Chip-scale solar thermal electrical power generation

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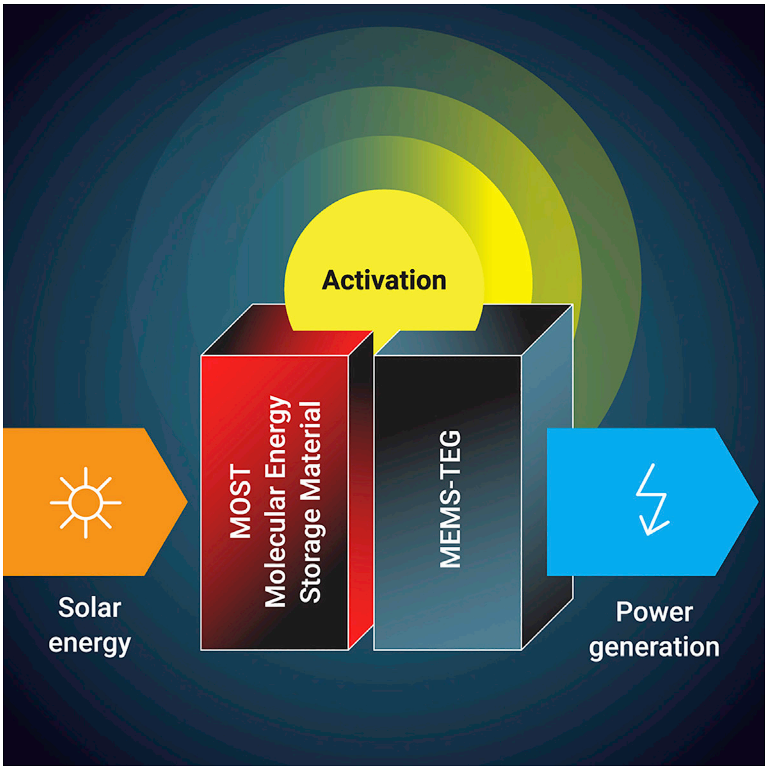

Molecular solar thermal energy storage is a technology based on photoswitchable materials, which allow sunlight to be stored and released as chemical energy on demand. Wang et al. demonstrate a molecular thermal power generation system that stores solar energy and converts it to electric power on demand.

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Highlights

Solar energy storage and conversion to electrical power generation is demonstrated

Continuous power output can be generated from the combined device

Photophysical properties of two photoswitches are fully characterized

A microelectromechanical ultrathin thermoelectric chip is designed and fabricated

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Chip-scale solar thermal electrical power generation

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SUMMARY

There is an urgent need for alternative compact technologies that can derive and store energy from the sun, especially the large amount of solar heat that is not effectively used for power generation. Here, we report a combination of solution- and neat-film-based molecular solar thermal (MOST) systems, where solar energy can be stored as chemical energy and released as heat, with microfabricated thermoelectric generators to produce electricity when solar radiation is not available. The photophysical properties of two MOST couples are characterized both in liquid with a catalytical cycling setup and in a phase-interconvertible neat film. Their suitable photophysical properties let us combine them individually with a microelectromechanical ultrathin thermoelectric chip to use the stored solar energy for electrical power generation. The generator can produce, as a proof of concept, a power output of up to 0.1 nW (power output per unit volume up to 1.3 W m^{-3}). Our results demonstrate that such a molecular thermal power generation system has a high potential to store and transfer solar power into electricity and is thus potentially independent of geographical restrictions.

INTRODUCTION

From the Industrial Revolution to 2018, the global average temperature increased by 1°C as a result of human activities and may hit 1.5°C as early as 2030, as warned by the United Nations Intergovernmental Panel on Climate Change (IPCC).[1] People have been actively looking for a technology that can slow down or reduce the rise in global temperature. As the global population increases, total worldwide energy use from all sectors is expected to reach 21 TWy by 2040, corresponding to an increase of 130% over 2019 levels.[2] Electricity is an essential commodity in modern society, and around 3 TW is currently used. To complicate matters, about 85% of this power is derived from fossil fuels.[3] Therefore, searching for new decarbonized energy sources to reduce greenhouse gas emissions is imminent. Nuclear energy is a low-carbon energy source, but its installations are complex, and their thermal pollution can potentially be serious. As the most common renewable energy at present, hydropower is geographically limited, while wind energy fluctuates with season or time.[4] It is noteworthy that solar energy is the most abundant energy resource on Earth, and maximizing the use of solar power can potentially meet the intensive demand for power while reducing detrimental effects to the environment.[5] For instance, an estimated 2.3×10^4 TWy of solar power reaches Earth each year, which equates to only 7 h of sunlight needed to meet current annual global energy requirements.[6,7]

