Washable textile embedded solar cells for self-powered wearables

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Abstract

Purpose – Solar cells could make textile-based wearable systems energy independent without the need for battery replacement or recharging; however, their laundry resistance, which is prerequisite for the product acceptance of e-textiles, has been rarely examined. This paper aims to report a systematic study of the laundry durability of solar cells embedded in textiles.

Design/methodology/approach – This research included small commercial monocrystalline silicon solar cells which were encapsulated with functional synthetic textile materials using an industrially relevant textile lamination process and found them to reliably endure laundry washing (ISO 6330:2012). The energy harvesting capability of eight textile laminated solar cells was measured after 10–50 cycles of laundry at 40 °C and compared with light transmittance spectroscopy and visual inspection.

Findings – Five of the eight textile solar cell samples fully maintained their efficiency over the 50 laundry cycles, whereas the other three showed a 20%–27% decrease. The cells did not cause any visual damage to the fabric. The result indicates that the textile encapsulated solar cell module provides sufficient protection for the solar cells against water, washing agents and mechanical stress to endure repetitive domestic laundry.

Research limitations/implications – This study used rigid monocrystalline silicon solar cells. Flexible amorphous silicon cells were excluded because of low durability in preliminary tests. Other types of solar cells were not tested.

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Originality/value – A review of literature reveals the tendency of researchers to avoid standardized textile washing resistance testing. This study removes the most critical obstacle of textile integrated solar energy harvesting, the washing resistance.

Keywords Encapsulation, E-textiles, Wearable devices, Smart textiles, Solar cell textiles, Sun-powered textiles, Energy harvesting textiles, Textile electronics

Paper type Research paper

1. Introduction

1.1 E-textiles: characteristics and requirements

Smart textiles, described as "functional textile material, which interacts actively with its environment, i.e. it responds or adapts to changes in the environment" (CEN ISO/TR 23383:2020:En, 2020), is a rapidly growing area of research. The industry report of Global Industry Analysts Inc. (2022) values the smart textiles global market as gaining US$5,9bn by 2026. The most potential application areas are sports and well-being, medicine, occupational health and professional and work wear. This study concentrates on smart textiles, which include electronic components, i.e. e-textiles. Here, the term wearable device comprises all the body worn applications, which incorporate electronic components.

An effective power supply is essential for the usability of wearable devices. Currently, most commercial e-textile solutions use removable and rechargeable or disposable batteries as energy sources, such as wearable devices from Movesense (2022), Therm-ic (2022) and CuteCircuit (2022). However, batteries are sometimes perceived as disadvantageous for the usability of wearable devices (Zhang *et al.*, 2016). Especially in safety and protection applications such as Image Wear lk3 light emitted diode (LED) jacket (Image Wear, 2022), the need for a battery change or reload could be experienced as a safety risk when the device becomes useless without energy. The textile-embedded commercial solar cell solution could provide a completely autonomous application that uses renewable energy sources to produce their own energy, continuously. The practical challenges of textile-embedded solar cells culminate in two aspects: the integration of solar cells into textiles as well as durability in use and care, and at this point, in several washing machine cycles. This study aims to solve both challenges and to improve user experience, as the solar cell component is not removed for washing, and it is always switched on.

When upgrading textiles to e-textiles, all electronic components integrated into textiles, such as solar cells, must meet the demands of garments or textile products (CEN ISO/TR 23383:2020:En, 2020). They must allow the flexing, stretching and washing (Guo *et al.*, 2020; Islam *et al.*, 2020; Sanchez *et al.*, 2021). Textiles are a natural platform for wearable devices because of their soft, flexible, lightweight, air-permeable, elastic and stretchable characteristics, which are adaptive to human body shapes and movements. Textiles can withstand rough handling, folding, bending, processing as well as a wide range of environmental and weather conditions. Moreover, textiles and garments endure storage and packing tightly for a long time, dropping onto the floor, exposing them to sunlight, chemicals and the most stressful laundry washing.

1.2 Solar cell development and textile encapsulation

Solar cell-integrated textiles were introduced in the 2010s (Hughes-Riley *et al.*, 2018). Solar cells have been applied in bags, tents and helmets to generate electrical power for wearable devices and other devices. However, solar cells applied on textiles are visible and cover a large area of the product surface (Schubert and Werner, 2006; Lam *et al.*, 2017), which limits their design possibilities and makes them prone to physical damage in use. Embedding solar cells into yarn would provide esthetic benefits (Zhang *et al.*, 2016), but their low surface coverage drastically lowers the power output per unit area. The solar cells stripes are easily distinguishable (Krebs and Hösel, 2015) and bulky (Satharasinghe *et al.*, 2020).

Commercial solar cells are compact, effective, lightweight and low cost (Ixus Solar Products, 2022; PowerFilm, 2022). Hence, their current properties make them attractive alternatives for powering the wearable devices. Both rigid and flexible solar modules are available in a wide range of sizes, allowing versatility for diverse applications and being durable under various external conditions (Ixus Solar Products, 2022; PowerFilm, 2022). The relatively small solar cells can generate enough power from ambient indoor or outdoor light for wearable sensor applications (Wang *et al.*, 2020). The reduced energy conversion efficiency caused by the fabric on top can be compensated by increasing the surface area of solar cell.

A washable e-textile system can be actualized using textile encapsulation (Molla *et al.*, 2018). For example, Kazani *et al.* (2014) showed that encapsulation with a thermoplastic polyurethane (TPU) layer improves the washing durability of screen-printed textile antennae, Tao *et al.* (2017) improved the washability of e-textiles with both TPU and latex-based barriers, Malm *et al.* (2019) demonstrated that encapsulation improved the washing durability of electrically conductive coatings on textiles and Jeong *et al.* (2019) enhanced the washability of textile-based polymer solar cells with SiO_2–polymer composites. However, in most current e-textile solutions, textile encapsulation has not been used, but the products include a removable electronics case, consisting of replacing batteries and a circuit board (Movesense, 2022). The need to replace batteries does not allow permanent encapsulation of electronics with textiles. However, permanent encapsulation of a complete electronic system, including the circuit board, cables, sensors and energy storage, is possible by including solar cells as an energy source in the same encapsulated system.

