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Optofluidics for energy applications

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Since its emergence as a field, optofluidics has developed unique tools and techniques for enabling the simultaneous delivery of light and fluids with microscopic precision. In this Review, we describe the possibilities for applying these same capabilities to the field of energy. We focus in particular on optofluidic opportunities in sunlight-based fuel production in photobioreactors and photocatalytic systems, as well as optofluidically enabled solar energy collection and control. We then provide a series of physical and scaling arguments that demonstrate the potential benefits of incorporating optofluidic elements into energy systems. Throughout the Review we draw attention to the ways in which optofluidics must evolve to enable the up-scaling required to impact the energy field.

The integration of fluids and optics has a long history. Early examples include fluid-core optical waveguides and liquid mirror telescopes[1], which were originally developed well over a hundred years ago. Following from the miniaturization and integration successes of semiconductors, microfluidics emerged in the early 1990s when researchers saw the potential for creating a 'lab on a chip'[2,3]. As this field grew, some of the first successful steps towards the development of integrated devices involved the incorporation of optical elements such as waveguides[4] and plasmonic surfaces[5]. Concepts for using microfluidic elements as a fundamental part of photonic devices began to emerge in the early 2000s with the development of technologies such as the bubble switch[6], liquid-crystal switchable gratings[7] and microfluidically tunable photonic crystal fibres[8]. In the mid-2000s these two research directions began to solidify into the new field of 'optofluidics'. The ideas and technological state-of-the-art devices at that time were identified in reviews by Psaltis *et al.*[9] and Monat *et al.*[10], which outlined a wide range of potential applications for optofluidics, including optical switching, imaging, sensing, data storage, data, light generation and optical manipulation[11].

One of the main strengths of optofluidics is the simultaneous and precise control it offers over fluids and light at small scales. The tools used by the optofluidics community to enable this control include micro- and nanofluidic channels and photonic elements such as waveguides, optical resonators, optical fibres, lasers and metallic nanostructures. This synergy has improved the tunability and reconfigurability[12–14], adaptability[15,16] and regeneration[17] of photonic systems, and has also led to technological advances such as reconfigurable lenses and photonic devices[12,18,19], tunable dye lasers[20] and new display technologies[21]. At the same time, microfluidics has benefited from improvements in biosensing[22–26], imaging[27–29] and particle manipulation techniques[30]. Recently, a number of demonstrations have shown how collocated and simultaneous control over both fluids and light can be used to manipulate single strands of DNA[31] and other nanoscale objects[32], or even induce optically driven reactions[33].

In this Review we discuss how similar approaches are being applied to challenges in the energy field and discuss some emerging opportunities for optofluidics. We focus on two general areas, illustrated in Fig. 1, in which we feel optofluidics is likely to have the most immediate impact: photobioreactors and photocatalytic reactors for solar-energy-based fuel production, and liquid-based systems for the collection and control of solar radiation. In the area of light-powered fuel production we discuss how the simultaneous control of light and fluids at small scales can offer several advantages. The use of small confined spaces can increase energy production rates because the reactants have only a short distance to diffuse before reaching the photocatalytic surface or photosynthetic microorganism. This allows for smaller systems, thereby increasing the associated power density and potentially reducing operational costs (for example, to maintain proper thermal control over the system). The principal opportunity of optofluidics is for facilitating the simultaneous distribution of light and fluid to such surfaces. In the area of solar collection and control, optofluidics offers adaptability and flexibility. Fluid-based optical interfaces can be readily modified using microfluidic handling techniques without the complications associated with moving solid components. Finally, we conclude with a series of scaling and physical arguments that quantitatively describe the potential impact of

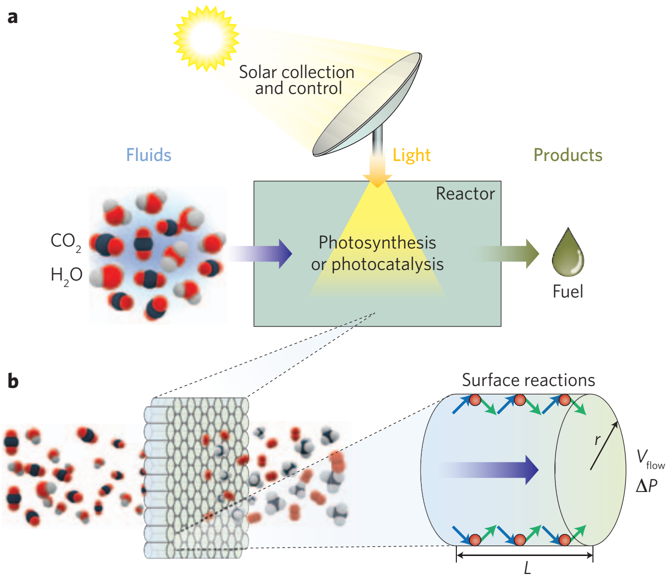

Figure 1 | Various optofluidic effects found in solar-energy collection and conversion processes. a, Schematic outlining a reactor used for photosynthesis or photocatalysis. **b**, Structures for surface-reaction-driven energy-conversion processes within the reactor.

