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Connection techniques of textile wires to the solid and flexible solar cells

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Foreword

Thanks to Foxa Ltd. for providing fabrics and Aalto University project Sun Powered Textiles for providing solar cells for the study. Also thanks to Dr. Janne Halme from Aalto University, about providing knowledge of measuring the capacity of solar cells, who gave inspiration when stabilizing the conditions with a light source and light intensity meter.

Abstract

In order to make better use of clean energy such as solar energy, textile on earth have the potential to be made into solar textiles. The commercial solar cells can be embedded between the textile layers by laminating to harvest energy for e-textile applications. Research about solar textiles is not mature enough, and many aspects of the problem need to be solved. However, connecting techniques of conductive textile wires to flexible and solid solar cells are not in-deep studied. In addition, solar textile products with these connection technologies must meet washable requirements.

To solve the problem of connecting textile wires to flexible and solid solar cells in the production of solar textiles, this study proposes three connection techniques for solar textiles, which are tape, adhesive and stitching based on literature and experimental validation.

The feasibility of tape and adhesive methods was analyzed by literature review and the feasibility of stitching method was verified by experiments. The stitching is unapplicable method for solid solar cells that are difficult to penetrate, but applicable for flexible solar cells. The machine-washing durability of solar textile which composed of solar cells with stitch-connected conductive textile wires was verified by experiments. First, the textile wires were joined to flexible solar cells by stitching with the sewing machine and then embedded between fabric layers with TPU-lamination to simulate real set up in e-textile application. The humidity stickers were attached to the surface of solar cells, and it was expected to present solar textile samples with or without water inside. After the machine-washing process is completed, the individual parts of the solar textile sample are disassembled by delamination.

For stitching method, after 15 machine wash tests by household washing machines, the performance of the solar cells was hardly affected, and the internal water resistance of the samples was good. The delamination process verifies that the components of the solar textile can be disassembled and have the potential to be recycled. The feasibility of tape connections has been proven by previous studies. Flexible adhesives that have the potential to connect textile wires to solar cells are listed.

Table of contents

List of tables

List of figures

List of abbreviations / Glossary

ACA	Anisotropic conductive adhesive
CNC	Computer numerically controlled
CPU	Central processing unit
DC	Direct current
ECA	Electrically conductive adhesive
ECG	Electrocardiogram
FPCBs	Flexible printed circuit boards
ICA	Isotropic conductive adhesive
IoTs	Internet of Things
MCEYs	Metal composite embroidered yarns
NCA	Non-conductive adhesive bonding
PEDOT	Poly(3,4-ethylene dioxythiophene)
PSS	Poly(styrenesulfonate)
SIPN	Semi-interpenetrating network
SoT	System on textile
TFE	Tailed fiber placement
TPU	Thermoplastic polyurethanes

1. Introduction

1.1 Object

The general objective of this study is to provide feasible and producible connection techniques of textile wires to the solid and flexible solar cells in solar textile.

The secondary objectives of this study are presented in the form of questions.

Questions:

1. What are potential flexible adhesives commercially available for solar textile based on literature review?
2. Is there an effect of some humidity on solar cells on the harvesting capability?
3. Are there any losses of light harvesting capacity in samples with stitching connection method after machine washing? Is harvesting capacity reduced?
4. Which method is most effective for mass production based on literature review and experiments?

1.2 Scope

Through a literature review, tapes, adhesive and stitching connection techniques were considered to connect textile threads and solar cells in solar textiles. The feasibility of both tape and adhesive methods were analyzed by literature review method when the stitching was experimentally validated.

In experiments for stitching method, the scope is below.

1. Solar cell. Only flexible solar was involved in the experiment. Solid solar cell was not involved since it cannot be penetrated by sewing machine.
2. Encapsulation. Encapsulation was applied to make waterproof solar textile samples in the experiments. This technique was not developed in this study.
3. Fabric. Different kinds of fabrics were not studied in the experiment, although 3 fabrics were involved in the experiment. These fabrics were made from different technology: woven and knitted, and one of them was with waterproof coating. To ensure the light passes smoothly through the fabric, white fabrics was selected and color of fabrics was comparably same.
4. Textile wire. Only one commercial conductive yarn was selected as the textile wire.
5. Durability test method. Only washing durability was selected in the experiment.
6. Solar cell performance test method. The energy harvest capacity of solar cell was tested by electric tests. Voltage or current between solar cell contact area was tested by multimeter and a luxmeter showed the intensity of light.

1.3 Requirements

This project aims to evaluate the feasibility of tape, adhesive and stitching method. The requirements of this study are as follows:

1. For tape method, the validation for feasibility should be found available.

2. For adhesive method, the potential flexible commercial adhesives should be thoroughly researched.

3. For stitching method, there are requirements as following.
    - The stitching for samples should be firm and reliable.
    - The samples in parallel groups should the same.
    - The electrical tests should be performed under relatively identical lighting conditions.