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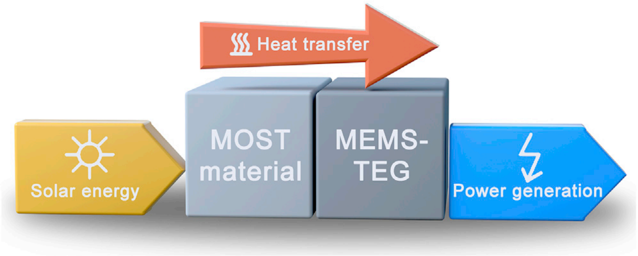
Photovoltaic (PV) cells can directly convert solar energy into electrical power with a maximum efficiency of around 30%, and most of the solar energy is not only lost as heat but also contributes to deteriorating the performance.[8–11] In addition, solar intensity naturally varies with time and geographical location and these variations currently limit the utilization of PV. Obviously, PV cells do not produce power during the night. Solar thermal power plants with phase-change molten salts can generate power for several hours after sunset; however, these plants require very large solar concentrators and consequently can be installed only in remote areas.[12,13] Previously, solar actuators based on hydrogen-bonded azopolymers for electricity generation have been investigated; however, the device cannot store solar energy for later on-demand power generation.[14] Hence, in addition to the above mainstream technologies, there is an urgent need for new alternative compact technologies that can derive and store energy from the sun, especially the large amount of solar heat that is not effectively used for future power generation. In this paper, we demonstrate a compact, chip-based device that allows for direct storage of solar energy as chemical energy that is released in the form of heat on demand and then converted into electrical energy in a controlled way.

To explore ways to store solar energy, we are investigating a class of materials that can capture sunlight via reversible photochemical reactions and later release this stored energy on demand. These materials operate in a closed cycle, and they use photochromic chemical compounds to form the basis of molecular solar thermal (MOST) energy storage systems.[15–18] Upon exposure to sunlight, a suitable MOST material (in the parent state) can photoisomerize to a high-energy metastable photoisomer that can be stored for extended periods of time. Depending on the photochrome used, the back-conversion reaction releasing heat energy can be triggered through different processes, including thermal,[19,20] catalytic,[21,22] electrocatalytic,[23,24] and photoinduced conversion.[25–27] It has been previously estimated that, for an ideal liquid MOST device, up to 21% of the solar energy can be stored as chemical energy for later heat production.[28] Such heat produced can be delivered locally and on demand, unlike other thermal storage technologies.

While MOST systems can be used in closed-cycle devices for efficient storage and release of heat, additional engineering is necessary to generate electrical power. Thermoelectric generators (TEGs) are able to directly convert thermal energy into electrical power via the Seebeck effect. TEGs have been widely used in various applications due to their attractive features such as silent operation, minimal maintenance, and long lifetime. And they have been considered as promising alternatives to meet the urgent demand for energy around the world.[29,30] Traditional solar thermal-to-electric power generation systems use heat engines to convert heat into electricity in two steps (heat to mechanical movements and then mechanical energy to electrical power generation).[31,32] However, a large amount of heat can be lost during the conversion process. To solve this issue, bulk TEGs have been combined with phase-change materials for power generation to convert heat to electricity directly.[31,33] Recently, low-dimensional material-based microelectromechanical system (MEMS) technology has enabled the production of ultrathin and highly sensitive TEG devices that can integrate large arrays of thermoelectric (TE) modules.[34] From our previous results, we explored a reliable and efficient hybrid method for ultrathin MEMS-TEG fabrication, and achieved up to 46,000 TE modules on a 3-in silicon wafer.[35,36] Such a MEMS-TEG equipped with an 800-nm-thin TE film has shown a steady electrical output, which was sensitive to small temperature differences and could effectively utilize low-grade thermal energy.[37] The temperatures accessible by the energy release reaction of the MOST are, at the current stage of



Scheme 1. Schematic illustration of the MOST to power generation concept

development, less than 100°C, which is not high enough to be utilized for electrical power generation by traditional means. Therefore, it is necessary to match the MOST systems with high-efficiency and sensitive TE devices to effectively utilize this relatively low-grade thermal energy.

Here, we design a compact, chip-based device that combines two different MOST systems operating either in the liquid or in the solid state with a novel designed MEMS-TEG to demonstrate the storage of solar energy to the release of heat energy and the cascading energy flow to the harvester that is finally used to generate power (see Scheme 1). Two molecular photoswitches with suitable properties—a norbornadiene derivative (NBD) investigated as a solution and a phase-interconvertible arylazopyrazole derivative (AZO) measured as a neat film—are selected for their potential to produce heat energy for electrical generation. The ultrathin MEMS-TEG with 572 TE modules is designed and fabricated, in which the TE films are only 1 μm thick. We characterize and couple each of these photoswitches individually with the MEMS-TEG chip (effective thermoelectricity area 10 × 6 mm), demonstrating that chemical energy stored in MOST systems (in Sweden) can successfully generate electrical power (in China) through the process of solar energy storage, heat release, and TE conversion, thus affirming that solar energy can generate electrical power independent of time and geographical restrictions.