In textile encapsulation, knitted fabrics and other flexible and stretchable fabrics provide a soft feeling, good fit and smooth and neat appearance to garment-embedded electronics (Wirtanen, 2018). In addition, textile encapsulation protects the solar cell modules from mechanical stress during use and washing and provides esthetic visual concealing (Blomstedt, 2020). Moreover, the lamination of the cell between the two fabric layers guarantees a stabilized position and location in the final product, which impacts the reliability of the product.

1.3 Machine washing of e-textiles

Depending on application, e-textiles are directly exposed to human skin, such as sweat, grease and cosmetics, and to environmental substances, such as dust, fumes, smoke, moisture, leaks and bacteria, requiring regular and comprehensive laundering. The textile "washing" or "laundry" is a repeated laundry machine procedure in automatic (home) laundry machine, where the water, temperature, process time, detergent and mechanical stress caused by drum spinning (800–1600 rpm) and other textiles load in the drum are always involved. The machine washing is rarely evaluated and what researchers mean by "washing" or "washable" varies from one textile-electronics study to another. These terms include ultrasonic cleaning, which is typical for medical gadgets (Zhou *et al.*, 2018), or 1 cycle of washing machines in cold water without detergent (Yin *et al.*, 2021), with programs of 10, 40, 70 and 100 min (Lim *et al.*, 2020), or 4 cycles of 10 min handwashing in cold water (Corchia *et al.*, 2018), or immersing the product for 35 min in water (Lam *et al.*, 2017). On the other hand, Kye *et al.* (2018) performed wash tests for electrodes for e-textiles by applying even strong bleaching agents instead of too gentle handling.

The recent studies do discuss the washability of the textile electronic components, such as selection of electrode materials (Ankhili *et al.*, 2018; Arquilla *et al.*, 2020; Kaappa *et al.*, 2017; Uz Zaman *et al.*, 2020), conductive fibers and yarns (Ismar *et al.*, 2019; Ryan *et al.*, 2017; Schwarz *et al.*, 2012; Zhang *et al.*, 2020), electronic yarns with embedded conductive copper wires, temperature sensing and LED attached to flexible circuit (Hardy *et al.*, 2020) and miniature solar cells (Satharasinghe *et al.*, 2020), pressure sensors (Lim *et al.*, 2020; Lin *et al.*, 2018), photodiodes (Satharasinghe *et al.*, 2018), stretchable printed electrodes (Kye *et al.*, 2018; Sliz *et al.*, 2020), optoelectronic modules with polymer solar cells (Jeong *et al.*, 2019), cut-and-sew e-textile circuits (Molla *et al.*, 2018), antennas (Corchia *et al.*, 2018; Kazani *et al.*, 2014; Kellomäki *et al.*, 2012; Shahariar *et al.*, 2018) and even more complex textile systems (Tao *et al.*, 2017; Yin *et al.*, 2021). Except for the prominent research by Satharasinghe *et al.* (2020) and Jeong *et al.* (2019), the true laundry durability of commercially available solar cells remains unstudied.

The term "waterproofness" is not equal to "washability." The electronics industry follows the standard EN 60529 for the validation of waterproofness (SFS-EN 60529 + A1, 2000). The waterproofness of electronics is measured by either spraying fresh water onto the electronic components or immersing them in water at a certain depth for 30 min. The electronic casing might be waterproof, but it does not automatically guarantee the endurance of machine washing. Uz Zaman *et al.* (2021) paid special attention to the importance of mechanical stress exposure to e-textiles in an automatic washing machine: pressure, bending, hit and friction among fabrics and the wall of the drum. Sliz *et al.* (2020) stated the destructive impacts of detergents and water on flexible electronic elements. Textile testing standards are more demanding than electronic testing standards. The CEN ISO/TR 23383:2020 clearly states that all smart textile products must tolerate periodic cleaning, for example, washing, and the process needs to be instructed. Textile product cleaning is understood as a machine-washing treatment, whereas cleaning by wiping is an appropriate cleaning procedure for solid plastic-covered electronic devices. This is an inadequate cleaning method for most textile products. The requirements of machine washing can be avoided only for disposable, single-use textile solutions.

Because there are no testing standards for laundering electronics, textile testing standards, such as ISO 6330:2012 (SFS-EN ISO 6330:2012, 2012), must be applied. Unfortunately, performing washing tests according to official test standards is time-consuming and expensive. Therefore, alternative methods for predicting the washing durability of e-textiles have been investigated. Uz Zaman *et al.* (2020) suggested using two testing methods to predict the robustness of unwashed textile electrode materials. The method consists of a pilling box, a Martindale abrasion test and dipping of the textile electrode materials in water and water detergent solutions at 40°C for 72 h. From the textile industry point of view, these tests might be suitable for predicting the robustness against mechanical stress and watertightness of single electronic components or sensor materials. Standardized washing tests are still required for all e-textiles, which require washing as a natural care process in their real use. They cannot be avoided without destroying future market acceptance of e-textiles.

This study reports the results of laundry tests and the washability of textile-encapsulated solar cells following the standard ISO 6330:2012. The studied materials and integration method were chosen to produce waterproof protective encapsulation while allowing a soft and comfortable textile feel and pleasant esthetics. The research questions were as follows:

RQ1. Do textile encapsulated solar cells sufficiently withstand repetitive domestic washing?

RQ2. How does domestic washing affect the energy harvesting capability of a solar cell module?

The tolerance of commercial solar cells integrated in textiles to laundry washing would significantly enhance the user acceptance and usability of self-powered e-textile solutions.

2. Materials selection and preparation of samples

2.1 Selection of solar cells

A set of commercial silicon solar cells was selected for this study. Silicon solar cells are suitable for textile-integrated solar cells because of their low cost and availability. The processing technologies for silicon have matured, resulting in durable and robust solar cells that are readily available for commercial applications.