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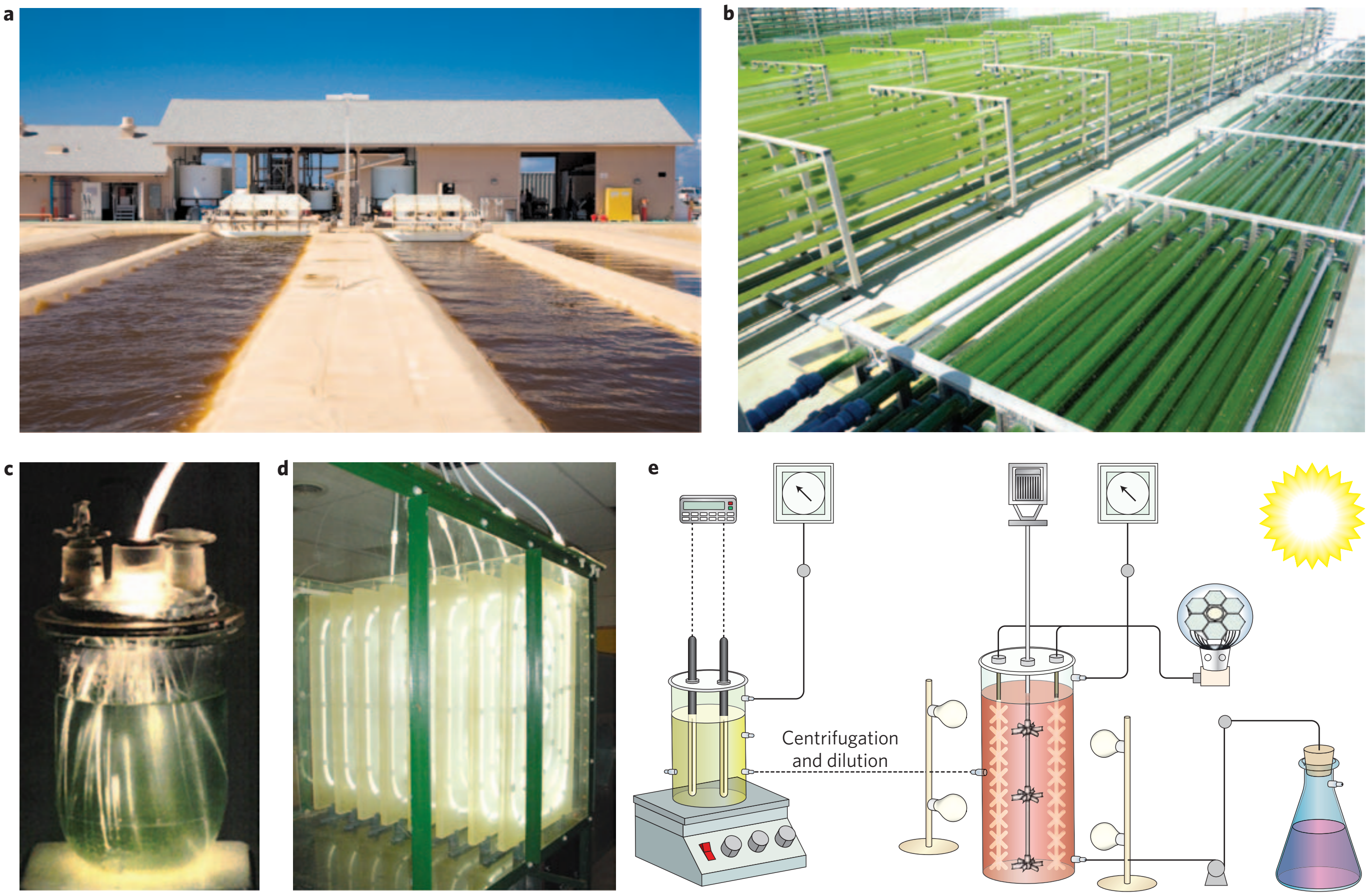

Figure 2 | Photobioreactors for microorganism-based energy production. a,b, Modern pond- (**a**) and tube-type (**b**) reactors for algae growth. Image **a** reprinted with permission from Cellana. Image **b** reprinted with permission from AlgaFuel. **c**, Early attempt at the US Department of Energy to integrate optical fibres with a photobioreactor. Image Courtesy of John Benemann. **d**, Using optical fibres excited with sunlight to transmit light to a photobioreactor. Image courtesy of D. L. Bayless. **e**, Fuel cycle comprising a dark fermentation process followed by a light fermentation process. The illuminated reactor uses, in part, solar radiation collected from a series of Fresnel lenses and transmitted to the reactor via optical fibres. Figure **e** reproduced with permission from ref. 50, © 2010 Elsevier.

incorporating optofluidic elements into these systems and some of the technical barriers that must be overcome before such integration can be achieved.

