicon (16.9 wt%), aluminum (4.7 wt%), etc. Experiments were carried out to further extract valuable components from such wastes involving their melting in a large solar furnace with a 1-MW thermal capacity. A method for smelting technogenic wastes with an average particle size of 74 μm in such a furnace was developed. The reduction smelting of a charge containing 5 kg of technogenic wastes, 0.5 kg of calcium oxide (10 wt%), and 0.25 kg of coke (5 wt%) was performed in a graphite crucible with a diameter of 250 mm and a height of 300 mm. The crucible was placed in the focal plane of the furnace, and the smelting process was carried out under the action of a concentrated solar radiation flux with a density of 100 W/cm².

It was shown that smelting the charge in this furnace, followed by water quenching of the melt, results in a product containing up to 22 wt% metals. A "small" solar furnace with a paraboloid concentrator of 12 m in diameter and a focal plane of 30 cm was also designed.

The results confirm the possibility of obtaining copper, iron, and rare elements with a high extraction efficiency, which makes the method promising for industrial application. Moreover, the technology reduces the carbon footprint of production and can be integrated into existing processing schemes.

Conclusion. The conducted studies demonstrate the unique capabilities of Uzbekistan's Big Solar Furnace as a highly efficient platform for the synthesis and processing of next-generation functional materials. The use of concentrated solar radiation enables the achievement of extreme temperatures, provides clean heating conditions, and allows processes that are difficult or impossible to perform using conventional electrothermal techniques. The results show that solar technology is an effective tool for producing oxide ceramics with tailored properties, thermally stable and optical materials, high-entropy alloys, as well as precursor structures for MXene materials.

The experimental findings confirm the durability and long-term stability of the developed antireflective coatings, the effectiveness of solar melting of refractory oxides, the formation of high-quality phases in HEA systems, and the high catalytic performance of MXene-based electrodes. For the first time, solar energy has been applied to the processing of technogenic wastes, demonstrating a high extraction efficiency of metals while maintaining a minimal carbon footprint.

The integrated use of solar energy in the synthesis of ceramics, alloys, two-dimensional materials, and environmentally friendly metallurgy underscores Uzbekistan's growing potential in developing advanced low-carbon technologies. The results open opportunities for expanding international cooperation, industrial implementation of "solar metallurgy," and establishing new research directions in sustainable energy and materials science.

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