RESULTS AND DISCUSSION

Solar energy storage properties

MOST systems can function in both liquid and film forms, which can be tailored toward different applications.[21,38–45] In liquid form, MOST systems can transport stored energy, meaning that energy can be stored and released in two different locations, whereas in film form, MOST systems can be used in smart windows and other device integrations.[43,46] In this study, we selected and tested two systems: an NBD in liquid form (in toluene solution, which can provide a low specific-heat capacity of ca. 1.6 $J\ g^{-1}\cdot{}^{\circ}C^{-1}$) and a neat AZO in thin films with suitable energy capture and storage functionality. The molecular structures of both photoswitch couples are shown in Figure 1A. The photoconversion of NBD proceeds via a [2 + 2π] cycloaddition reaction to its corresponding photoisomer quadricyclane derivative (QC). Thus, the energy storage density $\Delta H_{storage}$ was experimentally determined to be 93 $kJ\ mol^{-1}$ (0.37 $MJ\ kg^{-1}$). Meanwhile, QC has a thermal back conversion half-life of 1 month at room temperature, demonstrating the possibility for long-term storage in toluene. Spectroscopically, we previously showed that norbornadiene with a push-pull system has a spectral red-shifting effect on the absorption.[21] Hence, this NBD with dimethoxy donor units exhibits an absorption feature around 340 nm with a maximum absorptivity of $\varepsilon_{max@340\ nm} = 1.4 \times 10^4\ M^{-1}\ cm^{-1}$. In contrast, the absorption profile of QC is virtually negligible above 300 nm, leaving a transparent optical window of around 85 nm between both forms due to the selected push-pull substituents (see Figure 1B). This significant spectral

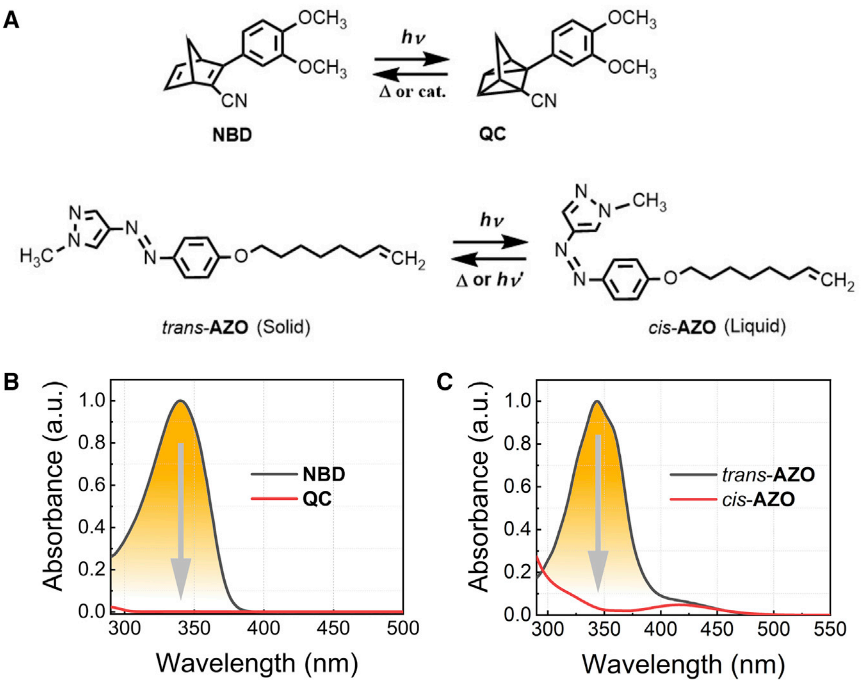


Figure 1. Structures and absorption spectra of the two MOST candidates used in this work
(A) Molecular structures of NBD-QC couple (top) and *trans*/*cis*-AZO photoswitch couple (bottom). A thermal (Δ) or catalytic (cat.) route can facilitate the back conversion of QC → NBD. The back conversion of *cis*- → *trans*-AZO can be achieved by a thermal or light-induced activation.
(B) Absorption profile of NBD before and after irradiation with 340-nm light (in toluene).
(C) Absorption profile of AZO photoswitch before and after irradiation with 365-nm light (in acetonitrile).

difference enables near-quantitative photoconversion, even in concentrated solutions. In addition, the photoisomerization quantum yield was 68% in toluene. Considering the above-mentioned MOST properties, solar energy storage efficiency of the system could exceed 0.70%[38] (see Note S1 for details).

