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Micro-cable structured textile for simultaneously harvesting solar and mechanical energy

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Developing lightweight, flexible, foldable and sustainable power sources with simple transport and storage remains a challenge and an urgent need for the advancement of next-generation wearable electronics. Here, we report a micro-cable power textile for simultaneously harvesting energy from ambient sunshine and mechanical movement. Solar cells fabricated from lightweight polymer fibres into micro cables are then woven via a shuttle-flying process with fibre-based triboelectric nanogenerators to create a smart fabric. A single layer of such fabric is 320 μm thick and can be integrated into various cloths, curtains, tents and so on. This hybrid power textile, fabricated with a size of 4 cm by 5 cm, was demonstrated to charge a 2 mF commercial capacitor up to 2 V in 1 min under ambient sunlight in the presence of mechanical excitation, such as human motion and wind blowing. The textile could continuously power an electronic watch, directly charge a cell phone and drive water splitting reactions.

In light of concerns about global warming and energy crises, searching for renewable energy resources that are not detrimental to the environment is one of the most urgent challenges to the sustainable development of human civilization[1–3]. Generating electricity from natural forces provides a superior solution to alleviate expanding energy needs on a sustainable basis[4–9]. With the rapid advancement of modern technologies, developing lightweight, flexible, sustainable and stable power sources remains both highly desirable and a challenge[10–16]. Solar irradiance and mechanical motion are clean and renewable energy sources[17–24]. Fabric-based materials are most common for humans and fibre-based textiles can effectively accommodate the complex deformations induced by body motion[25–32]. A smart textile that generates electrical power from absorbed solar irradiance and mechanical motion could be an important step towards next-generation wearable electronics.

Here, we present a foldable and sustainable power source by fabricating an all-solid hybrid power textile with economically viable materials and scalable fabrication technologies. Based on lightweight and low-cost polymer fibres, the reported hybrid power textile introduces a new module fabrication strategy by weaving it in a staggered way on an industrial weaving machine via a shuttle-flying process. Colourful textile modules with arbitrary size and various weaving patterns are demonstrated. Featuring decent breathability and robustness, the hybrid power textile was demonstrated to harvest energy simultaneously from ambient sunshine and human biomechanical movement in a wearable manner with or without encapsulation. The hybrid power textile is highly deformable in response to human motion. Mixed with colourful wool fibres, the hybrid power textile with a size of 4 cm by 5 cm is capable of stably delivering an output power of 0.5 mW with a wide range of loading resistances from 10 KΩ to 10 MΩ for a human walking under sunlight of intensity 80 mW cm^{-2}. More importantly, the power textile can be also adopted for large-area application such as curtains and tents. Under ambient sunlight with movement of a car or wind blowing, the textile delivered sufficient power to charge a 2 mF commercial capacitor up to 2 V in 1 min, continuously drive an electronic watch, directly charge a cell phone, as well as drive the water splitting reactions.

Structural design

The main idea for the design is to use a polymer-fibre-based solar cell as the basic component in fabricating a triboelectric nanogenerator (TENG) so that both light and mechanical energy can be harvested simultaneously. The wearable all-solid hybrid power textile has a single-layer interlaced structure, which is a mixture of two polymer-wire-based energy harvesters, including both a fabric TENG to convert mechanical movement into electricity and a photovoltaic textile to gather power from ambient sunlight, as schematically illustrated in Fig. 1a,b, respectively. An enlarged view of the interlaced structure is presented for both the fabric TENG (Fig. 1c) and photovoltaic textile (Fig. 1d). A scanning electron microscopy (SEM) image of the photoanode in the photovoltaic textile is shown in Fig. 1e. A counter electrode was also made of Cu-coated polymer fibre. It is worth noting that assembled on polymer fibres via a low-temperature wet process, all of the electrodes are fully compatible with high-throughput textile processing. Strings of the wire-shaped photoanodes, Cu-coated polytetrafluoroethylene (PTFE) stripes and copper electrodes were woven in a staggered way on an industrial weaving machine to fabricate the hybrid power textile via a shuttle-flying process[33], as shown in Supplementary Video 1. Here, to simplify the structural design of the hybrid power textile, both the photovoltaic textile and the fabric TENG employed copper as one of the electrodes. In the meanwhile, lightweight polymer fibre was chosen as the photoanode substrate of the photovoltaic component to improve its mechanical strength and flexibility, which greatly contribute to an effective combination of the two components in the hybrid power textile for simultaneously harvesting solar and mechanical energy. Figure 1f is a photograph of a piece of as-woven hybrid power textile mixed with commercial wool fibres, which is highly flexible, colourful and