Fuel production in photobioreactors

Photobioreactors[34,35] are devices that employ whole photosynthetic microorganisms, such as algae or cyanobacteria, to convert light and a low energy carbon source (often CO_2) into more useful higher-energy products such as hydrocarbon fuels. Chemically, the energy-conversion process is similar to photosynthesis in plants, with the main difference being that cyanobacteria contain their photosynthetic machinery in their thylakoid membranes[36] rather than within specialized chloroplast organelles. Energy production using these microorganisms is attractive because they can produce far greater volumes of fuel per hectare of arable land than traditional biodiesel crops. As described by Chisti[37], meeting 50% of the US transport fuel needs using biodiesel produced from corn, soybean or canola would require more than 100% of the existing US cropping land. Microalgae, in contrast, could meet this demand with sunlight collected from 1–3% of existing cropping land. Although many different designs of photobioreactors exist, the two most common industrial or large-scale implementations are the open-air pond-type (Fig. 2a) and closed-type (Fig. 2b). The primary goal of the reactor may be for carbon capture or to obtain an energetically useful by-product, such as oil from harvested organisms[34], or hydrogen[38] and isobutanol[39] from organisms that have been genetically engineered to produce them directly.

There are many challenges in the development of commercially viable photobioreactor systems, and readers interested in gaining a broad understanding are referred to recent reviews on the subject[34,37,40,41]. One challenge that optofluidic techniques may be able to address is the distribution of light in a photobioreactor. Although a number of interesting optically favourable reactor designs have already been developed[42], the light distribution within these reactors is generally quite poor. The main problem is that organisms farther away from the illuminated surface do not get sufficient light exposure to promote growth because they are shaded by those that are closer. The result is that relatively low bacteria concentrations can be employed and flow is required to circulate bacteria through the section of the reactor that receives the appropriate radiation[43]. Although improved light distribution within the reactor could help to increase its energy density, which could lead to a higher biomass concentration as well as several other advantages (discussed in the outlook section of this Review), this would not necessarily reduce its overall aerial usage because the irradiating solar intensity is fixed. Separating the collection of light from the reactor site has additional advantages because