Neat-film thermal storage devices have several attractive features, such as simple device integration and no need for mechanical pumping. Further, systems that combine energy input from solar irradiation with absorption of ambient heat have recently emerged.[46–55] Such systems couple a phase-change event to the photoconversion process found in MOST systems. One example is the AZO explored here (see Figure 1A). To take advantage of the exothermic process not only from the photoisomerization reaction but also from an additional phase-change process (liquid → crystal), we investigated the AZO photoswitch in its neat form. The energy stored in *cis*-AZO was easily released by triggering heat release following irradiation with a 532-nm light source (this wavelength is considered *cis*-AZO's onset of absorption). As shown in Figure 1C, the absorption maximum of the *trans* isomer was 344 nm with an absorptivity of $\varepsilon_{max@340\ nm} = 2.9 \times 10^4\ M^{-1}\ cm^{-1}$. The *trans*-AZO has a quantum yield of only 41%, but this is considered high for other azobenzene-based photoswitches. The photoisomerization energy density ΔH_{isom} was 52 kJ mol^{-1} (0.17 MJ kg^{-1}). In addition to heat release from the chemical reaction, the crystal-to-liquid transition (ΔH_{phase_change}) can provide an additional 50 kJ mol^{-1} (0.16 MJ kg^{-1}) of thermal energy because of its long alkenyl chain. As a result, the solar energy storage efficiency of the AZO couple was estimated to be 1.2%, which is much higher than that of other azobenzene photoswitches.[40] Moreover, *cis*-AZO is remarkably stable at room

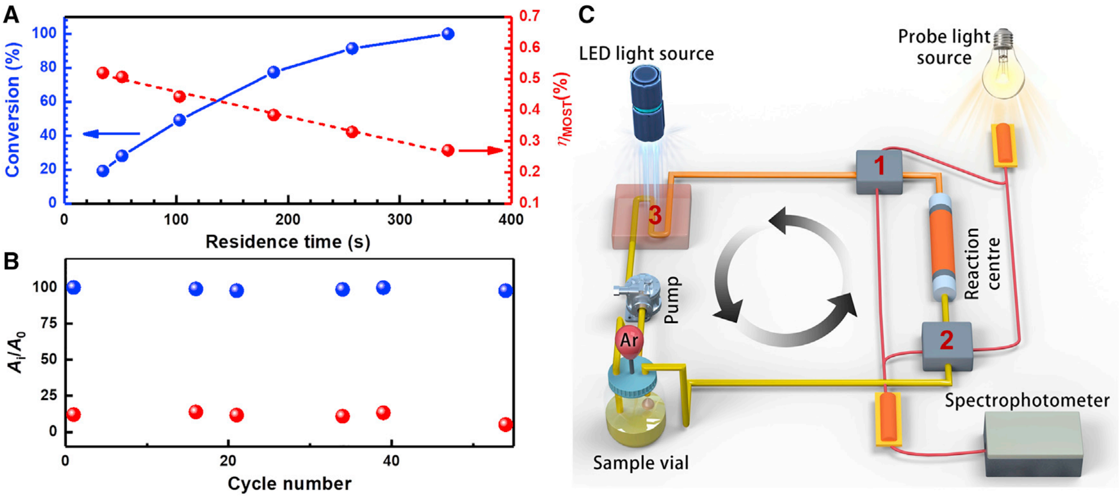


Figure 2. Conversion performance, cycling performance, and experimental setup of NBD in the device

(A) Conversion percentage (in blue) and calculated energy storage efficiency (in red) of 0.1 M NBD in toluene as a function of residence time in the device.

(B) Normalized absorbance before irradiation with 340 nm LED light and after catalytic reactor. Blue dots show the normalized absorbance at 340 nm, red dots show the normalized absorbance after irradiation.

(C) Cycling test setup for NBD. Boxes 1 and 2 represent the flow UV-vis spectrometer before and after a catalytic reaction center. Box 3 refers to the microfluidic chip. The conversion process has proceeded with irradiation from a 340 nm LED lamp.

temperature, with a thermal half-life of 3 months at 25°C. Thus, using this photoswitch from a neat film would allow two different sources of stored energy to be used: thermal ambient energy and light.[46,47]

Photoconversion in the device under various exposure times and complete interconversion through multiple cycles are important tests for photoswitch viability in a MOST system. These experimental factors have previously been reported for AZO[46] but not for NBD. Therefore, additional experiments were necessary to determine the compatibility of the NBD photoswitch. A custom-made 400-mm^2 microfluidic reactor was used for this photoconversion experiment (see Note S2 and Figure S1 for details). A solution of 0.1 M NBD (25 g L^{-1}) in toluene-d$_8$ was pumped through the microfluidic reactor with residence times from 34 to 343 s. The degree of photoconversion was monitored immediately afterward by ^{1}H NMR spectroscopy. For an ideal MOST system, where the absorption of the photoisomer (QC) does not compete with the absorption of the parent (NBD), the energy storage efficiency, η_{MOST}, should remain approximately unchanged prior to full conversion.[40,45,56] Here, we observed a decrease in solar energy storage efficiency from ≈0.5% at short residence times to 0.25% at full conversion. While not ideal, it is normal for efficiency to lower progressively during the conversion process. In this context, this system is better than our previous attempts at flow conversion (see Figure 2A and Note S3 for details).[21]