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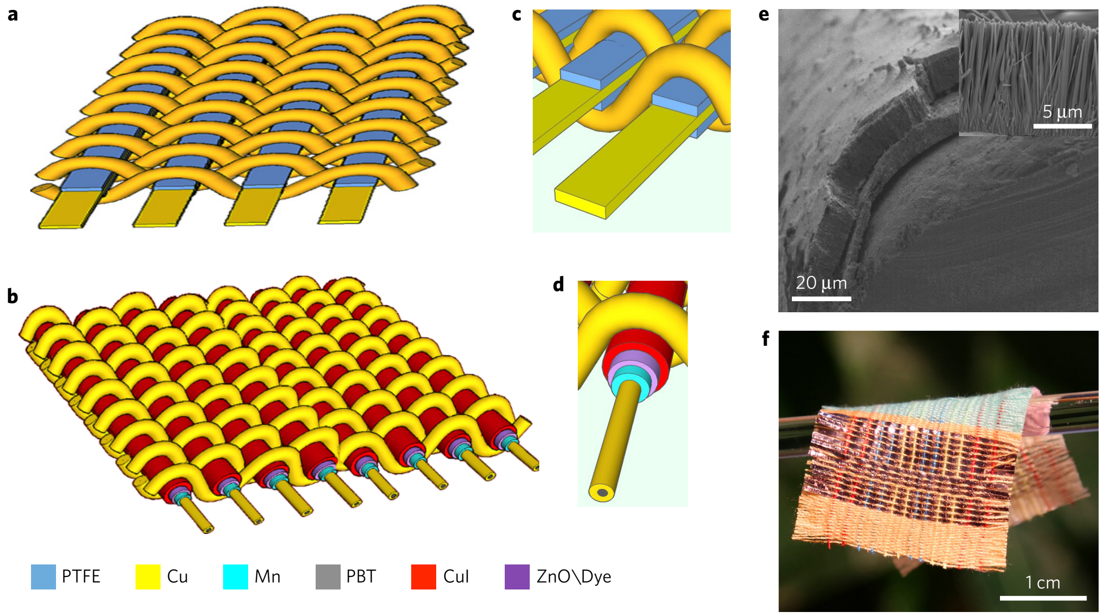

Figure 1 | Structural design of the hybrid power textile. a,**b**, Schematic illustration of the hybrid power textile, which is a mixture of two textile-based all-solid energy harvesters: fabric TENG (**a**) and photovoltaic textile(**b**). **c**,**d**, Enlarged view of the interlaced structure of both the fabric TENG (**c**) and the photovoltaic textile (**d**). **e**, SEM image of the photoanode employed in the photovoltaic textile. Inset: the ZnO-nanowire arrays grown on the Mn-plated polymer wire substrate. **f**, A photograph of the hybrid power textile mixed with coloured wool wires.

wearable, with a thickness of about 0.32 mm. As demonstrated in Supplementary Video 2, it is highly sensitive and deformable in response to external mechanical excitation.

Electrical signal generation

The working principle of the hybrid power textile for electrical signal generation can be elucidated from two aspects, namely, the photovoltaic textile to generate power from absorbed solar irradiance, and the fabric TENG to convert mechanical movement into electricity. In the first aspect, Supplementary Fig. 1 shows the working principle of the photovoltaic textile for solar energy harvesting. Excited by the photons, the holes and electrons on the ZnO\dye interface become separated and form hole–electron pairs. Then, the holes are injected into and travel along the axial direction in the all-solid hole-transporting layer, and are eventually collected by the wire-shaped counter electrode. Meanwhile, electrons are transported via the conducting band of the semiconductor, and finally collected by the photoanode. In this process, the absorbed solar energy was converted into electricity in the external load.

In the other aspect, as illustrated in Supplementary Fig. 2, taking two adjacent PTFE strips in the fabric TENG as an example, the interlaced copper electrodes can be brought into contact with PTFE stripes under a mechanical excitation applied to the power textile. The difference in electron affinity between the copper and PTFE causes a charge transfer at the interface, which results in positively charged copper and negatively charged PTFE. When the deformed fabric is released, the mechanical-motion-induced separation between the charged copper and PTFE results in a flow of electrons from the PTFE back-coated electrode to the copper strings[34,35]. Another return contact between the charged copper strings and PTFE strips generates a back flow of the electrons between the electrodes. This describes a full cycle of the electricity generation process of the fabric TENG for mechanical energy conversion.

Optimization of the photovoltaic textile

To comprehensively investigate the hybrid power textile, the first step taken was to study and optimize the individual components. Different from orthodox mosaic-like solar modules composed of small solar units, strings of the wire-shaped photoanodes and counter electrodes were woven in an interlaced manner, to form a single-layered textile. First, the electrical connection among the strings in the photovoltaic textile is a key factor to achieve a desired power output. As shown in Fig. 2a, in parallel connection, the current of the textile could be obviously improved by increasing the number of strings in the wire-shaped photoanode from one to five, without a serious negative impact on the textile voltage output. Meanwhile, the voltage output of the textile could be effectively improved by electrically connecting multiple strings in series, as demonstrated in Fig. 2b. As a result, the electrical output of the photovoltaic textile can be designed by tuning the number of strings and their electrical connections, providing great convenience in matching the power delivery from the fabric TENG part, and fulfilling the power requirements of various portable electronic devices.

