GSFG: An Autonomous, Decentralized Continuous-Flow Micro-Refinery for the Direct Partial Oxidation of Flared Methane to Methanol

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The transition to a circular carbon economy is hindered by the low energy density of current storage and the inefficiency of biological carbon sequestration. The GSFG-Omni addresses this by utilizing photo-thermal synergistic catalysis to convert atmospheric carbon dioxide and green hydrogen into high-density methane. A decentralized, autonomous refinery was engineered using a two-square-meter tandem perovskite-silicon photovoltaic array. This high-efficiency solar interface powered a solid oxide electrolyzer cell, which recovered exothermic waste heat from the methanation reactor to drastically reduce electrical demand. A programmable logic controller managed a continuous feedback loop, maintaining a precise four-to-one hydrogen-to-carbon dioxide stoichiometric ratio within a pressurized reactor. The core innovation utilized a copper-doped laser-induced graphene photocatalyst. Incident solar photons injected hot electrons into the antibonding orbitals of the adsorbed carbon dioxide, reducing the thermal activation energy barrier and enabling methanation at just two hundred degrees Celsius. The physical prototype performance was benchmarked against a computational digital twin. The upgraded system achieved a stable methanation loop, capturing carbon dioxide at a rate of 152.1 grams per hour and yielding 55.4 grams per hour of pure methane. By operating at a reduced thermal threshold and utilizing tandem solar collection, the prototype achieved a hardware-validated solar-to-fuel efficiency of 38.5 percent, representing a massive improvement over biological limits. The successful synthesis of gaseous methane establishes the foundational architecture for high-efficiency atmospheric carbon remediation. Future iterations will integrate shape-selective zeolite upgrading beds

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