Typically, for cyclability testing, solution-based photoswitches are irradiated at elevated temperatures.[21,45] However, this method seemed impractical as QC has a long half-life ($t_{1/2}$≈29 days) in toluene. To address this, an alternate protocol was employed, which hastened the time frame for each successive cycle. Cobalt(II) phthalocyanine is physisorbed on activated carbon (CoPc@C) and can rapidly facilitate the back reaction of a very similar quadricyclane structure.[21] This new setup involved converting and back converting an NBD solution (0.5 mM in toluene) continuously through a microfluidic photoreactor and a catalytic reactor in a closed

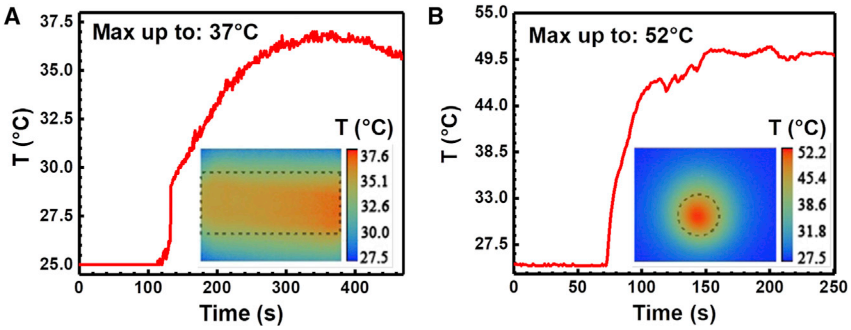


Figure 3. Macroscopic heat-release performance of QC and *cis*-AZO under infrared camera

(A) Recorded temperature increment of QC heat release over time; inset shows the thermal image from the heat-releasing copper device. The area indicated by the dashed line represents the device position.

(B) Recorded temperature increment of the *cis*-AZO system over time; inset shows the thermal image from the heat-releasing *cis*-AZO sample. The dashed line represents the position of the compound (maximum temperature gradient of 17°C after the heat generated from the laser is subtracted).

cycle. Happily, no obvious drop in performance was observed after 54 charge and discharge cycles on the NBD couple (see Figures 2B and 2C and Note S4 for details). This setup drastically reduced the total experimental time to only 61 h.

Stored energy release for NBD and AZO

Once solar energy is stored as QC and *cis*-AZO, one should be able to release the chemical energy from these metastable compounds as heat. However, we performed simulations to determine how much energy could be extracted from these charged materials. To achieve this, a simulation of possible temperature increases based on molecular parameters was performed. In the case of QC, the maximum temperature increase depended on the concentration of initial NBD in toluene. Based on the highest possible concentration of 0.78 M in toluene, the maximum estimated temperature difference under adiabatic conditions was 40°C (see Note S5 and Figure S2 for details).

To test the experiment in practice, we designed a fixed-bed catalytic heat-release device consisting of a copper tube flanked on two sides with copper plates to maximize heat transfer to the MEMS-TEG device (see Note S6 and Figure S3 for details). By taking advantage of the mobile nature of the QC solution, a heterogeneous CoPc@C catalyst[21] was loaded inside the copper tube, and a thermally conductive pad was used to provide a homogeneous thermal distribution from the tube to all areas of the device. A saturated NBD solution was initially photoconverted to QC and then pumped through the reactor at a flow speed of 5 mL h^{-1}. This speed leads to complete back conversion from QC to NBD and a maximum surface temperature of 37°C ($\approx$13°C maximum temperature gradient, see Figure 3A and Video S1 for details). A thermal camera recorded liquid-QC macroscopic heat release, determined by the camera focusing on the top of the device.

Concerning the *trans*/*cis*-AZO photoswitch couple, the charged *cis* isomer releases 0.17 MJ kg^{-1}, equating to a simulated thermal difference of 84°C. From here, an additional 0.16 MJ kg^{-1} can be extracted at the crystallization point of the *trans*-AZO (melting point 83°C) from the phase-change event. Thus, *cis*-AZO theoretically shows a larger potential thermal gradient than the QC solution. In this case, the experimental measurement of the heat release involved the placement of a droplet of liquid *cis*-AZO ($\approx$8 mg) under ambient conditions onto a glass substrate