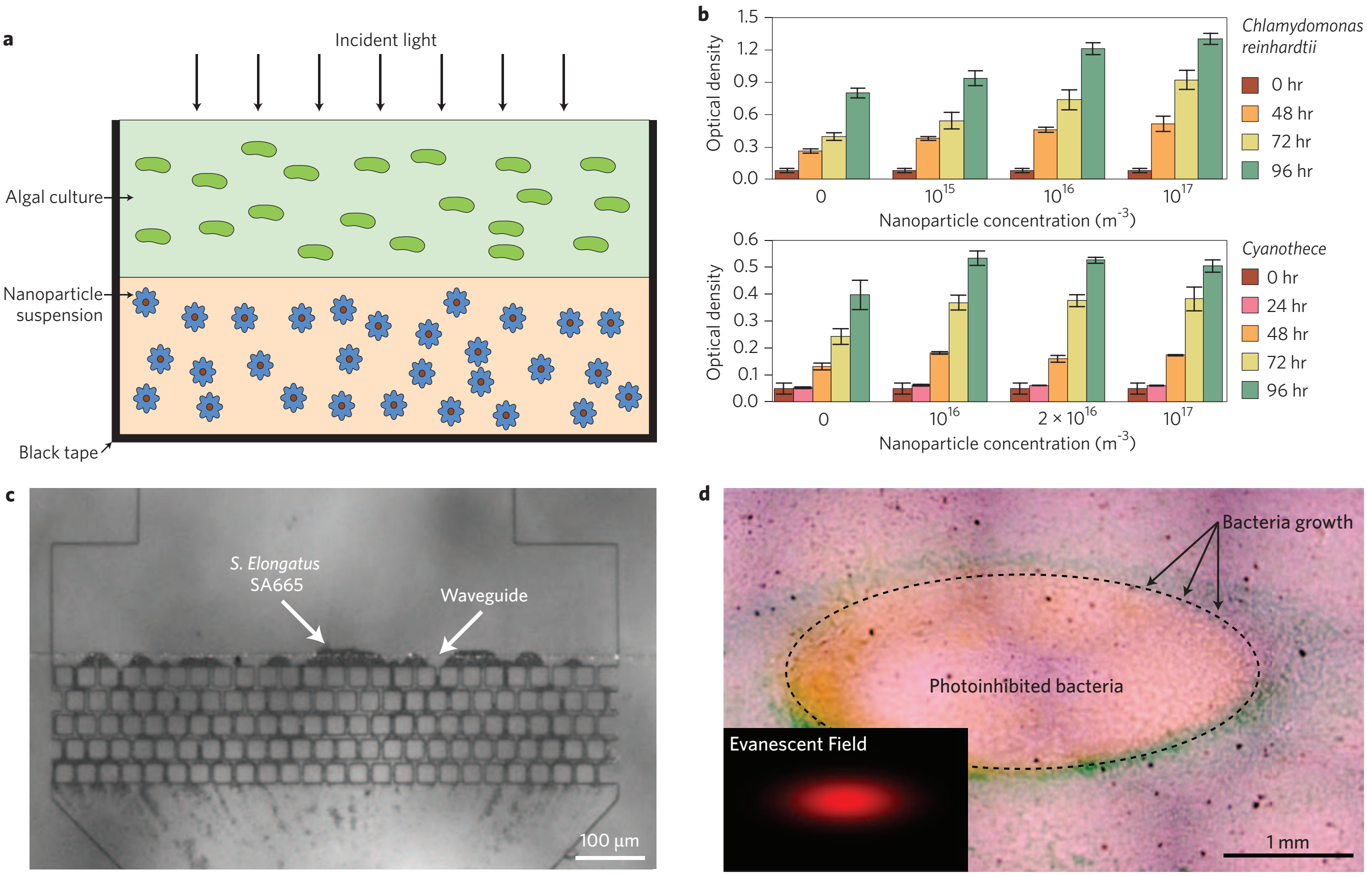

Figure 3 | Optofluidic efforts to improve photobioreactor performance. a, Plasmonic nanoparticle technique to selectively reflect particular wavelengths, which helps to promote the growth of photosynthetic algae. **b**, Enhanced growth of *C. reinhardtii* and *Cyanothece* with increasing concentration of plasmonic nanoparticles in the reflective layer. **c**, Use of the evanescent field of a waveguide to enhance cyanobacteria growth[58]. **d**, Cyanobacteria grown through the evanescent field on the surface of a prism[59]. The shape of the evanescent field is shown inset. Figure **a**,**b** reproduced with permission from ref. 56, © 2010 AIP.

it allows the spectrum to be tailored to the conditions that best promote growth.

One method that draws on the strengths of optofluidics for improving light distribution is the incorporation of light-guiding elements into the reactor. Early work in this area was performed over 40 years ago by Manley and Pelofsky at the US Department of Energy, who produced the experimental reactor shown in Fig. 2c. Mori *et al.*[44,45] attempted to integrate optical fibres with photobioreactors in the 1980s as part of a large research effort in Japan. These early efforts were held back by the cost and complexity associated with integrating fibre optics with the photobioreactor, as well as other technical challenges, such as heat sterilization and cell adhesion[46]. The reducing cost of low-loss optical elements and the increasing efficiency of techniques for coupling solar energy into such devices led to renewed interest in these systems, such as the illuminated flat plate photobioreactor presented by Bayless *et al.*[47] (Fig. 2d). Chen *et al.*[48–51] demonstrated a number of optical-fibre-based reactor designs that provided increased light distribution within the hydrogen-producing photobioreactor. Using the experimental set-up shown in Fig. 2e, the researchers demonstrated a 35% increase in H_2 production in a reaction that used *Rhodopseudomonas palustris* as the organism and acetate as the carbon source. Compact formats that consist of multiple chambers separated by light paths and thus allow light to be channelled directly into the reactor[52] have shown a 38% increase in H_2 production. The goal of all these approaches is to allow light to be collected from a larger area and distributed more evenly throughout the reactor than would be possible through simple surface illumination. These internal illumination schemes can lead to more compact 'volumetric' reactors with higher bacterial densities, which have the advantage of requiring less energy to maintain optimal growth conditions. Although the above approaches are generally successful at increasing reactor outputs, translating them to production-scale reactors in ways that are both practical and economically feasible remains a challenge[53–55].

There are other ways in which optofluidic techniques can be used to change the way light is delivered to a micro-organism. For example, plasmonic nanoparticles can provide wavelength-specific light backscattering and have been used to demonstrate an increase of more than 30% in the growth of *Chlamydomonas reinhardtii* and *Cyanothece* under blue light[56] (Fig. 3a,b). Selective reflection such as this is important because certain wavelengths can induce photo-inhibition, which slows growth[57]. Figure 3c,d shows recent attempts at using evanescent light to produce isobutanol from a genetically modified strain of *Synechococcus elongatus* SA 665[39] on a waveguide[58] and cultivate wild-type *S. Elongatus* on the surface of a prism[59]. In the latter case, successful growth was observed in the elliptical region where the evanescent field intensity was less than the expected photo-inhibition intensity. The advantage of this approach is that near-field illumination can be coupled directly to the photosynthetic machinery (the thylakoid membrane for cyanobacteria, for example) rather than broadly over the entire organism (where some of it is absorbed by non-photosynthetic processes). For *S. elongatus*, the thylakoid membrane exists in a