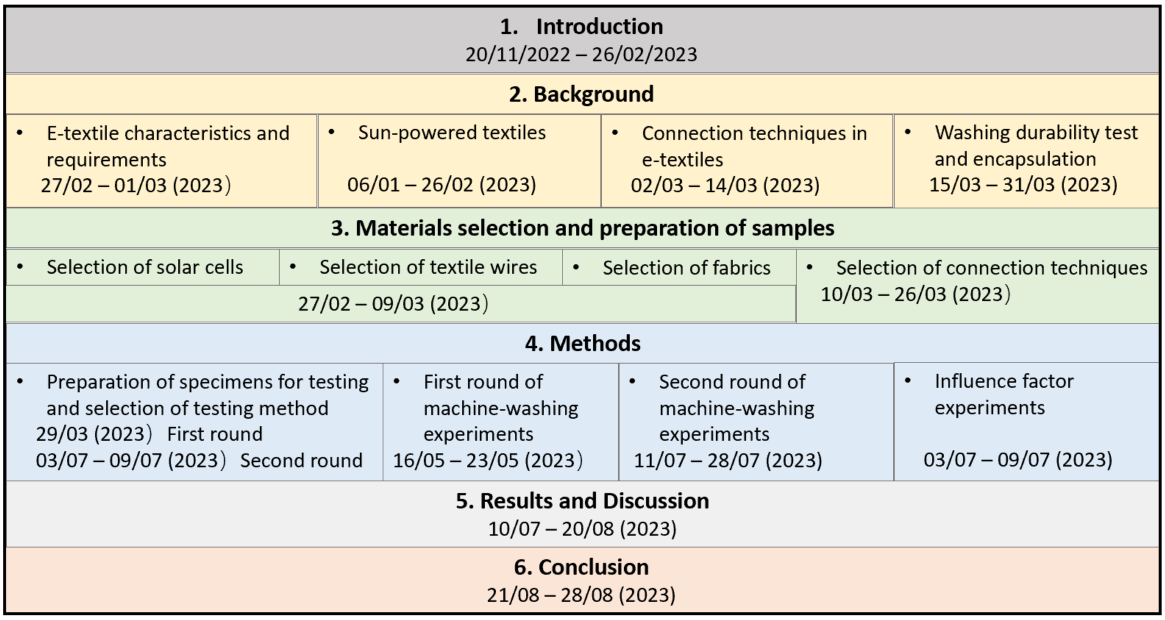
1.4 Rationale

In the textile industry, people are no longer satisfied with the traditional textile industry and create many smart textiles [1]. E-textile, as a part of smart textile has great potential to solve the many challenges from different industries. Energy supply element for instance is a necessary part in e-textile. Coin cell batteries are often used to power e-textiles, but they often need to be removed since they are not washable. The commercial solar cells can be embedded between the textile layers by laminating to harvest energy in the e-textile applications and to be washed in washing machine without having to be disassembled [2] [3]. Solar textile has an energy autonomous system with renewable energy, and solar cells can harvest energy from daylight and artificial light, so it is also suitable for indoor solutions. Solar textile can be used in architectural textiles that are often exposed to the sun, such as sunshades. Moreover, given that it can utilize artificial light, this makes it possible to use solar cells as a power source for all e-textiles. For example, clothing that monitors heart rate, yoga clothes that capture movement trajectories, and so on.

In solar textiles, standard wires cannot be used with solar cells. The conductive yarn, which is bendable and washable, can act as wires in e-textile. As a problem in all e-textile products, connection techniques of electronic components always remain to be solved. And in this study, the connection problem is to connect textile wires to solid and flexible solar cells in the production of solar textile. When making samples, it is difficult to place textile wires in the connection area corresponding to the solar cell without connection technology.

Although it has been proven that solar cells and conductive yarns can be connected with single-sided silver-plated conductive tape, and after being made into a solar textile, the performance is maintained after 50 machine washes [3], this approach is not comprehensive enough. This study aims to find methods for connecting conductive yarns to solid and flexible solar cells for solar textiles through literature review and experimental validation.

The project flow of this study is shown in Figure 1.



1. Introduction
20/11/2022 – 26/02/2023

2. Background

- E-textile characteristics and requirements
  27/02 – 01/03 (2023）
- Sun-powered textiles
  06/01 – 26/02 (2023)
- Connection techniques in e-textiles
  02/03 – 14/03 (2023)
- Washing durability test and encapsulation
  15/03 – 31/03 (2023)

3. Materials selection and preparation of samples

- Selection of solar cells
- Selection of textile wires
- Selection of fabrics

27/02 – 09/03 (2023）

- Selection of connection techniques
  10/03 – 26/03 (2023）

4. Methods

- Preparation of specimens for testing and selection of testing method
  29/03 (2023） First round
  03/07 – 09/07 (2023） Second round
- First round of machine-washing experiments
  16/05 – 23/05 (2023）
- Second round of machine-washing experiments
  11/07 – 28/07 (2023)
- Influence factor experiments
  03/07 – 09/07 (2023)

5. Results and Discussion
10/07 – 20/08 (2023)

6. Conclusion
21/08 – 28/08 (2023)

Figure 1. Development of the project's timing

2 Background and/or review of the state of the art

2.1 E-textile system and characteristics

In the 1980s, Steve Mann was one of the first researchers at the Massachusetts Institute of Technology (MIT) to develop smart textiles, also known as e-textiles [4]. Over the past few decades, the role of "textiles" in smart textiles has evolved over three generations: (1) rigid electronics on textile platforms, (2) devices embedded in textiles, and (3) all-textile equipment [5]. Smart textiles are described as "functional textile materials that actively interact with the environment, i.e. respond to or adapt to changes in the environment" (CEN ISO/TR 23383: 2020: EN,2020) [3].