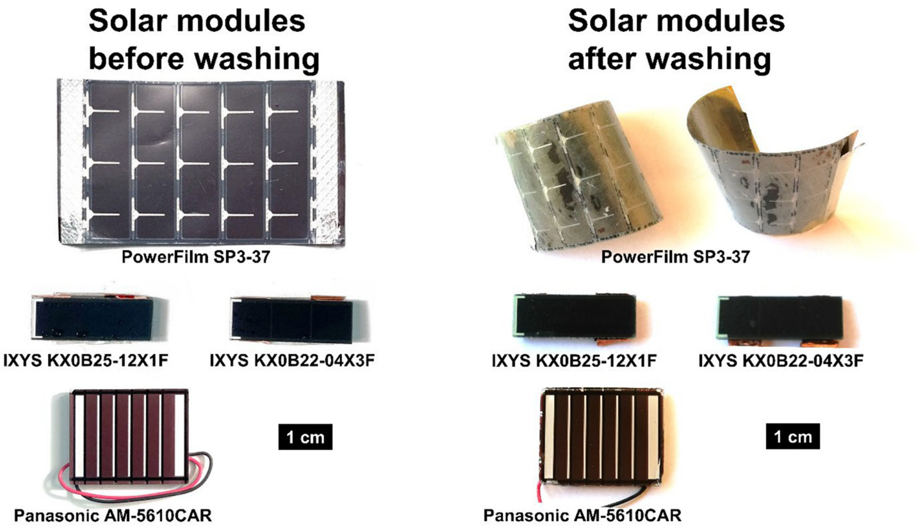
There are several types of silicon solar cells, including monocrystalline, polycrystalline and amorphous cells. Monocrystalline silicon solar cells show high efficiency in outdoor conditions owing to their wide absorption spectrum and durability under harsh conditions. However, they are generally manufactured as rigid solar cells because of their thick absorbing regions. Polycrystalline silicon solar cells demonstrate lower efficiency at a reduced cost while still requiring thick absorbers. Alternatively, amorphous silicon solar cells can be fabricated into flexible thin films owing to their high absorption, making them suitable for product integration. However, they require significantly larger surface areas to harvest the same amount of energy.

2.2 Preparation and pretesting of solar cells

First, a prestudy was conducted in which a limited set of as-received commercial solar cells were placed inside textile washing bags and then washed (Electrolux PerfectCare 800) for ten cycles at a temperature of 40°C in a 1-h program with 1,600 a spinning velocity. The initial set was composed of rigid monocrystalline silicon cells from IXYS, rigid amorphous silicon cells from Panasonic and flexible amorphous silicon cells from the power film (Figure 1). The set was not a representative sample of all available commercial solar cells, but it was considered a suitable foundation for the present study.

Figure 1 shows the initial sets before and after the washing. The rigid Panasonic modules are encapsulated in glass, which is fractured at the edges owing to impact during the laundry cycle. However, the flexible PowerFilm modules are encapsulated in a transparent polymer film, which peels off and exposes the module to water. The IXYS modules, being rigid and encapsulated by lamination with polycarbonate film, however, were almost unaffected by washing and were therefore selected for use in the textile-integrated solar cell washing tests. The maximum power point at the solar simulator was measured for the IXYS modules before and after the preliminary washing and was found to decrease by no more than 2% for both tested IXYS modules.

Next, a subset of three different IXYS solar modules was used for the rigorous washing tests. The surface area of each module is approximately 1.84 cm^2. The solar modules included single cells (IXYS KX0B25-12X1F and IXYS CSN4701) and a three-cell module (IXYS KX0B22-04X3F). The single cells provide a high current at a lower voltage, whereas the three-cell module provides a higher voltage at a lower current. The contacts were made by soldering low-resistance copper tape to the solar module contacts. An additional test sample comprised three modules connected in parallel to mimic a realistic wearable solar module system. The tested solar modules are listed in Table 1.



Note: The colors in these photos before and after washing are not comparable due to different lighting conditions used in the photography

Figure 1. Initial set of solar modules used in the preliminary tests to identify the suitable solar modules for this study

2.3 Selection of fabrics for solar cells

The studied fabrics consisted of eight fabrics representing textiles traditionally used in sports and professional wear (Table 1). Six of the fabrics had woven structures (codes 1–6) and two were knits (7 and 8). The woven fabrics are for relatively cold outdoor conditions, whereas the knits are more suitable for warmer conditions. All tested fabrics were functional fabrics with excellent mechanical properties, high abrasion resistance and high tear strength. The fabrics were constructed from polyamide (PA) or polyester (PES) with or without waterproof polyurethane (PU) coating. The fabrics had a hydrophobic and lightweight character. Four of the eight trials (2A, 3 B, 5C, 6D) were inherently waterproof, having the PU coating before the encapsulation, whereas the rest of the fabrics (1A, 4 B, 7D, 8D) were uncoated. All fabrics had a same recommended washing temperature 40°C, and tumble drying was allowed.

The studied fabrics had various colors (Table 1). The fabric color affects the energy harvesting capability because it affects the light transmittance through the fabric; however, the color has no connection to the washing durability of the textile–solar cell module. The chosen fabric colors were conventional in both outdoor and professional wear.

2.4 Textile–cell module construction and energy harvesting capability

Hot-melt encapsulation (Figure 2) was used to laminate the solar modules inside the selected fabrics because the waterproof hot-melt adhesive films prohibit unnecessary water and detergent penetration through the fabric to the solar cell. The textile cover protects the solar cell against mechanical stress (abrasion, impacts, etc.) during laundry and wearing it as a garment. The encapsulation also fixes the solar cell module securely at the correct position and orientation of the clothing. The elastic adhesive film was made of TPU and was 2 μm thick. The encapsulation process requires optimization of the lamination process parameters according to the construction and materials of the textile solar module component. The

Table 1. Description of the eight tested solar cell–textile combinations and their properties and measured initial power capacity before washing

Trial module	1A	2A	3B	4B	5C	6D	7D	8D
Solar cells								
IXYS product code	CSN4701	CSN4701	KX0B22-04X3F	KX0B22-04X3F	KX0B22-04X3F	KX0B25-12X1F	KX0B25-12X1F	KX0B25-12X1F
Cell construction	Single cell	Single cell	Three-cell module	Three-cell module	Three three-cell modules in parallel	Single cell	Single cell	Single cell
Solar cell external area (cm^2)	1.54	1.54	1.54	1.54	4.62	1.54	1.54	1.54
Textiles								
Structure	Weave, rib	Weave, plain 1/1	Weave, plain 1/1	Weave, plain 1/1	Weave, Oxford	Weave, plain 1/1	Knit, fleece, grid cut	Knit, pique
Composition	PA 88% EL 12%	PES 80% PU 20%	PES 80% PU 20%	PES 100%	PA 73% PU 27%	PES 74% PU 26%	PES 93% EL 7%	PES 100% recycled
Weight (g/m^2)	270	145	145	150	205	210	250	200
Color	Black	Black	Grayish White	Hi-vis yellow	Dark gray	Navy blue	Olive green	Black
Inherent waterproof coating	No	Yes	Yes	No	Yes	Yes	No	No
Power density before washing								
Bare solar cell (mW/cm^2)	11.1	11.1	9.74	9.74	8.87	11.2	11.2	11.2
With textile encapsulation (mW/cm^2)	0.18	2.30	1.61	4.32	3.53	2.18	1.58	1.75
Remaining (%)	1.65	20.7	16.6	44.5	39.8	19.6	14.1	15.7
Current density before washing								
Bare solar cell (mA/cm^2)	23.9	23.9	7.10	7.10	6.72	24.1	24.1	24.1
With textile encapsulation (mA/cm^2)	0.72	5.85	1.50	3.34	2.85	5.56	4.14	4.40
Remaining (%)	3.00	24.5	21.1	47.4	42.4	23.1	17.2	18.2