The weaving patterns used in the photovoltaic textile also have an impact on the ambient solar energy conversion. To investigate this, three basic weaving patterns, plain, twill and satin, were employed to study the weaving-pattern-dependent photovoltaic performance of the textile. The detailed procedures for obtaining various weaving patterns for the power textile are presented in Supplementary Note 1. As elucidated in Fig. 2c, the photovoltaic textile works well in different weaving patterns. Also it is found that the overall energy conversion efficiency is a monotonically increasing function of the ratio of the effective illuminated area of the textile, namely, the textile projected area, as illustrated in Supplementary Fig. 3. Also, for the mixed textile composed of both wire-shape solar cells and other fibres, the projected area of other fibres was deducted in the calculation. Of the three basic weaving patterns, the plain-weave structure has the largest effective illumination area ratio of 96.1%, which delivers the highest current density of 6.35 $mA\,cm^{-2}$, and the satin-weave pattern has the smallest effective illumination area ratio of 87.3%, corresponding to the lowest current output of 5.8 $mA\,cm^{-2}$. The light-intensity-dependent photovoltaic performance of the textile was also studied, as shown in Fig. 2d. Here, 100% represents the standard one-sun condition, corresponding to a light intensity of 1,000 $W\,m^{-2}$. A

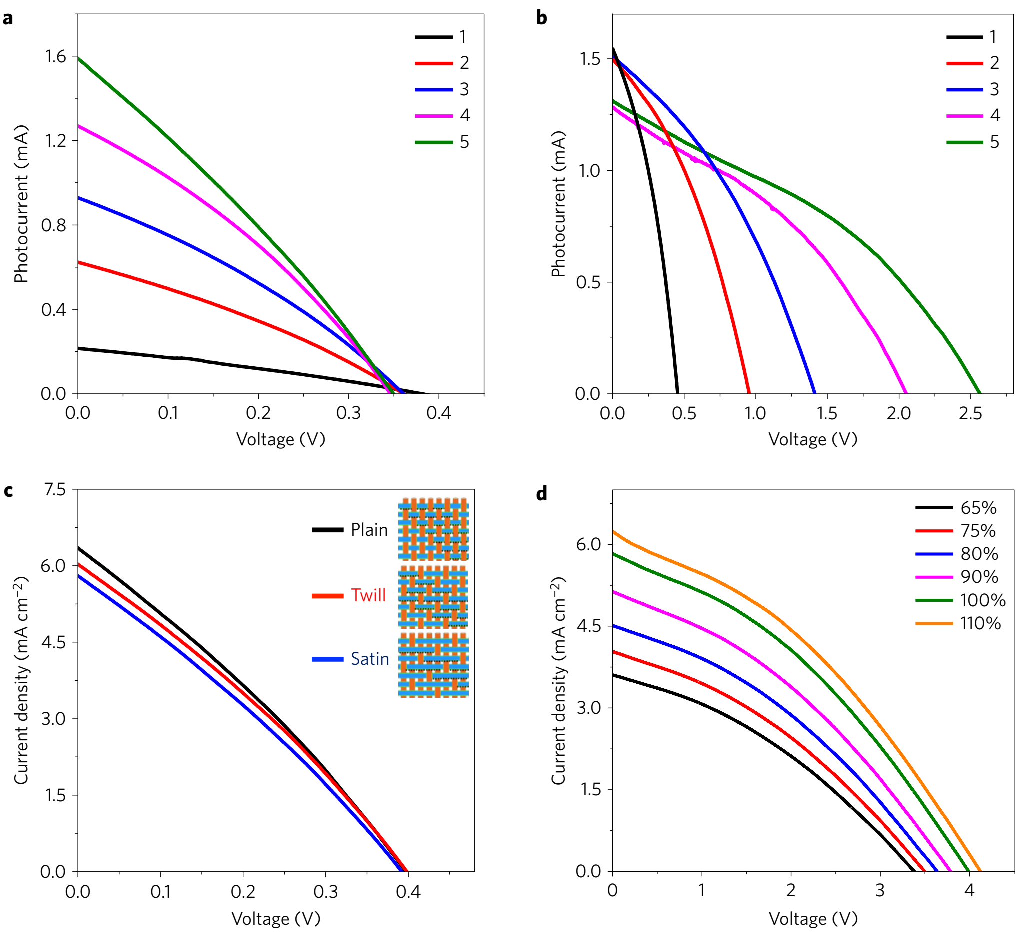

Figure 2 | Photovoltaic textile and its electrical output characterization. a,**b**, Electrical output of the photovoltaic textile with an increasing number of strings connected in parallel (**a**) and in series (**b**). **c**, Weaving-pattern-dependent photovoltaic performance of the textile. **d**, Light-intensity-dependent photovoltaic performance of the as-fabricated photovoltaic textile. Here, 100% represents the standard one-sun condition, corresponding to a light intensity of 1,000 W m^{-2}.

larger power output is expected at a higher light intensity for the photovoltaic textile.