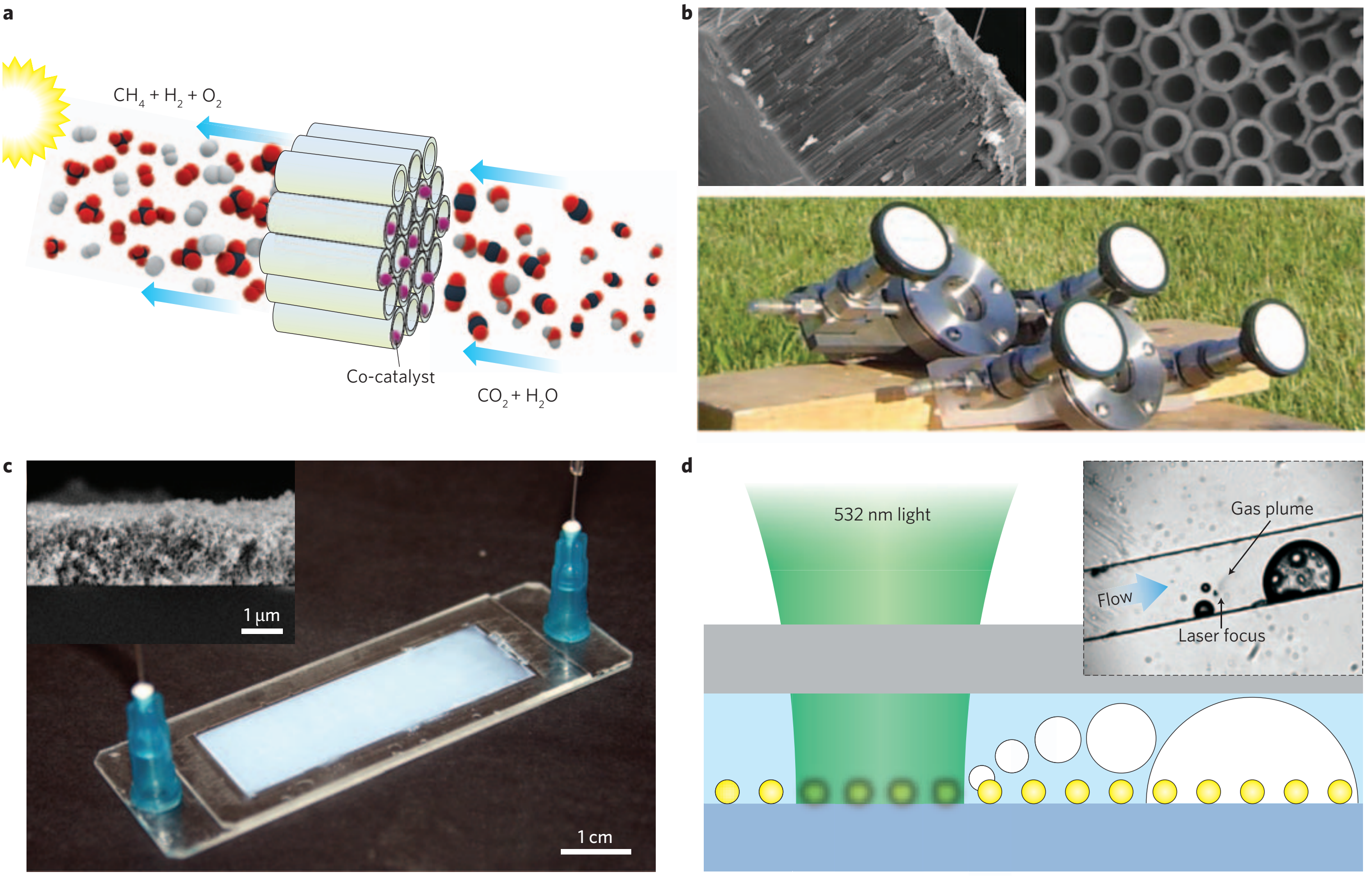

Figure 4 | Photocatalytic reactors for energy production. a, Schematic of flow-through photocatalytic fuel production. **b**, TiO_2 nanotube array photocatalysts[65] and a test reactor[69]. **c**, Optofluidic planar reactor for photocatalytic water treatment, with porous TiO_2 film shown inset. **d**, Heterogeneous catalytic steam reforming of ethanol with plasmon-heating activation. Figure reproduced with permission from: **a**, ref. 69, © 2009 ACS; **b** (top), ref. 65, © 2010 ACS; **b** (bottom), ref. 69 © 2009 ACS; **c**, ref. 33, © 2010 AIP; **d**, ref. 73, © 2009 ACS.

layer a few hundred nanometres[60] thick around the bacteria, which matches well with the length-scale of the evanescent field.

Photocatalysis and solar thermochemical reactions

In contrast with the photosynthetic organism-based strategies of fuel production, photocatalytic and solar thermochemical processes use incident light energy to drive an otherwise 'up-hill' chemical reaction. For example, light energy can be employed to split water into hydrogen and oxygen, or to convert carbon dioxide and water into hydrocarbon fuels. Photocatalytic fuel production is a photon-driven process that employs the photochemical mechanisms of the naturally occurring photosynthetic process[61]. In contrast, solar thermochemical fuel production is a heat-driven process that uses solar energy as the heat source. The distinction can be subtle, particularly as many thermochemical processes employ a catalyst, and in general photocatalytic processes benefit from increased reaction temperatures as a by-product of incident solar energy. The distinction is simply that a thermochemical process may be driven by any form of heating, whereas a photocatalytic process requires photons. These approaches are similar in the context of optofluidic reactors, and therefore both forms are discussed here.