Notes: EL = elastane: PA = polyamide: PES = polyester: PU = polyurethane parameters were optimized before the preparation: temperatures 120–130°C, pressure 2.3 bar and time 20 s.

Table 1 presents the power loss owing to the encapsulation of the solar cells inside the fabrics before washing. The solar cells retained between 1.65% and 44.5% of their power capacity after encapsulation depending on the fabric used. The variation in the remaining power capacity is because of the different optical transmittances of the textiles, which depend on their properties, such as material, thickness, density and color (Table 1). Although the relative power loss because of textile encapsulation may seem large at first, the harvested energy through the textile would nevertheless (disregarding sample 1A) be sufficient to run several devices, such as low-power wearable sensors.

3. Methods

3.1 Washing method

The test procedure followed the international standard, *Domestic washing and drying procedures for textile testing* (SFS-EN ISO 6330:2012, 2012). The procedure simulates common domestic laundry conditions in Europe.

The testing consisted of ten-cycle intervals, followed by flat drying at room temperature. After ten laundry cycles and drying, the samples were transported to a laboratory for light transmittance measurements and visual observation. This procedure was repeated 5 times, ending up 50 cycles of laundry. The 50 laundry cycles correspond to washing of a solar cell-embedded smart textile product once a week over the use period of one year or once a month over approximately four years.

The textile-encapsulated solar cells were washed in a washing bag with the program 4N, temperature 40°C, spin 1,000 rpm and 55 min per cycle, in a type A washing machine (Wascator FOM71 CLS). The washing bag protected the machine from damage that could occur. The reaching of a standard load of 2 kg a cotton ballast was used and Bio Luvil Professional Sensitive (by Unilever) as a detergent.

3.2 Electrical and optical measurements

The various solar modules were tested in a solar simulator Peccell PEC-L01 under uniform illumination, which corresponds to direct bright daylight (1000 W/m^2 intensity, AM1.5G reference solar spectrum). Current–voltage (I–V) curves were recorded after each of the ten wash cycle intervals using a Keithley 2401 source-measure unit. The I–V curves were used to obtain the maximum power point at which the solar module produced its peak power. The maximum power, P_{max}, was used as a metric to evaluate the performance durability of the solar modules in the experiment.

Optical measurements were conducted before and after 50 washing cycles using an Ocean Optics 2000 spectrophotometer equipped with a cosine receptor and radiometric calibration. The optical transmittance was measured in the wavelength range 280–980 nm. The measurements provided insight into the impact of washing on textile transmittance, which correlates directly with the short-circuit current and maximum power (P_{max}) of the solar modules.

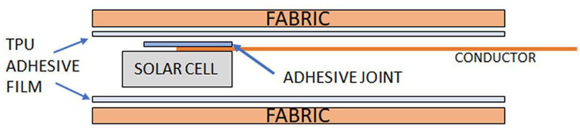


Figure 2.
Layer structure of the textile–solar cell module

4. Results

4.1 Effect of washing on the energy harvesting capacity and short-circuit current

Figure 3 shows that the energy harvesting capability of the textile-integrated solar cells remained on average almost unchanged over the whole washing test: the mean power loss was only 11% after 50 washings (Table A1 in Appendix 1). In fact, most of the samples maintained their power density within ca. ± 10% with variations up and down around the initial value [Figure 3(a)]. The changes in the power density correlated well with the changes in the short-circuit current [Figure 3(b) and Table A2], whereas the open circuit voltage and fill factor showed less variation and stayed practically unchanged by the washing (Figure A2). The fact that there were equally high increases and decreases in the values between the datapoints indicates that these variations represent nonsystematic experimental uncertainty.

The only systematic changes larger than the experimental uncertainty were seen with samples #3 and #5, which lost 18% of their power density and current after the first 10 washings and remained thereafter around 80% of the initial value, and in sample #4, which showed a sudden drop of approximately 20% in the last 10 washings. Cell #5 consisted of three solar modules electrically connected in parallel. The electrical contacts were soldered, which is the weakest point of the structure. The decrease in performance may have been because of breakage of the soldered contacts beneath the lamination, which may have led to an increase in the electrical resistance. Indeed, clearly broken contacts were renewed when observed, which may have introduced additional variance in the performance data.

These results indicate that laundry washing has no significant impact on the energy-harvesting capabilities of any of the studied IXYS monocrystalline silicon solar cells encapsulated inside the fabrics.

The optical transmittance spectra of the fabrics measured before and after 50 washing cycles did not show any significant or systematic changes by washing (Figure A1). The washing therefore did not significantly affect the optical properties of the fabrics.

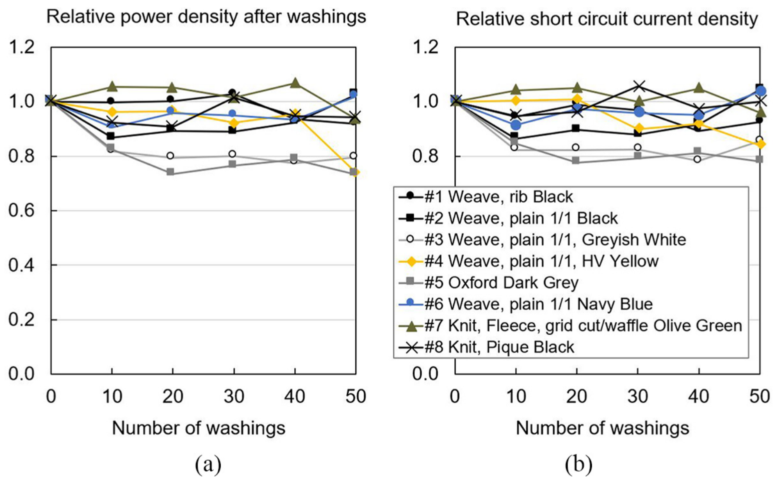


Figure 3. Evolution of (a) the relative output power and (b) the relative short-circuit current density in the washing test

4.2 Visual observation

Figure 4 shows photographs of the textile solar cell components under the study after 50 cycles of laundry. In visual observation under daylight coming through a window, only slight discoloring was detected but no significant fiber breakage on the surfaces of the fabrics. The color changes depend on fabric properties and not a textile–cell module structure itself. Delamination of the module structure did not occur either.