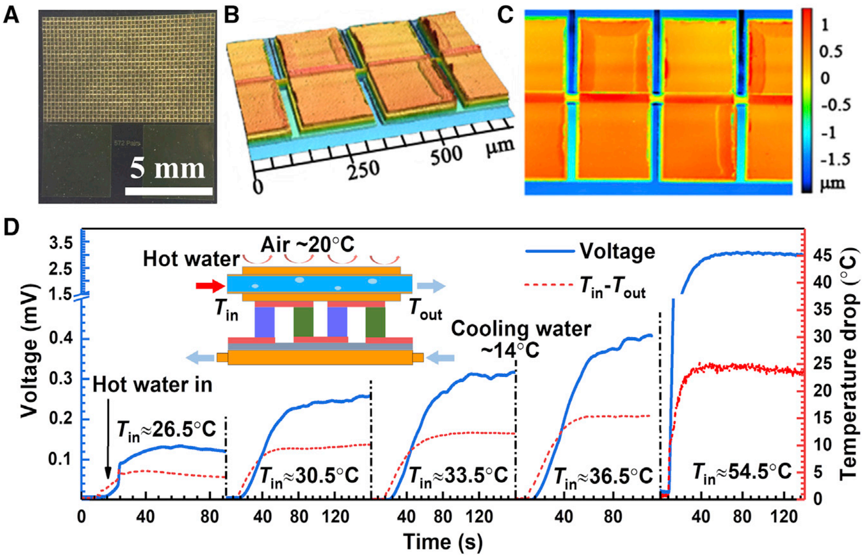


Figure 4. Thermal performance of MEMS-TEG used in this work

(A) Optical microscope photo of MEMS-TEG with 572 TE modules.

(B) Three-dimensional laser scanning confocal microscope images of the fabricated thermoelectric pairs.

(C) Top view of the fabricated thermoelectric pairs by laser scanning confocal microscopy. Scale bar shows the relative height of the device.

(D) Power generation of MEMS-TEG when hot water of different temperature flows through the copper tube at the hot end of the TEG.

(1 × 0.7 cm). A 532 nm laser was used to irradiate the sample and trigger the heat release in conjunction with a thermal camera. This triggered a full back conversion, affording a maximum surface temperature of 52°C, corresponding to a 17°C maximum temperature difference after accounting for heat from the laser. The large difference in temperature gradient between theoretical and experimental values is likely due to the strong heat dissipation from the thin film under ambient conditions (see Figure 3B and Video S2 for details). The thermal camera recorded the *cis*-AZO film macroscopic heat release.

These results showed that both solution-based NBD and neat AZO photoswitches can successfully generate heat. Next, we wanted to use this thermal energy by converting it to electrical power using the MEMS-TEG device.

Single-layered microelectromechanical thermoelectric chip

Theoretically, the figures of merit (ZT_{ave}) of low-dimensional TE materials are higher than those of bulk TE materials and can potentially yield a higher TE conversion efficiency.[57] Thin-film-based TE devices are also sensitive to small temperature differences.[35] Such technology can be used to monitor local thermal variations at micro-nano scales, such as bioactivity in yeast cultures.[58] On the other hand, if the number of integrated TE modules is high enough, the output electrical power can be significantly increased.[59] To effectively convert the heat released from MOST systems to electrical power, a large array integrated MEMS-TEG based on Bi_2Te_3 (n type) and Sb_2Te_3 (p type) TE modules was fabricated. The unit structure is designed in a Π shape, with a resistance of 72.8 Ω and a single p/n surface area of 200 × 200 μm. The fabrication process and structure diagram of the MEMS-TEG device are shown in Note S7, Figures S4–S9, and Table S1. In total, 572 TE modules were connected in series, where the height of each TE column was increased to ∼1 μm with the aim of improving the TE performance at low temperature gradients,

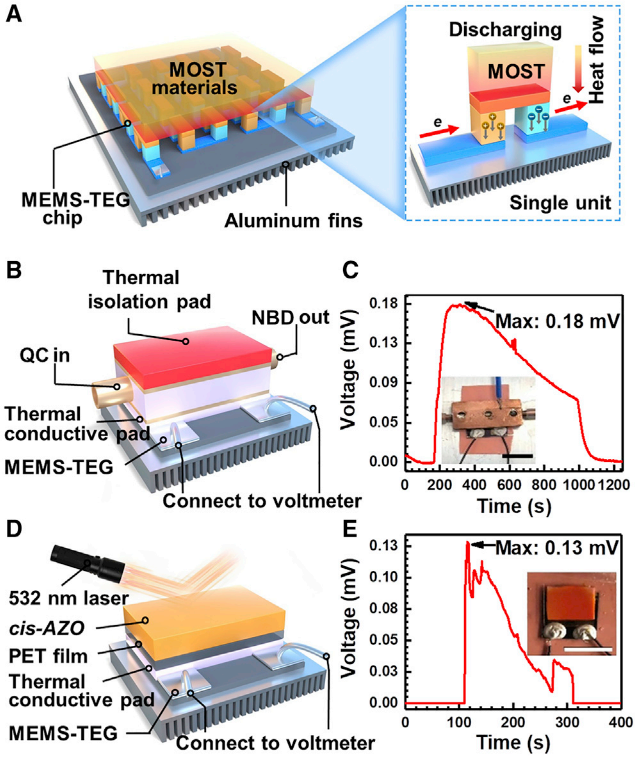


Figure 5. MOST to power generation performance

(A) Schematic concept of MOST to power generation.