Optimization of the fabric TENG

Another pivotal component of the hybrid power textile, the fabric TENG, was also systematically investigated and optimized. Figure 3 reports a fibre-based TENG and characterization of its electrical output. The fabric TENG was fabricated via a shuttle-flying process, as pictured in Fig. 3a. Given that all the copper electrodes are simply connected in parallel, both the voltage and current output of the fabric TENG increase with an increasing number of PTFE stripes. Here, an average of nine deformation cycles were needed before reaching a stable electrical output, which is mainly ascribed to the requirement for surface charge accumulation and a saturation process in the course of contact electrification[36,37]. Furthermore, as a wearable textile, the weaving patterns of the fabric TENG are not only important for commercial applications, but also have a great impact on its electrical output, as demonstrated in Fig. 3b. Under mechanical excitation, such as hand clapping, the electrical output with three basic weaving patterns—plain, satin and twill, as well as their mixed patterns—was systematically investigated, as shown in Fig. 3c. To ensure quantitative and reproducible results in the experiment, the hand clapping was simulated by the impact force of a flat object with controllable heights of fall and acceleration, as elaborated in Supplementary Fig. 4. The results indicated that the output performance of the fabric TENG is dependent on the pattern, and works well for various weaving patterns. Of all the weaving patterns, the plain-weave structure delivers the highest electrical output, while the twill-weave pattern exhibits the lowest. This is mainly attributed to a disparity in the effective contact area due to a variation in string-packing density between the PTFE stripes and copper electrodes in the weaving patterns[38,39]. Also it is interesting to find that the output performance of the fabric TENGs with mixed weaving patterns is intermediate between the corresponding basic patterns.

To systematically investigate the fabric TENG for mechanical energy conversion, four basic excitation modes were studied for the plain-woven fabric TENG, as illustrated in Fig. 3d. Excitation modes I and II are respectively to fold the textile parallel or perpendicular to the PTFE stripes. Mode III is to fold the textile along its diagonal line, while mode IV is to clap the textile with a flat surface, as illustrated in Supplementary Fig. 5. As presented in Fig. 3e, of all the excitation modes, the output power from mode IV is the highest, followed by mode I, and then modes II and III. In addition, a further step was taken to study the dependence of the electrical output on the impact momentum under excitation mode IV. As shown in Fig. 3f, the output power of fabric TENG is an increasing function of the external impact momentum. This observation is mainly attributed to the fact that, under external impact, both contact separation and relative sliding could occur between the electrodes and the PTFE stripes, where the relative-movement-induced friction would contribute a large portion to the total electrical output. At larger impact momentum, the air gaps between the electrodes and PTFE strips obviously decreased, which contributed to a larger electrical output[40,41].

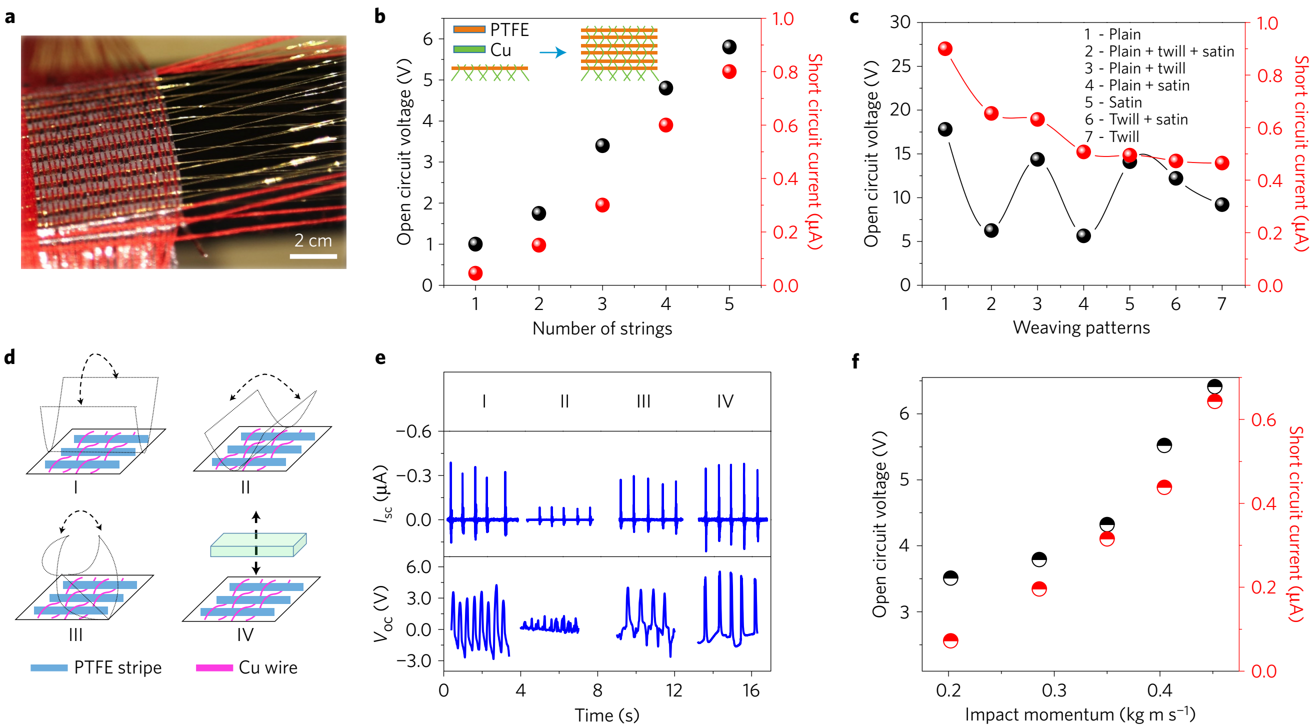

Figure 3 | Fabric TENG and its electrical output characterization. a, Photograph showing the textile weaving process. **b**, Influence of number of PTFE stripes on the textile electrical output. **c**, Weaving-pattern-dependent electrical output. **d**,**e**, Sketch showing the four basic excitation modes of the fabric TENG (**d**) and the corresponding directly measured electrical signals (**e**). **f**, Dependence of the electrical output of the fabric TENG on the impact momentum under working mode IV.