Since the first demonstrations of photocatalytic CO_2 reduction[62,63], research efforts have focused primarily on the development and refinement of photocatalysts[61,64–66], rather than on the science and engineering of reactor development. The general concept, as envisioned by the US Department of Energy Panel on Catalysis for Energy[67], involves the absorption of photons by a semiconductor, resulting in the generation of electrons and holes. The holes are used to split, or oxidize, H_2O. The electrons are used in combination with protons to reduce CO_2 into a fuel such as methanol[67]. The key to this approach is the use of semiconductor materials, most commonly those based on naturally abundant TiO_2, and suitable co-catalysts. Semiconductors such as TiO_2 are particularly well-suited to photocatalytic reactions because they can use a large portion of the visible light spectrum and their bandgap matches the redox levels of many reactions of interest[65]. Copper and platinum nanoparticles are typical co-catalysts employed with TiO_2 for the visible-light-powered photocatalytic conversion of CO_2 (refs 68,69).

Nanostructured semiconductor photocatalysts have many advantages, including a high surface area available for reactions, close proximity of point charges to the reactant fluid, rapid charge transfer and low refractive index, which helps minimize the reflection of incident light[65]. As illustrated in Fig. 4a, through-hole catalytic nanostructures exhibit these advantages and also allow fluidics to be introduced into the optical structure for achieving flow-through fuel conversion[65]. The reactor schematic in Fig. 4a is similar to the generic reactor outlined in Fig. 1b, and would exhibit analogous scaling with respect to reactor length, throughput, volume and surface area. The photocatalytic nanotubes in Fig. 4b are approximately 100 nm in diameter with 20 nm sidewalls, and can grow in a dense collimated clusters of up to 1 mm thick[70]. Using these structures, platinum and copper co-catalysts and a reactor of

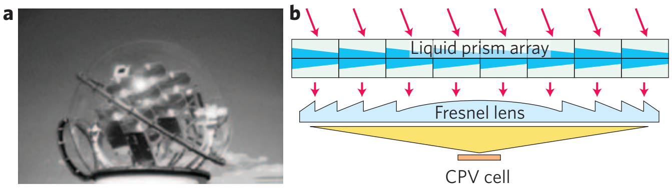

Figure 5 | Optofluidic techniques for guiding and collecting light in energy applications. a, Fresnel-lens-type solar collector. **b**, Electrowetting based solar collector array. CPV, concentrator photovoltaic. Figure **a** reproduced with permission from ref. 78, © 2004 Elsevier.

the type shown in Fig. 4b, researchers demonstrated the conversion of CO_2 to hydrocarbons at a rate of 111 ppm cm^{-2} hr^{-1} (ref. 65). The corresponding incident solar light efficiency was around 0.03%, although the theoretical maximum is much higher (~17%)[65]. The nanotubes used so far in such schemes have been closed or dead-ended, although free-standing membranes (as shown in Fig. 4a) have also been fabricated[70]. The widespread application of photocatalytic solar fuel production will require naturally abundant catalysts that are inexpensive and effective at neutral pH and ambient conditions. A particularly important breakthrough in this area was the development of an oxygen-evolving catalyst in neutral water containing phosphate and cobalt[71]. In this study, the catalyst structure, sitting on an indium tin oxide base, rapidly created product gases at neutral pH, room temperature and atmospheric pressure[71].

In solar thermochemical reactors, solar energy is used to provide the heat required to drive endothermic reactions. The thermodynamic parameter that governs the theoretical efficiency of such an energy-conversion process is the Carnot efficiency, $\eta_{max} = 1 - T_{cold}/T_{hot}$, where T_{cold} is the temperature of the sink and T_{hot} is the temperature of the source. A process operating between the temperature of the sun (5,800 K) and the temperature of earth (300 K) could, in theory, convert up to ~95% of incident solar energy into fuel energy. Approaching this high efficiency level requires the solar energy to be concentrated into small areas to reach temperatures of >1,000 K (ref. 72). This is typically achieved by collecting incident light from a large area into a small aperture of a compact, highly insulated reactor. A common application of solar thermochemical reactors is for reforming fuel, for instance the production of hydrogen fuel from cracking, the gasification of fossil fuels, or direct water splitting[72].