5. Discussion

This study is one of the first published works in which commercial solar cells were exposed to standardized repetitive laundry washing to test their suitability for textile integration in e-textiles and wearable devices. Therefore, it is necessary to critically discuss the methodology used in this study from the perspective of engineering research and practical applications.

Although there is a specific test standard for washing resistance, an e-textile laundry standard is still lacking. The need for standardization is well known, and some organizations such as ASTM, AATCC and IEC have been developing more sensitive but adequate washing program parameters for e-textiles (Uz Zaman *et al.*, 2021). However, the

Figure 4.
Textile solar modules before (right) and after 50 cycles of washing (left)

washing procedure of e-textiles must face the needs of the fabric and the end-product use conditions. Finding a balance between these requirements can be challenging. For example, the limited durability of the embedded electronic and electrical components could require only mild washing, whereas the use conditions of the garment could require more thorough laundry at higher temperatures. In this work, the studied integrated textile-solar cell components were considered as textile products for consumers and consequently a textile testing standard designed for home laundry (ISO 6330:2012) was applied to test their washing durability. The recommended care instructions for the studied fabrics determined the washing temperature (40°C) for the study.

The number of washing cycles (50) corresponds to one to four years of normal use by consumers, depending on the application. However, as the washing test was conducted within a couple of weeks, the results do not fully represent the real-world durability in use, in which fabric wear and tear could influence the washability of the integrated cells and their electrical connections.

Controlled drying process of the samples was not applied. The dryness of the samples was instead verified after every ten washing cycles by visual and hand-feel inspection. This method was considered sufficient because it conforms to the practice of how consumers verify the dryness of their garments.

The studied fabrics were fabricated for professional and functional wear applications and the TPU adhesive film applied in the textile–cell encapsulation process is common in the manufacturing of waterproof garments. Hence, it was expected that no visual changes in the fabric or textile encapsulation (lamination) would be observed. The results confirmed this expectation. Moreover, textile encapsulation protects the solar cells mechanically from strikes and bending, which may have contributed to the washing resistance results obtained in this work.

E-textile researchers often ignore the scalability and industrialization of the manufacturing methods they apply in their research. Hot-melt encapsulation used here is an effective, scalable and industrialized method that fixes securely and durably the position and orientation of the cells in the final textile product. Hence, based on the results reported here, textile encapsulation of solar cells is an appropriate method for clothing manufacturing. In this process, the layers are laminated in one or several steps at high temperature (120–140°C) and pressure (2–3 bar) for a certain time (20–30 s). Depending on the application, the cell integration by lamination can be performed to cut textile pieces before their assembly to a textile product, for example, by sewing, or to the final textile product as a final step of production. The lamination process is also advantageous for recyclability which a well-known challenge in textile-based wearable devices (Veske and Ilén, 2020). The recycling can be achieved by reheating the component: The TPU film becomes soft and textile concealment can be stripped off. Hence, both the fabrics and electronics can be recycled using their own processes.

Considering the selection of solar cells, the study included single solar cells and three-cell modules of the monocrystalline silicon type from the IXYS. In one sample, three three-cell modules were electrically connected in parallel to increase the harvesting capacity. Because the IXYS cells are rigid and relatively thick (1.8 mm), using multiple small cells or modules instead of a single large one is more appropriate for textile integration because the flexible electrical conductors (wires or yarns) between the cells provide mechanical flexibility and even three dimensional conformability to the structure. In addition, locating smaller cells in different places in the garment might allow them to produce energy more reliably than one big cell, as the orientation of the cells with respect to the light source greatly influences their light-harvesting capability.

Overall, this study shows that commercial solar cells can tolerate several cycles (50) of machine washing under conditions typical for home laundry, when the cells are integrated into textiles by lamination using materials and components that are common in textile garment manufacturing. The results showed that textile encapsulation is a reliable and effective method for producing such a component. The method can be reliably applied to different types of fabrics, making it suitable for a wide range of applications such as sports, medical and professional wear.

Nevertheless, we stress that these results do not guarantee the washability of other solar cells, textiles or lamination parameters. The end product with all components integrated must always be tested by laundry washing as well as in real use conditions over the long term. The process parameters required to achieve good washability most likely depend on the materials and components used. In addition, the lack of e-textile-compatible washing-tested electronics underlines the importance of testing end products. The work reported here is a step toward a situation in which washing tested e-textile component modules, such as textile–solar cell laminates, could become available on the market, which could shorten the time for expensive and time-consuming washing processes in the future.

6. Conclusions

The laundry durability of eight textile–solar cell modules encapsulated with a TPU adhesive lamination film was evaluated. The chosen textiles, two PA and six PES textiles, were conventional, strong fabrics applied for outdoor professional wear and sport wear. The weight of the materials varied from 145 to 270 g/m^2. All the studied fabrics provided adequate protection for the small commercial monocrystalline silicon solar cells laminated inside sheets of these fabrics. The solar cells tolerated 50 cycles of laundry washing at 40°C while keeping their energy harvesting capability at an appropriate level for many e-textile solutions. A notable decrease in the electrical power output, that is, a 20%–26% drop, was observed only for three samples that had three electrically connected solar cell modules, possibly because of the increase in the electrical resistance of their cell interconnections. No significant color variation or fiber breakage was observed in the fabrics.

This washing experiment was performed with three different models of one type of commercial solar cell (by IXYS) that were composed of the same material (monocrystalline silicon), had the same construction and came with built-in cell encapsulation (lamination with a polycarbonate film). In the preliminary washing test, amorphous silicon modules, a flexible type from PowerFilm and a rigid glass-based type from Panasonic, were tested but were omitted from the final study because of their lower inherent washing durability.

