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Can photosynthesis enable a global transition from fossil fuels to solar fuels, to mitigate climate change and fuel-supply limitations?

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ABSTRACT

This review article considers Earth as an energy-storing (photosynthetic) and energy-consuming (metabolic) system. We evaluate whether and how photosynthetic, solar fuel-production systems can be engineered and deployed sufficiently rapidly to supplant enough fossil fuel supply to sustain a complex human economy and natural ecosystems over the long term. Geophysical, ecological, economic, technological and political constraints are quantified. We consider the potential to innovate and scale up promising systems such as microalgal and artificial photosynthetic systems to economic viability within a time frame meaningful for mitigating the effects of climate change and fuel-supply limitations. A future global society powered sustainably by solar fuels is forecast to require increased global photosynthetic productivity, through increased photon-conversion efficiency and production area. Increasing the efficiency of socioeconomic energy utilisation is also important. Meeting these challenges on the required time scale demands historically unprecedented technical progress, highlighting the need for both advanced international policy frameworks and scientific excellence. Based on evidence from a broad range of fields, a multiscale systems optimisation approach is identified as important, to integrate analyses from the scale of the global climate, economy and energy systems, down to the nanoscale of light-harvesting and carbon-fixing machinery that drives photosynthesis.

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Abbreviations: PAR, Photosynthetically active radiation; AM0, Air Mass 0 reference solar spectrum; AM1.5, Air Mass 1.5 reference solar spectrum; TPES, Total primary energy supply; GPP, Gross primary production; NPP, Net primary production; HHV, Higher heating value; 1P reserves, reserves with a 90% probability of recovery; URR, Ultimately recoverable resources; IEA, International Energy Agency; HANPP, Human appropriation of NPP; NPP_{LC}, NPP lost due to land conversion; NPP_0, Total potential NPP; NPP_{act}, Actual NPP; NPP_h, NPP harvested; NPP_t, NPP not appropriated by humans; PPR, Primary production required; GDP, Gross domestic product; NGL, Natural gas liquid; CTL, Coal to liquid; GTL, Gas to liquid; EROI, Energy return on energy investment; EV, Electric vehicle; LHC, Light-harvesting complex; PPC, Pigment–protein complex; EET, Excitation energy transfer; PSI, Photosystem I; PSII, Photosystem II; BTL, Biomass to liquid; GWP, Global warming potential; NPQ, Nonphotochemical quenching; HVP, High-value product; LCA, Life cycle analysis; GHG, Greenhouse gas; AP, Artificial photosynthesis; OEC, Oxygen-evolving complex; XFEL, X-ray free-electron laser

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1. Introduction

Photosynthesis is nature's solar energy conversion technology, refined through natural selection over approximately three billion years in higher plants, eukaryotic algae, a few genera of bacteria and a few species of animals that have harnessed these processes for their own benefit [1–3]. The photosynthetic machinery captures energy from electromagnetic radiation and stores it as chemical energy by breaking and creating molecular bonds against the chemical equilibrium. In biological systems, oxygenic photosynthesis builds relatively energy-dense organic products such as carbohydrates and lipids out of relatively diffuse radiation, carbon dioxide (CO_2) and water (H_2O) from the environment, while oxygen (O_2) and heat are emitted as by-products (see Section 3.1). This process has been responsible for almost all carbon fixation and oxygen evolution on Earth. It therefore provides most of the energy driving the biosphere and (through fossil fuels) ultimately also the human economy. Due to growing concerns over fuel security and the consequences of anthropogenic climate change, there is increasing interest in the potential for renewable solar fuel-production technologies to meet society's energy needs sustainably. Such technologies may harness higher plants, algae, cyanobacteria, artificial photosynthetic systems or combinations of these.

This review article considers Earth as an energy-storing (photosynthetic) and energy-consuming (metabolic) system. The coupling between these processes is taken to have two components: (1) a short time-scale component through which current photosynthetic systems supply primary photosynthates to energise natural ecosystems and a fraction of the human economy (e.g. food, bioenergy); and (2) a long time-scale component through which photosynthetically-derived fossil fuels meet most of the human economy's energy needs. The central question addressed is whether and how photosynthetic systems can be engineered and rapidly deployed to supplant enough fossil fuel supply to sustain a complex human economy while also sustaining natural ecosystems over the long term. Geophysical, ecological, economic,