Optofluidic approaches are well-suited to facilitate photocatalytic and solar thermochemical reactions. An early example of such an application is the use of a microfluidic channel structure in conjunction with photocatalysts. Lei *et al.*[33] measured the degradation of methylene blue in a planar optofluidic reactor measuring 5 cm × 1.8 cm × 100 µm and containing a porous TiO_2 catalyst (Fig. 4c). The reaction rate in the reactor was then compared to that of a bulk container with the same photocatalytic area; due primarily to the improved transport of the reactants, the optofluidic approach provided reaction rates of up to 8% s^{-1} and an output two orders of magnitude higher than the bulk reactor for the same light input[33]. A prime example of a thermochemical optofluidic approach is the plasmon-assisted catalysis of endothermic reactions, such as the steam reforming of ethanol[73]. As shown in Fig. 4d, plasmon heating can provide the energy required to generate both ethanol and water vapour products[73]. Related small-scale thermochemical reforming efforts include methanol reforming using a continuous-wave green laser[74] and the the combination of a microsolar collector and reformer[75]. Lee *et al.*[74] demonstrated the potential of the optofluidic approach in solar steam–methanol reforming for hydrogen production. The researchers found that a 1-mm-diameter capillary-based liquid reaction chamber with nanoparticle co-catalysts generated hydrogen at 0.59 mL min^{-1} under focused green laser light. This production rate is more than 1,000 times better than the performance of a comparable bulk reactor[74]. The wetting nature of the capillary also facilitated the passive pumping of reactants into the reaction area. It is worth noting that in many of these studies optofluidics not only enabled the photocatalytic reaction of interest, but also provided the ideal environment in which to study the process. In this regard, the advantages of optofluidics in sensing and analytical applications will accelerate its application in the energy field.

In addition to the generic scaling benefits associated with optofluidics, it is important to note that many photocatalysts are extremely sensitive to their light, chemical and thermal environment[71]. It is in this context that the application of optofluidics to photocatalysis is perhaps most exciting. Specifically, the precision offered by optofluidics for controlling both the fluidic and optical environment now positions the field to solve long-standing challenges in photocatalysis.

Solar energy collection and control

Solar collectors are used in a number of energy applications, and many different designs have been developed as a result[76,77]. The largest sub-set of these systems is solar concentrators, which allow relatively diffuse sunlight to be concentrated down to a higher intensity. In most cases, these devices are used to drive a thermal cycle or enhance the efficiency of a photo-energy-generation process. Cavity-receiver-type collectors are common when sunlight must be concentrated to provide intense process heat, such as for solar thermochemical fuel reforming[72]. In such cases, light is focused through an aperture into a well-insulated volume, and optimizing aperture size involves striking a balance between maximizing input energy and minimizing radiant losses. Alternatively, solar collection systems can be used to collect light into a format that can be more easily transported, such as the system shown in Fig. 5a, which is a Fresnel lens-type solar collector array used to collect and focus sunlight directly into optical fibres[78]. Coupling sunlight to a guiding element allows the light to be channelled to otherwise inaccessible areas (for indoor illumination, for example) and to tailor the light spectrum to the wavelength range of interest[35] with relative ease. In the context of the photobioreactors discussed above, the concentration, guiding and spectral tuning of solar radiation enables the separation and independent optimization of collection and reaction functions.

One of the first applications of optofluidics was in the development of liquid lenses[15,79] for imaging. Using optofluidics to manipulate a lens' shape (through electrowetting or an alternative microfluidic effect) provides a much larger focal range and shorter focal depth than that of solid lenses, as well as being more robust as fewer mechanical elements are required. Although liquid-lens-based solar collectors can be traced back to Lavoisier (who used this concept to create a 'solar oven' capable of reaching temperatures as high as 1,800 °C), modern approaches dating back to the 1970s[80] demonstrate how the higher index contrast available from liquid lenses can lead to shorter focal lengths[81] and thus facilitate solar tracking[82]. Recent research in this area by Teledyne Scientific is shown Fig. 5b. In this approach, electrowetting is used to tune the interface shape of a series of liquid prisms so they can adaptively track the seasonal and daily changes of the Sun's orbit and thus more efficiently transfer sunlight onto a concentrator lens for delivery to a photovoltaic cell. The advantage of this approach is that it can provide dual-axis tracking without the need for traditional mechanical elements.

There have also been a number of recent attempts to incorporate solar collectors into microfluidic-type devices. For example, Zimmerman *et al.*[75] demonstrated the ability to use a solar-collecting adsorbing substrate to provide the heat for a microfluidic-chip-based methanol reformation reaction. Although the throughput was small, the researchers proposed that such a system could be used for portable *in situ* hydrogen production via methanol reformation. Otanicar *et al.*[83] and Tyagi *et al.*[84] examined how different highly adsorbing nanoparticles embedded in a working fluid can increase the solar thermal energy conversion efficiency. Chen and Ho[85] used a similar direct solar absorber system to drive a desalination process based on direct contract membrane distillation in a miniaturized device at rates of 4.1 kg m^{-2} h^{-1}. The major advantage of these approaches is that such highly efficient solar absorbers provide an energy-efficient method of producing heat for a thermal reaction, thus enabling operation at very low incident powers.