Smart clothing is part of the Internet of Things (IoTs), especially for monitoring the user's physical condition. The product design process for e-textile solutions is often technology-oriented and is developed by combining various electronic components into new products. The design of e-textiles offers excellent opportunities in the field of sports and leisure clothing. This design concept will integrate "electronic components" into textiles, increasing the functionality of the textile without compromising the user experience and usability of the garment [2]. One good example of e-textile product in life is Xiaomi Mijia Cardiogram T-shirt (Figure 2). This e-textile product is a sports smart t-shirt designed for amateur athletes, which includes an advanced heart rate monitor to achieve real-time electrocardiogram (ECG) monitoring.

Figure 2. The Xiaomi Mijia Cardiogram T-shirt for ECG monitoring. Source: [*https://xiaomiplanets.com/xiaomi-mijia-cardiogram-t-shirt-2/*](https://xiaomiplanets.com/xiaomi-mijia-cardiogram-t-shirt-2/)

Moreover, there have been some promising applications in the last decade. E-textiles are the medium of interaction between humans and computers, and robots are designed to "connect human intent with machine behavior" [6]. The device configuration and working principle of the triboelectric interacting patch by developing interaction patch can be attached to the human arm is shown in Figure 3.

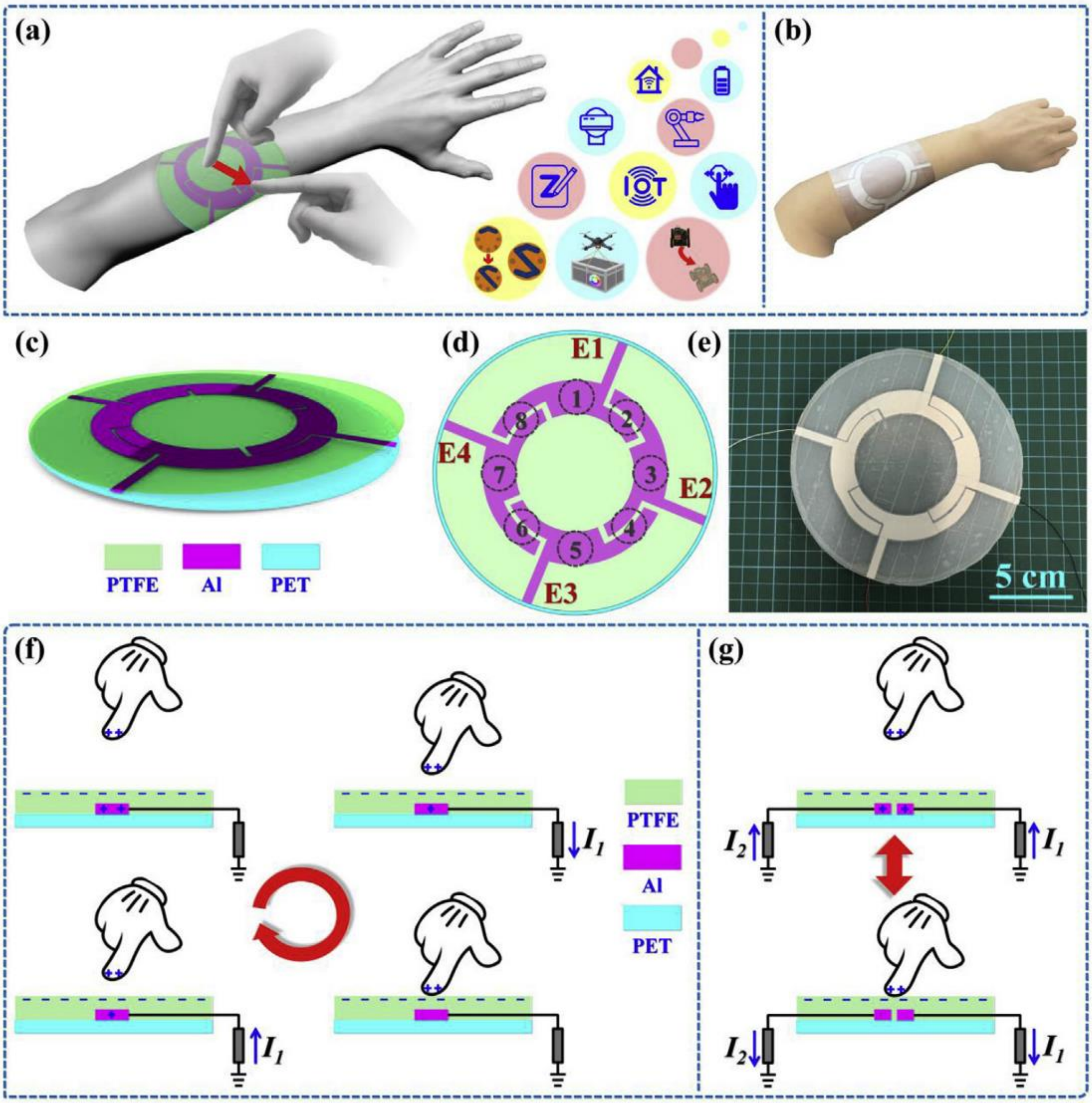


Figure 3. The device configuration and working principle of the triboelectric interacting patch. Source: [6]

A textile-based tactile learning platform that can be used to record, monitor and learn human–environment interactions was reported (Figure 4). The tactile textiles are created via digital machine knitting of inexpensive piezoresistive fibers and can conform to arbitrary three-dimensional geometries [7].