These results indicated that encapsulation by lamination is a reliable method for integrating solar cells into textiles. No delamination was detected after laundry washing. Textile encapsulation prohibits unnecessary water and laundry chemicals in contact with the solar cells while also protecting them against mechanical stress caused by the laundry process. The encapsulation could be a potential method also for other energy harvesting methods, such as piezoelectric and electromagnetic (human motion), thermoelectric (body heat) and radiofrequency (ambient radio fields) converters within textiles.

Commercial solar cells met the textile laundry requirements, and no changes in the appearance of the fabrics were observed after exposing them to laundry with encapsulated solar cells. Hence, in conclusion, the textiles that are specified to stand for over 50 washing cycles also maintain their properties as protective and aesthetic covers for solar cells. This means that laminating commercial solar cells between the textile layers provides a large design freedom for textile products. This concept is promising for professional and occupational wear applications.

Adequate washing durability was obtained with small rigid solar cells with built-in encapsulation. Applying the lamination method to encapsulate larger flexible thin-film solar modules, which were omitted here because of their lower inherent durability, is an important topic for further research. In addition, studying the durability of laminated cells in industrial washing is required to confirm the suitability of this solution for professional wear. Further development and testing of electrical connection techniques using different cell types are required.

This study demonstrates the washability of textile-encapsulated commercial solar cells, which removes a remarkable obstacle to e-textile development. Their energy source is now washable, in addition to providing continuous operation without charging or replacing batteries. However, the success of washing solar cells does not mean that laundry testing can be avoided in the research and development of e-textiles, but it must be conducted according to the requirements of each application.

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Appendix 1

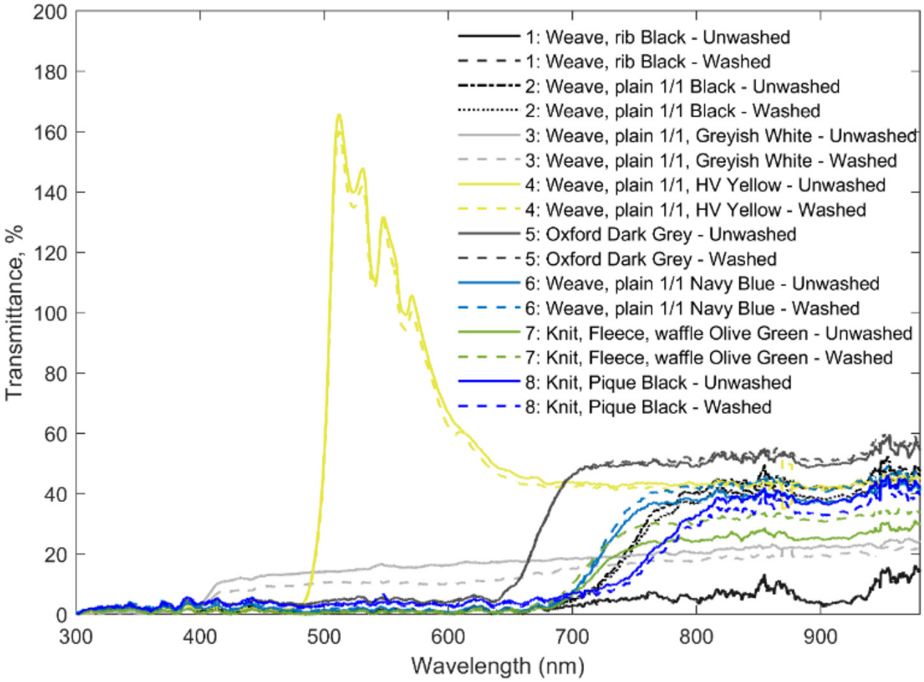
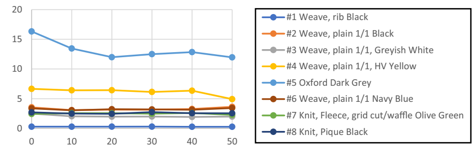


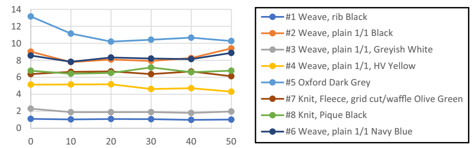
Figure A1.
Transmittance spectra of unwashed and washed samples

Notes: Note that the measured transmittance value of the HV yellow fabric exceeds 100% because of significant fluorescence in this fabric. The peak in the data at 500– 650nm corresponds to light emitted by the fabric at longer wavelengths and detected by the broadband silicon detectors of the spectrophotometer. The data do not show any significant or systematic changes by the washing: the values after washing are for some samples slightly higher and for others lower than before washing

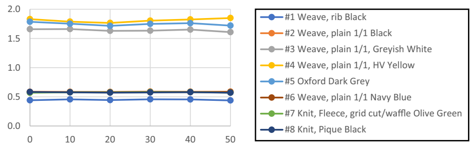
Area (cm²)	Sample	Power (mW) Number of washings 0	10	20	30	40	50
1.54	#1 Weave, rib Black	0.28	0.28	0.28	0.29	0.26	0.26
1.54	#2 Weave, plain 1/1 Black	3.54	3.07	3.16	3.14	3.26	3.63
1.54	#3 Weave, plain 1/1, Greyish White	2.48	2.03	1.97	1.99	1.92	1.98
1.54	#4 Weave, plain 1/1, HV Yellow	6.66	6.41	6.43	6.14	6.35	4.92
4.62	#5 Oxford Dark Grey	16.33	13.45	11.99	12.50	12.85	11.96
1.54	#6 Weave, plain 1/1 Navy Blue	3.36	3.04	3.22	3.19	3.14	3.42
1.54	#7 Knit, Fleece, grid cut/waffle Olive Green	2.43	2.56	2.55	2.46	2.59	2.27
1.54	#8 Knit, Pique Black	2.69	2.49	2.45	2.73	2.55	2.54