(B) NBD couple-based solar energy storage for power-generation experimental setup.

(C) Heat release monitoring by thermocouple and voltage generated from MEMS-TEG chip over time. The inset is a photo of the device. Scale bar, 1 cm.

(D) Schematic experimental setup of AZO film-based solar energy for power generation.

(E) Net voltage generated from MEMS-TEG chip over time. The inset is a photo of the device. Scale bar, 1 cm.

as shown in Figure 4.[37] Most importantly, the thickness of the whole working part from the chip did not exceed 2 μm. This ultrathin structure (thickness of top contact layer of only ~300 nm and a mass of only a few picograms) responded effectively to small variations in temperature. The structure and properties of the TE materials constituting the MEMS-TEG and the power generation performance of the device are shown in Table S1 and Figures S5–S8. Since the heat released by QC in the copper tube does not cover all the tubes uniformly, as shown in Figure 3, a reference experiment was conducted to investigate the power generation of the MEMS-TEG by passing hot water into the copper tube at a flow speed of 73 mL h^{-1} in advance (see Figure S9). When the temperature of the inlet hot water was 36.5°C and 54.5°C, the corresponding voltages generated by the MEMS-TEG were 0.4 mV (maximum power output of density 6 W m^{-3}) and 3 mV (maximum power output of density 349 W m^{-3}), respectively. This shows that the higher the average temperature in the MOST reaction chamber, the greater the power output density can be reached.

Power generation from NBD and AZO

Based on the physical properties of NBD and AZO couples, two heat-to-power generation device concepts were put forth (see Figure 5A). For the NBD system, a saturated solution of QC in toluene was prepared in Gothenburg, Sweden, using a photochemical flow reactor (see Note S8 and Figure S10 for details) and shipped to Shanghai, China. For this experiment, 5 mg of CoPc@C was loaded inside the catalytic reactor (inside the central copper tube), where a thermally conductive pad was used to fill the gap between copper plates in the device (see Figure 5B). The reactor was placed above the MEMS-TEG chip, and the whole setup was then placed on top of an aluminum brick heat sink, which ensured a stable ambient temperature and served as the cold side of the device. Importantly, the hot side of the system was covered with thermally insulated plastic foam to ensure that the heat generated was reflected instead of being lost to the environment. As a result, with less than 1 mL of a 0.78 M solution and a flow speed of 5 mL h^{-1}, a measured bias voltage of up to 0.18 mV was recorded. According to the MEMS-TEG chip characterization, this voltage can generate a maximum power output of $\approx$0.1 nW (power output density of 1.3 W m^{-3}, see Figure 5C). With the same flow speed, a continuous operating test with slightly lower concentration of 0.62 M in toluene was also performed. This successfully generated, for the first time, a total electric energy of up to 0.44 W $h \cdot m^{-3}$ over 24 min (see Note S9 and Figure S11).

In the case of AZO, a smaller amount of material was used; 7 mg of *cis*-AZO, generated from a 365 nm LED light source, was loaded onto the thermally conductive pad. A polyethylene terephthalate (PET) film was gently pressed on top of the material to allow it to fully cover the surface of the MEMS-TEG chip evenly. Laser irradiation at 532 nm triggered the back conversion (see Figure 5D), leading to a bias output voltage of up to 0.13 mV. This corresponds to a maximum power output of 0.06 nW (power output density of 0.7 W m^{-3}) (see Note S10 and Figures S12–S15 for details). Interestingly, various peaks were observed when the voltage approached the maximum. This was likely due to the complex release of heat, which involved both photoisomerization and phase transitions (see Figure 5E). We observed that less power is generated from *cis*-AZO than from QC, although the former reached a higher surface temperature, but the temperature distribution in the latter tube is more even. Not surprisingly, this is because the amount of heat released from these two systems is markedly different: 1 mL of 0.78 M QC could produce 72.5 J, while 7 mg of *cis*-AZO could produce only 2.3 J of energy.

Here, we noticed that the maximum temperatures reached by the NBD couple and the AZO couple are 37°C and 52°C, respectively, while the corresponding voltages generated by MEMS-TEG are 0.18 and 0.13 mV, respectively. However, compared with the hot water with similar temperature, the maximum power output density generated by the NBD couple and the AZO couple is greatly reduced. It is worth noting that the hot water flowing continuously and rapidly in the copper reactor has a better thermal contact surface with the pipe wall than the discharging QC solution and *cis*-AZO film. Consequently, the hot water flowing at a temperature of 36.5°C makes the power density generated by MEMS-TEG nearly 5 times that of the QC solution with similar temperature (37°C). This demonstrates that, with the MOST materials at hand, better thermal management and TE materials may increase the power output of the next generation of devices.