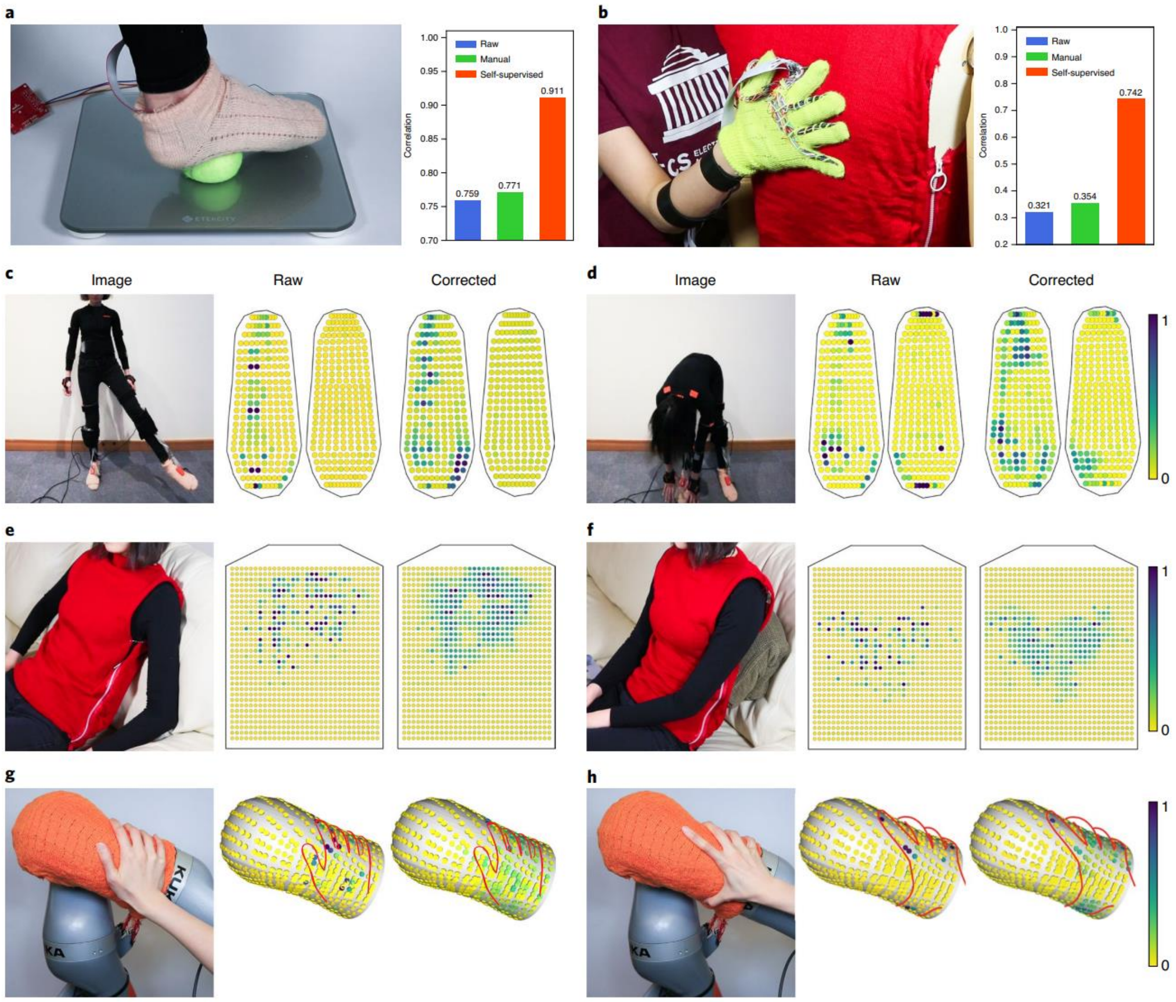


Figure 4. A textile-based tactile learning platform. Source: [7]

As shown in Figure 5, the four-mode controller can take advantage of the gripping motion detected by the PVDF microelectromechanical system (MEMS), which is printed on artificial skin and attached to the left and right wrists [8]. Using gesture capture gloves with embedded strain sensors can reduce human visual cognitive load and attention switching during driving [9].