Outlook

This Review has focused on the collection and control of solar energy and the use of light to drive fuel-producing reactions. Figure 1 outlines some of the optofluidic effects found in solar-energy collection and conversion processes, as well as providing a vision of an optofluidic system capable of enabling surface reaction-driven energy conversion. Although there are other applications for optofluidics in the field of energy, the abundance of solar energy and the ubiquitous use of fluid fuels suggest that these areas as likely to be explored first. Simultaneous control over optics and fluids will play an important role within these application areas, thus allowing many of today's optofluidic techniques to contribute. Energy problems, when compared with the traditional problems optofluidics has addressed in the past, require extremely large-scale solutions. If optofluidics is to tackle these challenges, it will need to utilize the precise control over fluids and optics offered at small scales while providing implementations at much larger scales. For instance, most optofluidic implementations so far have been essentially planar, using traditional microfluidic chips; utilizing the third dimension would be one way of scaling optofluidic concepts.

Simple scaling considerations can illustrate the scale-up potential of an optofluidic reactor approach. Reconsider the system shown in Fig. 1a, in which solar energy is collected in a concentrator and funnelled to a reactor. Reactant fluids enter from the left and pass through a series of channels, where their interaction with light near the surface produces an energy product. These light-based reactions could be based on either photosynthetic microorganisms or photocatalysts. Using Fig. 1b as a guide, consider the following two relations: (1) the average velocity for laminar flow in a circular channel is $V_{flow} = \Delta P r^2/(8\mu L)$, where ΔP is the pressure drop, r is the radius of the channel, μ is the viscosity and L is the length; and (2) the diffusion timescale for a reactant to be transported to the surface is $t = 2\langle r\rangle^2/D$, where D is the diffusion coefficient and $\langle r\rangle$ is the average diffusion distance. These two relations govern a number of reactor metrics, as detailed below.

Reactor length. By combining the two relations and solving for L, the length of reactor required to completely consume the reactants can be determined. The result, $L_{complete} = (\Delta P/4D\mu)^{1/2}r^2$, shows that a small-channel reactor can be much shorter than a large-channel reactor, for a given conversion rate. This approximation, although generally applicable, does not account for the mixing enhancement that is achievable in systems exploiting turbulent transport.

Throughput. By splitting the inlet flow into an array of microchannels (Fig. 1b), the flow resistance can be parallelized and the required channel length reduced as outlined above. The resulting total volume flow rate is $Q = V_{flow}A = (\Delta PD/16\mu)^{1/2}A$, where A is the total exit area of the reactor. This indicates that the smaller channel size does not fundamentally affect the total throughput.

Reactor volume. The total volume of the reactor is important because it governs power density, material costs and the ability to control reaction conditions (such as temperature). The total volume of a reactor is $AL_{complete} = A(\Delta P/4D\mu)^{1/2}r^2$, which indicates that smaller channels lead to much smaller reactor volumes.

Surface area. The most expensive element of many reactions is the surface-bound catalyst. The amount of catalyst required in an array of small channels compared with one large channel can be quantified using the ratio of surface areas $A_{array}/A_{single} = n2\pi r_{small}L_{small}/2\pi r_{large}L_{large}$, where n is the number of channels required in the array to maintain the same flow area. Putting $L_{complete}$ into the above yields $A_{array}/A_{single} = r_{small}/r_{large}$, which indicates that an array of small channels requires less catalyst than a single, large channel.

These well-established fluid transport arguments, in addition to their applicability for optofluidic reactors, form the basis of several existing industrial processes. Prime examples of such applications include fluidized bed reactors in the petrochemical industry (where fluids react within a bed of small catalytic particles) and membrane desalination systems (which transport sea water through nanochannel arrays to remove ions).

Thermal control at small scales is another opportunity offered by optofluidics in energy systems. Reducing the reactor volume significantly reduces the amount of energy required to maintain proper thermal conditions for photosynthetic growth or photocatalytic reactions. The same structures used to define fluidic flows and optical pathways can also be used to regulate the temperature of a fluid throughout a system. In a traditional photobioreactor, the large pipes are exposed to sunlight and light absorption through the volume of the fluid causes both a temperature increase and an exponential decay in light intensity. The result is a non-uniform light intensity distribution and corresponding non-uniform heat generation and/or photoreactions. In a microstructured reactor, arrays of optical waveguides can distribute the light uniformly throughout the volume. This can be achieved by using the same fluid channels to transport both the reactants and products. Alternatively, the fluid could surround the optical waveguides and be illuminated evanescently or through an outcoupling mechanism. Similar techniques are currently used in optofluidics, and they can be readily applied to solar reactors. It is worth noting that these applications will generally involve more complex fluids than those traditionally employed in optofluidic systems. The introduction of active photosynthetic microorganisms will present additional challenges with respect to light scattering, transport and biofouling, in addition to organism-specific temperature requirements.

As outlined in this Review, the ability of optofluidics to control light and fluids has particular relevance to energy applications. Examples covered here include energy conversion using photobioreactors, photocatalytic processes and light collection and control. The widespread use of optofluidics in the energy field will require further research in, for instance, facilitating complex photochemical reactions and addressing challenges in the creation of microstructured reactors, such as fabrication, clogging and fouling. These efforts will be well-motivated by the tremendous potential of optofluidics in energy. Looking ahead, we expect the fundamental strengths and scales of optofluidics to enable a broad spectrum of applications in the energy field.

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