To the best of our knowledge, these results show the first proof of principle that solution-based MOST and PCM-MOST systems can generate electric power. Future work should focus on red shifting the absorption band (capturing more sunlight) and increasing the temperature gradient produced by the back reaction (improving energy density). The next generation of combined devices should include a better thermal management system to avoid heat dissipation from the MOST system to the surrounding environment, thereby increasing the amount of heat energy converted to electrical power output. Based on the TE film preparation method,[60] the TE efficiency can be simulated to be over 8% at room temperature (ZT_{ave} = 2.4) and around 29% between 0 and 100 K (ZT_{ave} = 1.0) with a temperature difference of 100°C (see Note S11 and Figure S16 for details), assuming that MOST systems can achieve this absolute temperature of 100°C, which is close to what has recently been demonstrated.[21] Producing a highly soluble photoswitch of ca. 1.5 M, accompanied by a heat release of 100 kJ mol^{-1} with a 5 mL h^{-1} flow speed, would allow the system to produce a power output of 16.7 mW (0.2 GW m^{-3}) at room temperature and 60.4 mW (0.7 GW m^{-3}) at temperatures of 0–100 K. This would be enough to power a low-power-supplied Internet of Things device on Earth or in the outer space environment.[61]

In this work, we have shown two molecular photoswitches in different physical forms (liquid-based NBD and neat AZO film) for coupling MOST systems with electrical power generation via MEMS-TEG devices. The liquid-based NBD exhibits a solar energy storage efficiency of ≈0.5% in 0.5 mM toluene, which is more efficient than photosynthesis (0.1%–0.3%).[62] NBD was also, for the first time, tested through 54 charge and discharge cycles in a continuously operating energy storage and catalyzed release cycle, and showed no sign of degradation. Alternatively, the PCM-MOST hybrid neat AZO film captures and releases energy in photochemical solid-liquid transitions, which allows the MOST system to harness energy both from sunlight and from the ambient environment, meaning that upgraded heat can be produced on demand. Comparing the two candidates, both of them can store solar energy in the visible range for over a month at room temperature. To improve the macroscopic heat-release capability, future investigation of increasing the solubility of liquid-based NBD is necessary. For neat AZO, with addition phase-change properties, the overall energy storage capacity has been greatly improved. However, due to the light-induced back-conversion property of AZO, for future real-world-conditions device design, it is necessary to add a band-pass filter that is able to filter out the photons that initiate back conversion of AZO.

To demonstrate generation of power from the MOST system, an ultrathin-film-based, highly sensitive MEMS-TEG device was used to capture the heat released from either scenario. For the first time, electricity was produced in this setup, with power output up to 0.1 nW (power output per unit volume up to 1.3 W m^{-3}). Furthermore, this device continuously generated electricity, for the first time, for over 25 min. We note that this is a very compact and local solar energy storage-power generation system that operates through a mechanism entirely different from traditional PV-battery storage combinations. Furthermore, these systems can be charged and discharged across different geographic locations (Sweden to China in this work) over a few months, showing that solar energy can be stored for power generation on demand. Although the efficiency of these systems needs to be improved, we envision that they can be used in local power generation applications in the future.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and procedures should be directed to the lead contact, Prof. Kasper Moth-Poulsen (kasper.moth-poulsen@chalmers.se).

Materials availability

NBD and AZO were synthesized by following the existing procedure in the literature.[38,46] All QC samples were prepared by irradiating an NBD solution with a 340 nm LED light source from Thorlabs. The conversion percentage was checked by either a ^{1}H NMR 400 MHz instrument or a Cary 60 UV-vis spectrophotometer.

CoPc@C catalyst was produced by following the existing procedure.[3] The *cis*-AZO state was prepared using a 365 nm LED light source. For photoinduced back conversion, a 532 nm laser (110 mW cm^{-2}, the beam diameter of 1.3 cm) was used to prepare the *trans*-AZO state by irradiating the *cis*-AZO sample. All solution-based spectroscopic measurements were performed in a cuvette with path length of 1 cm on a Cary 100 UV-vis spectrophotometer, scanning the wavelength from 750 to 290 nm. Absorption spectra for the outdoor test were recorded by two microflow cells and a portable spectrometer, which was purchased from Avantes. Teflon plastic tubing used was from Cole-Parmer Instrument Company.

Data and code availability

All of the data supporting the findings are presented within the article and supplemental information. All other data are available from the lead contact upon reasonable request.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2022.100789.

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AUTHOR CONTRIBUTIONS

Z. Wang performed all the material and MEMS-TEG chip characterizations, conversion tests, cycling tests, heat-release experiments, and power-generation demonstrations. Z. Wu carried out the MEMS-TEG chip fabrication, characterization, and TE efficiency simulation. E.M. and Z.Y.Z. performed the heat-release experiments and power-generation experiments. Y.L., X.F., and F.W. performed MEMS-TEG chip fabrication. J.O.H. performed the sample preparation with an automated flow system. M.J. and Z.Y.Z. synthesized the used compounds. Z. Wang, Z.H., T.L., and K.M.P. designed the experiments. All authors contributed to writing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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