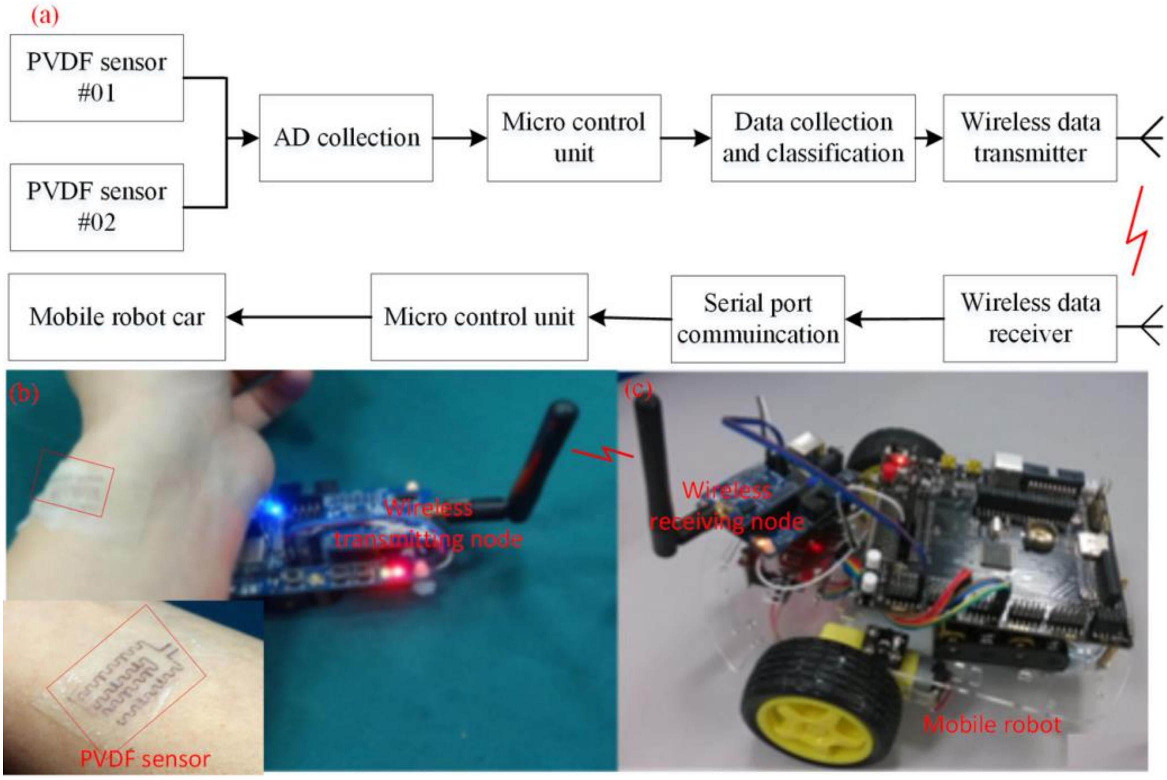


Figure 5. The four-mode controller gripping motion detected by the PVDF MEMS.
Source: [8]

In general, smart textiles consist of basic fabrics, interconnections, sensors, actuators, power supplies or generators, and computer processing units. Smart textiles are classified by masking or highlighting their textile and electronic properties: (1) interaction with the environment–passive (sensed), active (perceived and reactive) or very intelligent (perceived, reacted and adapted), (2) form, location or attachment mode, such as "soft systems", (3) the components involved and the degree of human interaction, and (4) electronic, which requires a computer and batteries, or non-electronic [5].

Components of e-textiles consists of 5 parts [4]:

(1). Conductive materials. Electrical components such as resistors, capacitors, inductors, and interconnects require conductive materials.

(2). Interconnects and Communication. Interconnects, wires, or antennas carry information and power between components, computers, and wearers. The wire is manufactured by extrusion process or embroidered conductive wire, while the antenna can be made of conductive wire, embroidery or fabric. Wired interconnects both attach items to textiles and conduct power for power and data communication between components and wearers.

(3). Electronic Sensors and Actuators. Sensors can monitor movement, physiology, or the environment and require signal processing. Common sensors are motion sensors, strain sensors, resistive pressure sensors, capacitive pressure sensors, storage or release of electrical energy, and physiological sensors.

(4). Power–Energy Generation and Storage. E-textiles require the use of batteries or energy generators to power electronic components throughout the life cycle of the device.

(5). Computer or Central Processing Unit (CPU). The computer or central processing unit "CPU" is the brain of the system. Computers operate the control system, process information, and store data inside and outside the garment.

The e-textile system framework is shown in Figure 6. The e-textile system always includes signal inputs (e.g., fabric electrodes on the human body), output devices (e.g., a cell phone), a CPU and an energy source for data processing and transmission between all these components. The sensors collect the input signals are transmitted to the CPU for data processing and then the output devices display the processed data [2].