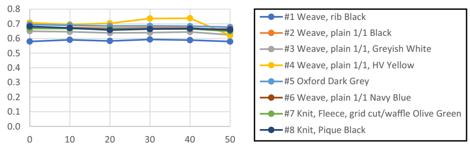
Area (cm²)	Sample	Short circuit current (mA) Number of washings 0	10	20	30	40	50
1.54	#1 Weave, rib Black	1.10	1.04	1.09	1.07	0.99	1.02
1.54	#2 Weave, plain 1/1 Black	9.02	7.79	8.09	7.92	8.26	9.40
1.54	#3 Weave, plain 1/1, Greyish White	2.31	1.90	1.90	1.90	1.81	1.97
1.54	#4 Weave, plain 1/1, HV Yellow	5.14	5.15	5.18	4.62	4.71	4.31
4.62	#5 Oxford Dark Grey	13.16	11.14	10.20	10.42	10.66	10.27
1.54	#6 Weave, plain 1/1 Navy Blue	8.56	7.82	8.33	8.21	8.14	8.87
1.54	#7 Knit, Fleece, grid cut/waffle Olive Green	6.38	6.64	6.69	6.37	6.68	6.12
1.54	#8 Knit, Pique Black	6.77	6.42	6.51	7.16	6.60	6.78



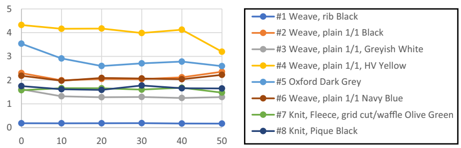
Sample	Open circuit voltage (V) Number of washings 0	10	20	30	40	50
#1 Weave, rib Black	0.44	0.46	0.44	0.46	0.45	0.44
#2 Weave, plain 1/1 Black	0.59	0.58	0.58	0.59	0.59	0.59
#3 Weave, plain 1/1, Greyish White	1.66	1.66	1.63	1.63	1.65	1.61
#4 Weave, plain 1/1, HV Yellow	1.83	1.79	1.77	1.80	1.82	1.85
#5 Oxford Dark Grey	1.79	1.75	1.72	1.75	1.76	1.72
#6 Weave, plain 1/1 Navy Blue	0.58	0.58	0.58	0.58	0.58	0.58
#7 Knit, Fleece, grid cut/waffle Olive Green	0.57	0.58	0.58	0.58	0.58	0.57
#8 Knit, Pique Black	0.58	0.58	0.57	0.57	0.58	0.57



Sample	Fill factor (%) Number of washings 0	10	20	30	40	50
#1 Weave, rib Black	0.58	0.59	0.58	0.59	0.59	0.58
#2 Weave, plain 1/1 Black	0.67	0.67	0.67	0.67	0.67	0.66
#3 Weave, plain 1/1, Greyish White	0.65	0.65	0.64	0.64	0.64	0.62
#4 Weave, plain 1/1, HV Yellow	0.71	0.70	0.70	0.74	0.74	0.62
#5 Oxford Dark Grey	0.70	0.69	0.69	0.69	0.68	0.68
#6 Weave, plain 1/1 Navy Blue	0.68	0.67	0.67	0.67	0.66	0.66
#7 Knit, Fleece, grid cut/waffle Olive Green	0.67	0.67	0.66	0.67	0.67	0.65
#8 Knit, Pique Black	0.68	0.67	0.66	0.66	0.67	0.66



Sample	Power density (mW/cm2) Number of washings 0	10	20	30	40	50
#1 Weave, rib Black	0.18	0.18	0.18	0.19	0.17	0.17
#2 Weave, plain 1/1 Black	2.30	1.99	2.05	2.04	2.12	2.35
#3 Weave, plain 1/1, Greyish White	1.61	1.32	1.28	1.29	1.25	1.28
#4 Weave, plain 1/1, HV Yellow	4.32	4.16	4.17	3.98	4.12	3.20
#5 Oxford Dark Grey	3.53	2.91	2.60	2.71	2.78	2.59
#6 Weave, plain 1/1 Navy Blue	2.18	1.97	2.09	2.07	2.04	2.22
#7 Knit, Fleece, grid cut/waffle Olive Green	1.58	1.66	1.66	1.60	1.68	1.47
#8 Knit, Pique Black	1.75	1.62	1.59	1.77	1.66	1.65



Sample	Short circuit current density (mA/cm2) Number of washings 0	10	20	30	40	50
#1 Weave, rib Black	0.72	0.68	0.71	0.69	0.64	0.66
#2 Weave, plain 1/1 Black	5.85	5.06	5.25	5.14	5.36	6.11
#3 Weave, plain 1/1, Greyish White	1.50	1.23	1.23	1.24	1.17	1.28
#4 Weave, plain 1/1, HV Yellow	3.34	3.35	3.36	3.00	3.06	2.80
#5 Oxford Dark Grey	2.85	2.41	2.21	2.26	2.31	2.22
#6 Weave, plain 1/1 Navy Blue	5.56	5.08	5.41	5.33	5.28	5.76
#7 Knit, Fleece, grid cut/waffle Olive Green	4.14	4.31	4.34	4.14	4.34	3.98
#8 Knit, Pique Black	4.40	4.17	4.23	4.65	4.28	4.40

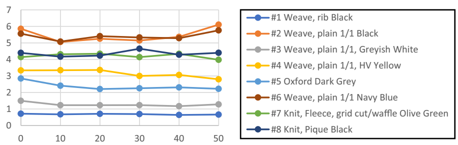
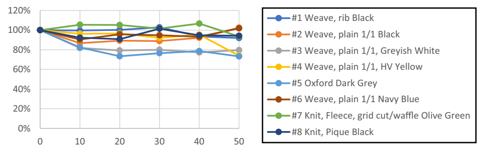


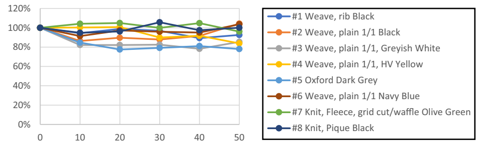
Figure A2. Evolution of the photovoltaic performance characteristics in the washing test, complete data set

(continued)

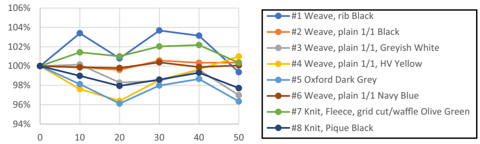
Relative power density (%)	Number of washings					
Sample	0	10	20	30	40	50
#1 Weave, rib Black	1.00	1.00	1.00	1.03	0.94	0.92
#2 Weave, plain 1/1 Black	1.00	0.87	0.89	0.89	0.92	1.02
#3 Weave, plain 1/1, Greyish White	1.00	0.82	0.79	0.80	0.77	0.80
#4 Weave, plain 1/1, HV Yellow	1.00	0.96	0.97	0.92	0.95	0.74
#5 Oxford Dark Grey	1.00	0.82	0.73	0.77	0.79	0.73
#6 Weave, plain 1/1 Navy Blue	1.00	0.90	0.96	0.95	0.93	1.02
#7 Knit, Fleece, grid cut/waffle Olive Green	1.00	1.05	1.05	1.02	1.07	0.94
#8 Knit, Pique Black	1.00	0.92	0.91	1.01	0.95	0.94