Optimization of the hybrid power textile

After a comprehensive investigation of the individual components of the hybrid power textile, the electrical connections and hybridization patterns between components need also to be systematically optimized to maximize its energy efficiency. On one hand, due to a much lower internal impedance of the photovoltaic textile than that of the fabric TENG, the two are complementary in electricity generation and the latter delivers a relatively low current output in comparison to its voltage output[42–45]. A mismatch of the impedance would result in a large current leakage, which will seriously contaminate the final output power of the hybrid textile. As illustrated in Fig. 4a and Supplementary Fig. 6, three electrical connection strategies—in series, in parallel and regulated with unidirectional blocking diodes—were systematically designed and tested to optimize the electrical inter-connection between the triboelectric and photovoltaic textile components. Owing to the high internal impedance of the fabric TENG, a direct series connection between the two would lead to a dominance of the current and voltage by the fabric TENG, and thus a low electrical output of the hybrid power textile. In the case of a direct parallel inter-connection, due to the lower impedance of the photovoltaic textile, the fabric TENG will be shorted, rendering the hybrid power textile ineffective for mechanical energy harvesting. Taking this into account, functioning as a unidirectional blocking unit, a diode was employed as an inter-component connection to prevent this short circuit case, without harming the output of the solar cell as a large resistor would do, and thus effectively combining the output power of the two textile components, as shown in Supplementary Fig. 7.

On the other hand, the hybridization pattern between components is another concern towards maximizing the textile conversion efficiency. Based on the diode-regulated electrical connection, two representative hybridization patterns, stripy and mosaic patterns, were extensively investigated for the hybrid power textile. Figure 4b shows an illustration of the power textile with a stripy pattern produced by parallel weaving the triboelectric and photovoltaic textile components. Here, two configurations were specifically investigated for the stripy pattern. One is with the two textile components connected via insulating polymer wires (Fig. 4c), the other is with the two components sharing the copper electrodes (Fig. 4d).

The mosaic pattern is another common and basic weaving mode employed in textile production, as illustrated in Fig. 4e. Two configurations were also studied for the mosaic hybridization pattern. One used photoanodes of the photovoltaic textile interlaced with the copper electrodes of the fabric TENG (Fig. 4f), whereas the other used photoanodes interlaced with the PTFE stripes of the fabric TENG (Fig. 4g). As demonstrated in Supplementary Figs 8–11, different hybridization patterns under identical light and mechanical excitation could realize comparable electrical output. In relative terms, with the stripy hybridization pattern, the photovoltaic textile could be optimally employed in areas with greater light illumination, whereas the mosaic pattern is more suitable for applications in areas with uniformly dispersed light illumination. Furthermore, the electrode alignment of the fabric TENG should be designed to match the direction of larger strain change to deliver greater electrical power.

Hybrid power textile as a flexible power source

Through optimization of the structure and weaving pattern of individual component textiles, and a further investigation of the inter-component electrical connection and structural hybridization, a piece of comprehensively optimized hybrid power textile was woven with a size of 4 cm by 5 cm, including a triboelectric component of 4 cm by 4 cm, and a photovoltaic component of 4 cm by 1 cm, mixed with wool fibres. The photovoltaic textile was made from 15 wire-shaped solar-cell units connected in series, with the photoanode in each unit having a length of 3 cm. With plain weaving patterns, the textiles were electrically connected via a diode as a regulated unit. For quantitative characterization, a linear