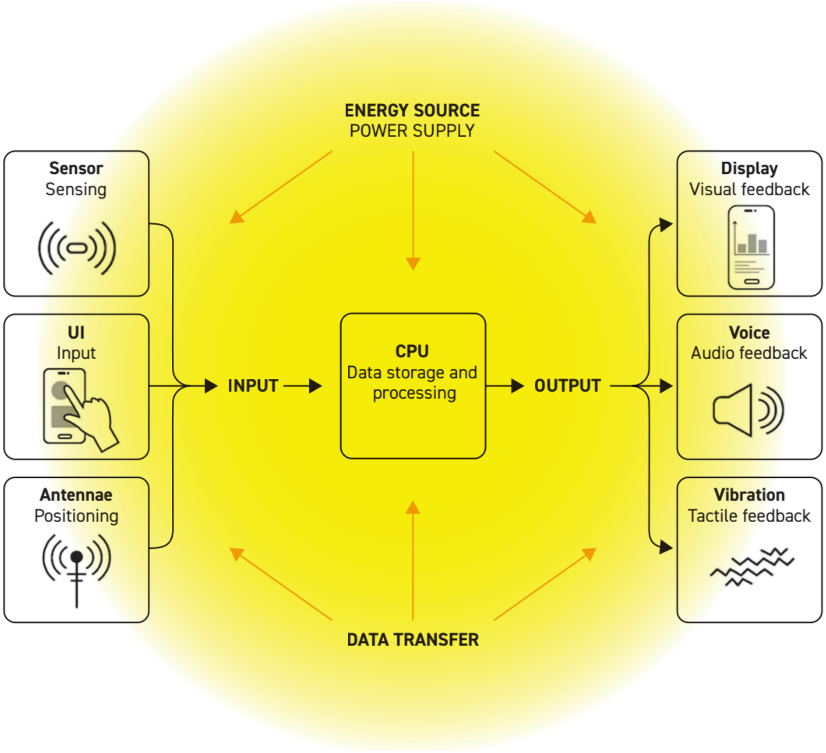


Figure 6. E-textile system framework (source: [2]*)*

Power is necessary for the operation of the components in the system. E-textile requires the use of batteries or energy generators to power electronic components throughout the life cycle of the device. To meet the design of e-textile, the batteries are often in the same enclosure as the electronics always replaceable and rechargeable, which makes them unreliable in terms of protection and safety [10] [11]. In addition, traditional batteries often are clumsy, robust, non-washable and do not meet the basic requirements for textiles. Harvestable energy sources including light, heat, piezoelectricity or friction and wind have the potential to solve this problem. Hybrid energy generators can increase and stabilize the output of a constant power source. Using inductive coupling, electricity can be transmitted wirelessly to a woven polyester glove through a flat spiral coil embroidered with conductive wires [12]. The energy of human movement can be collected by triboelectric or piezoelectric methods, for example, a simple and low-cost 3D-printing process for preparing a flexible PVDF-TrFE copolymer with multiple thin layers, and a Polydimethylsiloxane (PDMS) rugby ball structure was studied [13]. Of certainly, it cannot be ignored that solar energy is also a good option for the e-textile energy source, which will be introduced in 2.2.

2.2 Solar textiles

Theoretically, e-textiles need an energy source, such as a battery, to fulfill its function. Batteries always need to be charged or replaced, and they need to be removed during e-textile washing. Solar textiles are designed with the idea of removing e-textile's dependence on traditional power sources and providing a clean, unnecessarily removable and washable power source. The principle of solar textiles: solar cells are used as the energy source of electronic textiles to provide energy for electronic textiles [2].

There are some studies that have involved solar textiles. The latest research reports on different types of textile solar cells, including details of their manufacturing technologies, are presented [14]. The paper designed textiles that combine solar power and triboelectricity to power electronic devices [15]. A biomorphic textile actuator that can be manufactured at scale by conventional textile routes and triggered autonomously by sunlight has been investigated, in which the active and passive layers of the bimorph are composed of polypropylene tapes and MXene-enhanced polyamide filaments [16]. The solar cells were embedded into the textile to make solar textiles, which were machine washed and tested [3].

Among the many studies on solar textile, the solar textile model that best fits the idea of commercial production is the one shown in Figure 7. Commercial solar cells are designed to be placed under the textile, replacing the solar cell integrated above the textile, and the principle of light passing through the fabric to reach the solar cell [2]. The fabric is covered with solar cells, and light hitting the fabric is reflected, refracted and absorbed. The reflected light reflects the color of the fabric, and the absorbed light becomes thermal radiation. The part of the light that passes through the fabric is converted into usable energy by the solar cells. Although some energy harvesting is sacrificed, this scheme improves aesthetics. And to a certain extent, the solar cell is protected from damage caused by impact and scratches, making it more durable. Fiber material, textile structure, density, color, and post-treatment all affect the optical properties of textiles and thus the energy harvesting capacity of solar cells. Optimizing the design of these textile properties is crucial for textile solar modules. From a functional application point of view, many factors need to be considered, such as the choice of solar cells, the choice of fabric, and the choice of connection methods, among others.

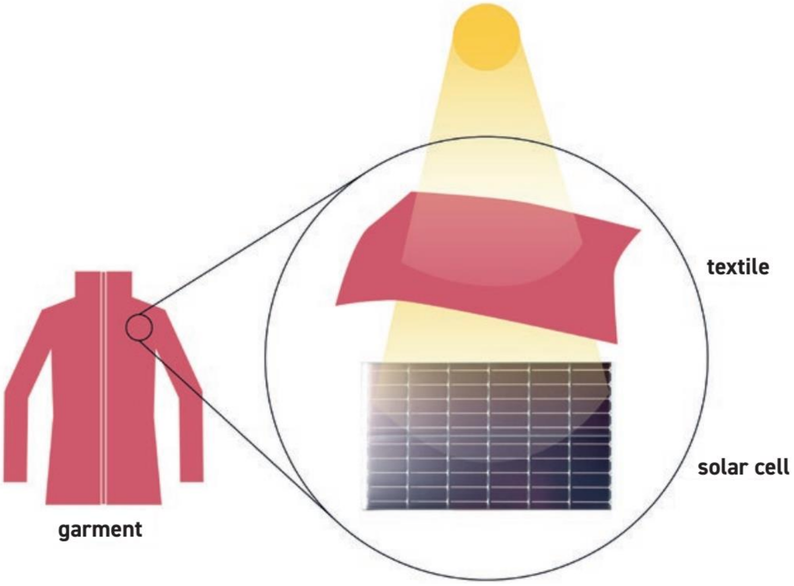


Figure 7. Light passes through the fabric to reach the solar cells. Source: [2]

According to visioning the applications for solar textiles, solar energy can be designed for lightning, body sensing, cooling or heating and mechanical movements. Beautiful and durable textile solar cell energy harvesting modules can be widely used in smart textiles and wearable technology solutions. They are potentially useful in the following fields and industries: agriculture, sports, medicine and building. Textiles which frequently exposed to sunlight, can be developed as a brilliant use of solar energy. For example, cargo covers have a large surface and exposed to sun but have no mains power to be utilized added with the that truck brands have launched the fully electric trucks such as BYD T10ZT 31T 8X4 5.6M Full Electric Dumper (BYD3310EH9BEV). A high potential for solar power can be found from interiors of passenger cars, as the glass roofs of cars are become common, textile solar panels could be integrated to the seat, hat rack or shades for instance. Similarly, in agriculture and farming the large areas of fabrics are used to protect plants from unfavorable weather conditions or wild animals. Depending on location and season of the year the solar power is available even more than 12 hours per day. In robotics, especially in the area of person assistive robotics used in personal care where robot look is softer being associated as more emphatic product in comparison to industrial robots, the sun powered textile could be an attractive solution in the future [2]. The above usage ideas are for reference only. Careful technical analysis is required in order to confirm the feasibility of the idea of solar textile applications.