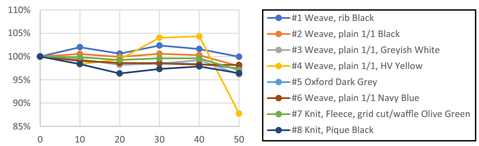
Relative short circuit current density (%)	Number of washings					
Sample	0	10	20	30	40	50
#1 Weave, rib Black	1.00	0.94	0.99	0.97	0.89	0.93
#2 Weave, plain 1/1 Black	1.00	0.86	0.90	0.88	0.92	1.04
#3 Weave, plain 1/1, Greyish White	1.00	0.82	0.82	0.82	0.78	0.85
#4 Weave, plain 1/1, HV Yellow	1.00	1.00	1.01	0.90	0.92	0.84
#5 Oxford Dark Grey	1.00	0.85	0.78	0.79	0.81	0.78
#6 Weave, plain 1/1 Navy Blue	1.00	0.91	0.97	0.96	0.95	1.04
#7 Knit, Fleece, grid cut/waffle Olive Green	1.00	1.04	1.05	1.00	1.05	0.96
#8 Knit, Pique Black	1.00	0.95	0.96	1.06	0.97	1.00



Relative open circuit voltage (%)	Number of washings					
Sample	0	10	20	30	40	50
#1 Weave, rib Black	1.00	1.03	1.01	1.04	1.03	0.99
#2 Weave, plain 1/1 Black	1.00	1.00	1.00	1.01	1.00	1.00
#3 Weave, plain 1/1, Greyish White	1.00	1.00	0.98	0.98	1.00	0.97
#4 Weave, plain 1/1, HV Yellow	1.00	0.98	0.96	0.99	1.00	1.01
#5 Oxford Dark Grey	1.00	0.98	0.96	0.98	0.99	0.96
#6 Weave, plain 1/1 Navy Blue	1.00	1.00	1.00	1.00	1.00	1.00
#7 Knit, Fleece, grid cut/waffle Olive Green	1.00	1.01	1.01	1.02	1.02	1.00
#8 Knit, Pique Black	1.00	0.99	0.98	0.99	0.99	0.98



Relative fill factor (%)	Number of washings					
Sample	0	10	20	30	40	50
#1 Weave, rib Black	1.00	1.02	1.01	1.02	1.02	1.00
#2 Weave, plain 1/1 Black	1.00	1.01	1.00	1.01	1.00	0.98
#3 Weave, plain 1/1, Greyish White	1.00	0.99	0.98	0.98	0.99	0.96
#4 Weave, plain 1/1, HV Yellow	1.00	0.98	0.99	1.04	1.04	0.88
#5 Oxford Dark Grey	1.00	0.99	0.99	0.99	0.98	0.97
#6 Weave, plain 1/1 Navy Blue	1.00	0.99	0.99	0.98	0.98	0.98
#7 Knit, Fleece, grid cut/waffle Olive Green	1.00	1.00	0.99	1.00	1.00	0.97
#8 Knit, Pique Black	1.00	0.98	0.96	0.97	0.98	0.96



Notes: The same data is shown as a table and a graph. In the graph, the horizontal axis is the number of washing cycles and the vertical axis is the measured or calculated quantity corresponding to the table

Figure A2.

Table A1. Relative power loss (%) after laundry washings

Trial module	Cell type	Cell construction	Power loss (%) after 10–50 laundry washings relative to the module power after lamination before washing 10	20	30	40	50
1	A	Single cell	0.38	−0.23	−2.87	6.40	8.05
2	A	Single cell	13.3	10.7	11.1	7.78	−2.50
3	B	Three-cell module	18.2	20.7	20.0	22.6	20.4
4	B	Three-cell module	3.68	3.46	7.82	4.58	26.0
5	C	Three three-cell modules in parallel	17.6	26.6	23.5	21.3	26.7
6	D	Single cell	9.55	4.24	5.20	6.67	−1.81
7	D	Single cell	−5.46	−5.22	−1.57	−6.67	6.43
8	D	Single cell	7.68	9.21	−1.44	5.28	5.74
		Mean	8.1	8.7	7.7	8.5	11.1
Standard error of the mean			2.9	3.8	3.5	3.3	4.1

Note: Negative value for power loss means that the measured power of the solar cell textile module had increased compared to the previous measurement before that washing round

Trial module	Cell type	Cell construction	J_{SC} of module after 10–50 laundry washings (mA/cm^2) 10	20	30	40	50
1	A	Single cell	0.68	0.71	0.69	0.64	0.66
2	A	Single cell	5.06	5.25	5.14	5.36	6.10
3	B	Three-cell module	1.23	1.23	1.23	1.18	1.28
4	B	Three-cell module	3.34	3.36	3.00	3.06	2.80
5	C	Three three-cell modules in parallel	2.40	2.21	2.25	2.32	2.23
6	D	Single cell	5.08	5.41	5.33	5.29	5.76
7	D	Single cell	4.31	4.34	4.14	4.34	3.97
8	D	Single cell	4.17	4.23	4.65	4.29	4.40

Table A2. Short-circuit current density (J_{SC}) after laundry washings

Fabrics	Mean transmittance (%) Unwashed	After 50 wash cycles
#1 Weave, rib, black	3.67	3.50
#2 Weave, plain 1/1, black	16.7	15.6
#3 Weave, plain 1/1, grayish white	15.5	12.4
#4 Weave, plain 1/1, HV yellow	42.1	41.1
#5 Oxford, dark gray	25.7	26.4
#6 Weave, plain 1/1, navy blue	16.3	18.2
#7 Knit, fleece, grid cut/waffle, olive green	10.9	13.6
#8 Knit, pique black	15.4	14.0

Table A3. Mean transmittance over the wavelength range 280–980 nm before and after the washing test

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