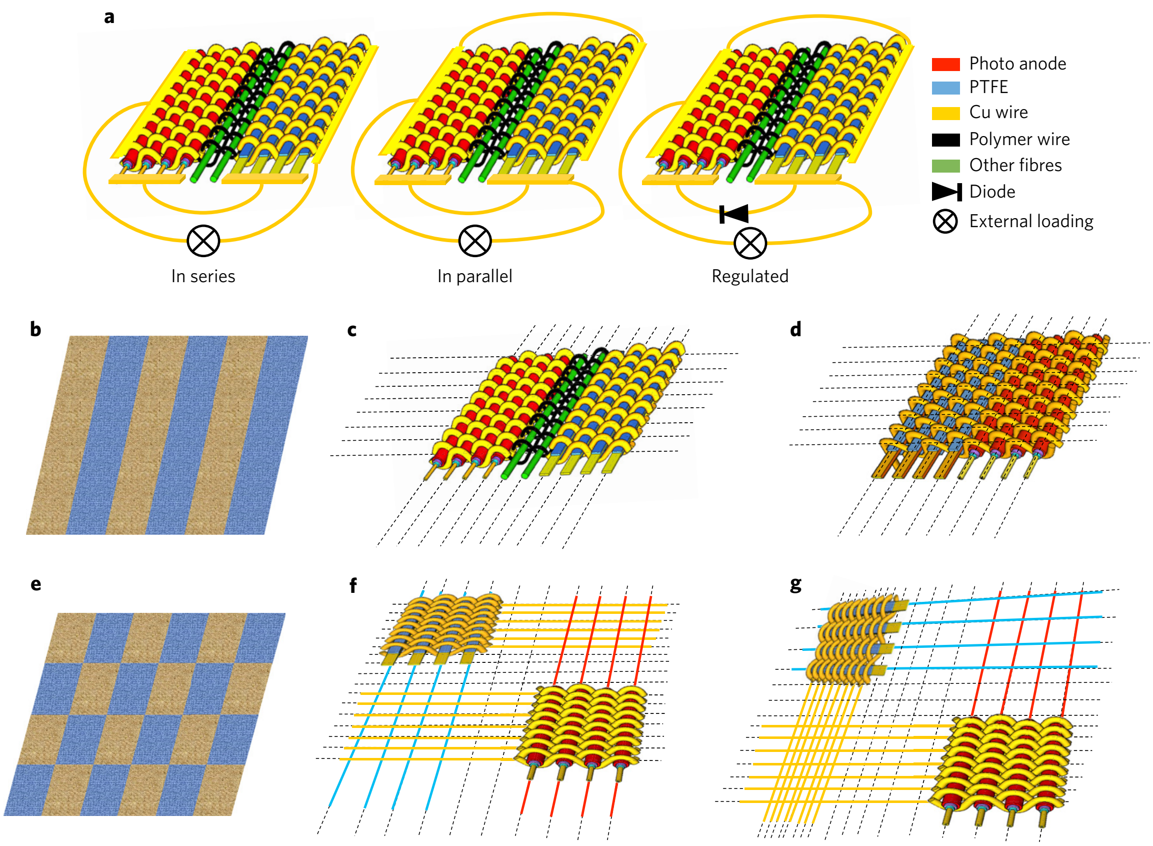

Figure 4 | Electrical connection- and weaving-pattern-optimized hybrid textiles. **a**, Illustration of three electrical connection strategies: in series, in parallel and regulated with blocking diodes. **b**, Schematic illustration of a power textile with a stripy pattern. **c**, Stripy pattern with fabric TENG and photovoltaic textile separated by insulating polymer wires. **d**, Stripy pattern with fabric TENG and photovoltaic textile sharing the copper electrodes. **e**, Illustration of a power textile with a mosaic pattern. **f**, Mosaic pattern with the copper electrodes of the fabric TENG interlaced with the photoanodes of the photovoltaic textile. **g**, Mosaic pattern with the PTFE stripes of the fabric TENG interlaced with the photoanodes of the photovoltaic textile.

motor with mechanical transmission kit was employed to mimic various environmental mechanical movements. Figure 5a shows the electrical output of the textile under different circumstances. When the textile is at rest in sunlight, the photovoltaic component is capable of delivering power by converting solar irradiance, which also works for the triboelectric part under mechanical excitation. When the textile is exposed to light with mechanical excitation, for instance, when people wear the textile and walk in sunlight, it can generate power simultaneously from both ambient sunshine and human biomechanical movement. Resistors were utilized as external loads to further investigate the output power of the hybrid textile. As displayed in Supplementary Fig. 12, all the current amplitudes drop with increasing load resistances owing to ohmic loss, whereas the voltages follow a reverse trend. As a result, the instantaneous peak power is maximized at matched load resistances for the hybrid textile and its components. The hybrid power textile with a size of 4 cm by 5 cm is capable of stably delivering an average output power of 0.5 mW under a remarkably wide range of load resistances from 10 KΩ to 10 MΩ for a human walking under a solar intensity of 80 mW cm^{-2} (Fig. 5b). Here, the light intensity was calibrated by a standard silicon solar cell, as certificated in Supplementary Fig. 13. Consequently, via hybridization optimization, not only was the output power evidently enhanced compared to that of individual components, but also the range of load resistances was greatly expanded, which is a significant improvement in using the hybrid textile as a power source since the operational resistances of small electronics vary considerably.

To demonstrate the capability and feasibility of the hybrid power textile as a flexible and sustainable power source for practical applications, a colourful, lightweight, larger thin textile with various weaving patterns was fabricated into cloths. Under natural daylight with human biomechanical movement, such as hand shaking, the power delivered from the woven fabric is capable of charging a 2 mF commercial capacitor up to 2 V in 1 min (Fig. 5c and Supplementary Fig. 14 and Supplementary Video 3). It can also act as a wearable power source to directly charge a cell phone (Fig. 5d and Supplementary Video 4), as well as continuously drive an electronic watch (Fig. 5e and Supplementary Video 5). It is worth noting that the hybrid power textile is not limited to wearable applications. It can also act as a piece of flag, harvesting energy from sunlight and ambient wind blowing, and the delivered power is also capable of charging personal electronics as well as driving electrochemical reactions for self-powered water splitting (Supplementary Fig. 15 and Supplementary Video 6). In addition, the hybrid power textile was also demonstrated to generate power from weak sunlight and wind from a moving car in a city location on a cloudy day (Supplementary Fig. 16 and Supplementary Video 7), which also indicates its decent capability of working even in a harsh environment.