2.3 Connection techniques in E-textiles

This section introduces several connection methods commonly used in e-textile through extensive literature research. Without the use of connection technology, wires and electronic components would come into poor contact and even make it impossible to connect the circuit. In addition, without the fixing effect of the connection technology, wires or electronic components may lose performance due to friction. E-textiles require the connection of components and traditional connection techniques include sewing and embroidery, adhesives, crimping, soldering, welding and tape, as shown in Figure 8. The connection method written here refers to the connection method commonly used in smart textiles and only some of them are suitable to apply to solar textile.

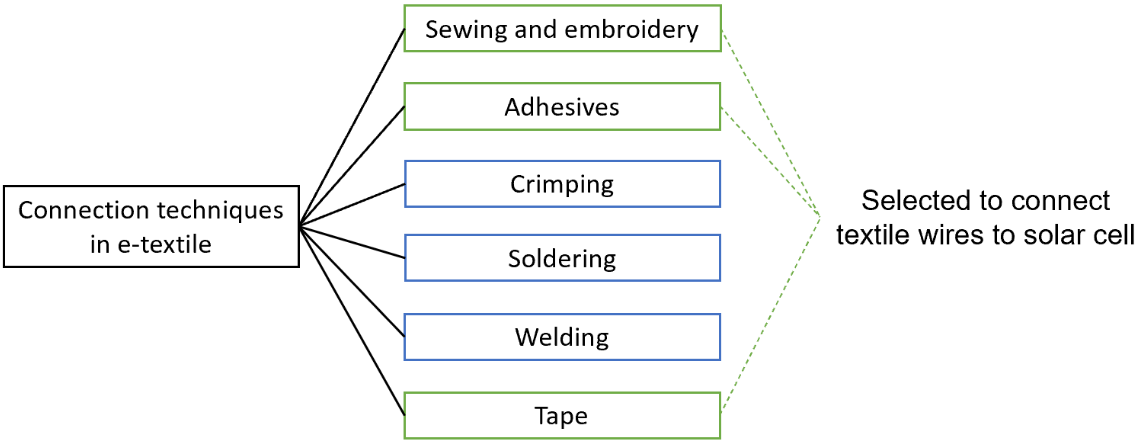


Figure 8. Connection methods applied to e-textile.

2.3.1 Sewing and embroidery

Sewing and embroidery techniques, which are the conventional methods of interconnection of electronic components, create designs by stitching strands of certain materials onto an appropriate substrate. Embroidery is a connect method that is also often used e-textiles [17]. In general, sewing and embroidery connection with conductive yarn on insulating fabrics with sewing machines or embroidery machines or even by hand [18]. For instance, chip elements, Printed Circuit Board (PCBs), and sensors are sewn together by sewing method (as shown in Figure 9), providing a connection between the circuit elements and fabric [19]. In addition, conductive yarns for touch sensing can be used as user interfaces for smart clothing by building embroidery circuits [20]. Embroidery machines are expected to be put into the production of smart textiles, which can be adjusted to embroider beautiful patterns.

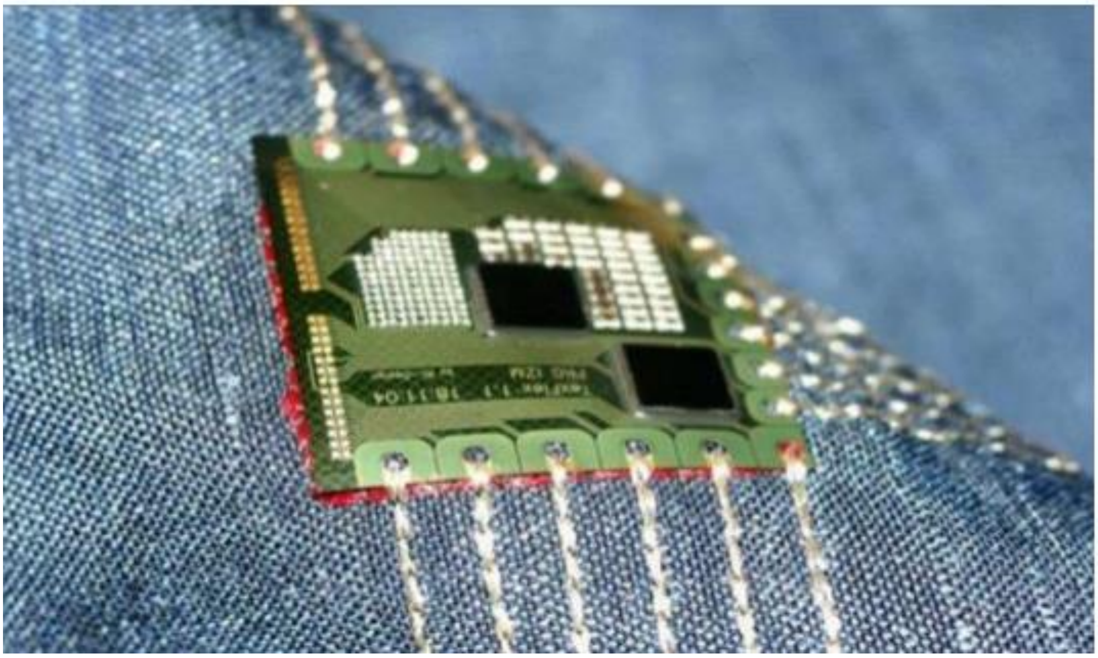


Figure 9. Chip components, PCBs and sensors placed on the substrate are connected by sewing. Source: [19]

From a textile point of view, the vast majority of fabrics can be used, woven, non-woven or knitted. This embroidery circuit formation process ensures to a large extent that the conductive threads are embroidered onto the fabric to fit any shape [20].