As a sustainable power source, the robustness of the hybrid power textile was also systematically investigated. As elaborated in Supplementary Note 2, it had sufficient mechanical durability and chemical stability for practical applications. In addition, the influence of environmental humidity on the power textile was also studied. As demonstrated in Supplementary Note 3, at fixed pressure and applied impact, the electrical output of the triboelectric component gradually decreased to ~73.5% of its original value as the relative humidity increased from 10% to 90%. This is mainly attributed to the negative impact of humidity on the triboelectric

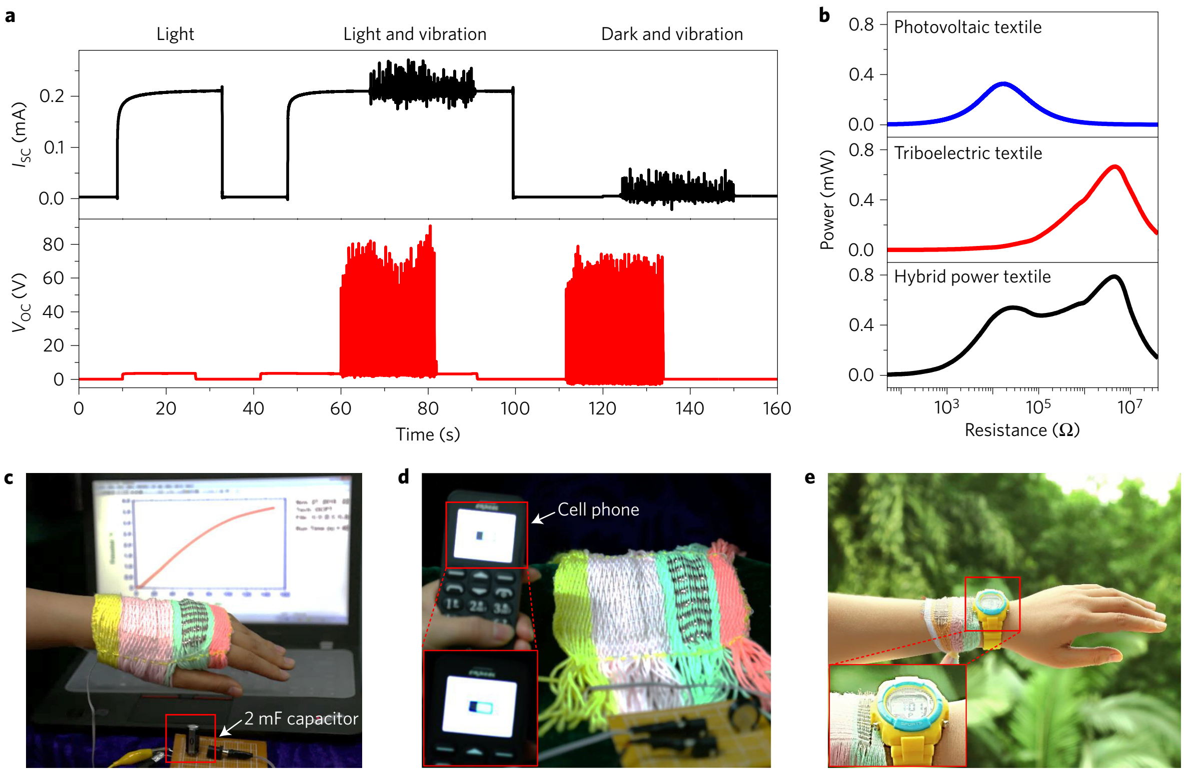

Figure 5 | Demonstration of the power textile to drive portable electronics. a, Electrical output of the wearable all-solid hybrid power textile under various circumstances. **b**, Dependence of the output power of hybrid power textile as well as individual components on the load resistances. Under natural daylight with mechanical excitation, the delivered power from a small piece of hybrid power textile is capable of charging a 2 mF commercial capacitor up to 2 V in 1 min (**c**), directly charging a cell phone (**d**) and continuously powering an electronic watch in a wearable manner (**e**).

charging process[46,47]. It is worth mentioning that the performance degradation can be recovered if the textile is subsequently dried, and this negative impact can be easily resolved by device encapsulation.

Conclusions

In summary, we have presented a lightweight, flexible, foldable and sustainable power source by fabricating an all-solid wearable hybrid power textile in a staggered way on an industrial weaving machine via a shuttle-flying process. Based on the lightweight and low-cost polymer fibres, the reported hybrid power textile introduces an innovative module fabricating strategy with greatly reduced device thickness, weight, total cost and suitability for mass production. Having an ultrathin single-layered interlaced structure with a thickness of 320 μm, the power textile is highly deformable, breathable, and easy to transport and store. Under ambient sunlight with mechanical excitation, such as human motion, car movement and wind blowing, the as-woven textile was capable of generating sufficient power for various practical applications, including charging a 2 mF commercial capacitor up to 2 V in 1 min, continuously driving an electronic watch, directly charging a cell phone and driving the water splitting reactions. The hybrid power textile could be extensively applied not only to self-powered electronics but also possibly to power generation on a larger scale.

Methods

Fabrication of the photoanode. A layer of copper was first deposited on insulated polybutylene terephthalate (PBT) polymer wire with a diameter of 0.26 mm via a chemical plating method[48]. Mn was then plated on the Cu-coated wire substrates via an electroplating method. A layer of ZnO-nanowire arrays was grown on the Mn-plated substrate in a solution of zinc acetate (0.03 M) and hexamethylene tetramine (0.03 M) at 95 °C for 10 h. After cleaning with de-ionized water and drying in vacuum, the as-prepared photoanode was sensitized in an ethanol solution of N719 (Solaronix, Switzerland) for 24 h. After dye sensitization, a layer of CuI was deposited onto the ZnO nanoarrays as the hole-transfer material, using CuI/CH_3CN solution at 130 °C under a N_2 atmosphere, thus avoiding possible contamination of traditional liquid-state electrolyte onto human skin[49–51].

Fabrication of PTFE electrode. To fabricate the wire-shaped PTFE electrodes, copper foil (thickness ~30 μm) sandwiched between two polytetrafluoroethylene (PTFE) layers (thickness ~33 μm) was cut into narrow strips with a width of 0.3 mm via a slicing machine. The copper layer was lead out from the tip of the strips via conductive silver paste and copper wire with a diameter of 33 μm.

Weaving process for the hybrid power textile. PBT wires of different thickness coated with a layer of chemical-plated Cu were employed as the counter electrodes for both the TENG and the photovoltaic textile. Different wire-shaped electrodes were woven into plain, twill and satin patterns on an industrial weaving machine via a shuttle-flying process. The tensional stress on the strings was finely controlled and kept constant during the whole weaving process by means of a specially designed pulley system. To stabilize the contact status of strings inside the textile, the edge of the textile is fixed by sticking strings of photoanodes onto strings of counter electrodes. For the fabric TENG and photovoltaic textile, wire-shaped counter electrodes were employed as the fixed shuttle, and photoanodes or PTFE electrodes were inserted as the flying shuttle. To weave different hybridized patterns, the fixed shuttle or flying shuttle could alternate with others. It worth noting that, due to the woven fibre structure, different power sources could be integrated and hybridized freely in a single piece, which could not only harvest the ambient energy efficiently via a thin and light textile, but also provide comfortable and safe contact to human skin, owing to its excellent flexibility, breathability and freedom from electrolyte leakage. The fabrication procedures of the hybrid power textile are straightforward and compatible with possible large-scale manufacturing. More details of fabric weaving can be found in Supplementary Video 1, Supplementary Fig. 6 and Supplementary Note 1.

Weaving strategy for the stripy pattern. For the stripy pattern with TENG and photovoltaic textile separated by insulative polymer wires, polymer wires coated with a segmentally distributed Cu layer were employed as the fixed shuttle in the longitudinal direction, while the wire-shaped photoanodes and PTFE electrodes were respectively inserted as the flying shuttle into different segments in the latitudinal direction. For the stripy pattern with fabric TENG and photovoltaic textile sharing the copper electrodes, Cu-coated polymer wires were employed as the fixed shuttle in the longitudinal direction, while the wire-shaped photoanodes and PTFE electrodes were inserted as the flying shuttle in the latitudinal direction.

Weaving strategy for the mosaic pattern. For the mosaic pattern with the copper electrodes of fabric TENG interlaced with the photoanode of photovoltaic textile, Cu-coated polymer wires were employed as the fixed shuttle in the longitudinal direction. Wire-shaped photoanode and PTFE electrode were inserted as flying shuttle in the latitudinal direction, sectionally, while their Cu cores were led out and aligned in different directions. For the mosaic pattern with the PTFE stripes of fabric TENG interlaced with the photoanodes of the photovoltaic textile, Cu-coated polymer wires and photoanodes with their copper cores leading out were employed as the fixed shuttle and aligned in the longitudinal direction. Wire-shaped PTFE electrodes with their copper cores leading out and other Cu-coated polymer wires were inserted as the flying shuttle in the latitudinal direction.

Structure and performance characterization. The morphology of the electrode was characterized using scanning electron microscopy (SEM) (S570, Hitachi). The photo-electrochemical tests were conducted on an electrochemical working station (CHI660D, Shanghai Chenhua). The ambient light intensity of 80 mW cm^{-2} was calibrated by a standard silicon solar cell. The effective area employed in the photocurrent density calculation was the projected area of the photoanodes. For a quantitative characterization of the hybrid textile for power delivery, a linear motor with mechanical transmission kit was employed to mimic various mechanical movements.

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Author contributions
J.C., X.F. and Z.L.W. conceived the idea, designed the experiment and guided the project. Y.H., J.C., X.F., N.Z., R.L., H.Z. and C.T. fabricated the device and performed electrical measurements. J.C., X.F. and Z.L.W. analysed the experimental data, drew the figures and prepared the manuscript.

Additional information
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Competing interests
The authors declare no competing financial interests.