However, it must be considered that ordinary machines do not perfectly achieve conductive yarn embroidery and sewing. Because of the stress caused by bending and shearing, as well as the difficulty in forming strong stitches and the special properties of conductive yarns, custom machinery may be required to produce the perfect finished product, or threads with high strength and flexibility may be used [18].

The study "Conductive Yarn Embroidered Circuits for System on Textiles" introduces new conductive embroidery yarns for touch sensing and signal transmission in textile systems (SoT). Conductive yarns for touch sensing can be used as user interfaces for smart clothing by building embroidery circuits. Conductive yarns for signal transmission can be embroidered on smart clothing and used as transmission lines to transmit power and signals.

New metal composite embroidered yarns (MCEYs) were introduced for touch sensing, textile-based interconnects, signal communication, and power transmission for smart wearable devices. Robust and reliable MCEY embroidery circuits are used for sensing, interconnect, and signal and power transmission [20].

Two computer numerically controlled (CNC) embroidery methods (Figure 10) are introduced:

a). In the standard embroidery method, the stitch and bottom thread form a double-lock stitch that creates a technically recognizable appearance on the upper and lower sides, respectively (Figure 10-a). The CNC standard embroidery process can undertake complex work and connect flexible printed circuit boards (FPCBs) or small electronic components and embroidery circuits during the embroidery process.

b). The tailed fiber placement (TFP) method, on the other hand, is a three-threaded system. The TFP method is used when the thread is very hard, inelastic, and very thick like fiberglass or carbon fiber and cannot work on a standard embroidery machine (Figure 10-b). A set of top and bottom threads is used to fix the substrate fabric, and the coarse conductive yarn is fixed to the substrate fabric, forming a zigzag stitch. In the TPF method, it is not possible to connect small electronic components directly to the embroidery circuit during the embroidery process.

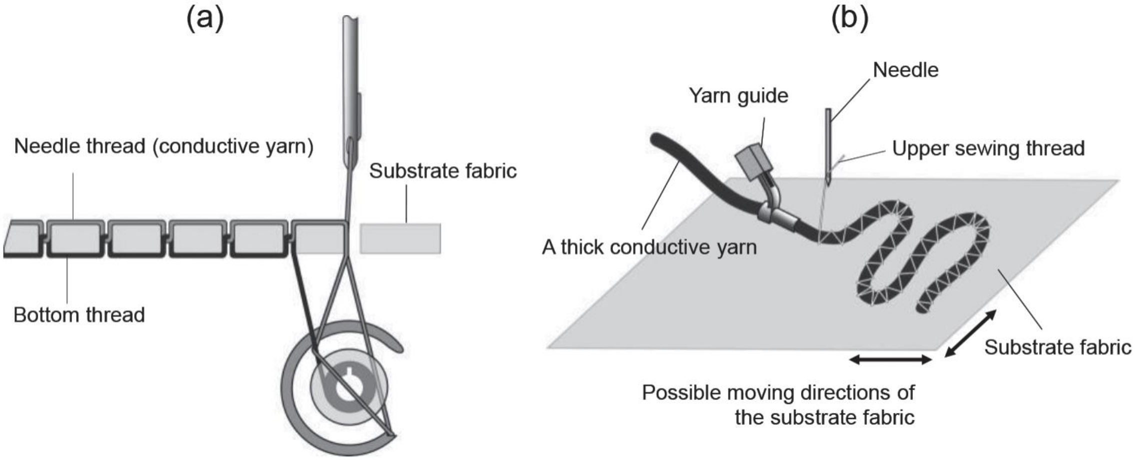


Figure 10. Embroidery methods: (a)standard embroidery forming double lock stitch and (b) the tailored fiber placement method. Source: [20]

The design of the needle thread and bottom thread in standard embroidery forming double lock stitch is not restricted. Conductive yarn can act as needle thread or bottom yarn or even both.

2.3.2 Adhesives

The adhesive method has a lower curing temperature, making it suitable for a wider range of e-textile applications. There are many types of conductive adhesives, and several types of adhesives are used in e-textile: non-conductive adhesive bonding (NCA), isotropic conductive adhesive (ICA), and anisotropic conductive adhesive (ACA). The method of adhesive bonding to be applied to e-textile can be done on an industrial scale using special machines or to provide technological developments, such as the control of the process and its variables (temperature, pressure, etc.) [21]. One example of conductive adhesive is shown in Figure 11.

Figure 11. Example of conductive adhesive. Source: *https://mgchemicals.com/products/adhesives/thermally-conductive-adhesives/thermally-conductive-epoxy-adhesive/*

In NCA, a layer of thermoplastic adhesive is applied to the parts in contact. Subsequently, the components are pressed together to remove the adhesive out of the contact area, and the part is then cured at the required temperature. And the schematic of this NCA bonding method by the example of an encapsulated electronic module and a fabric circuit made from embroidered insulated conductive yarn is shown in Figure 12 [22].

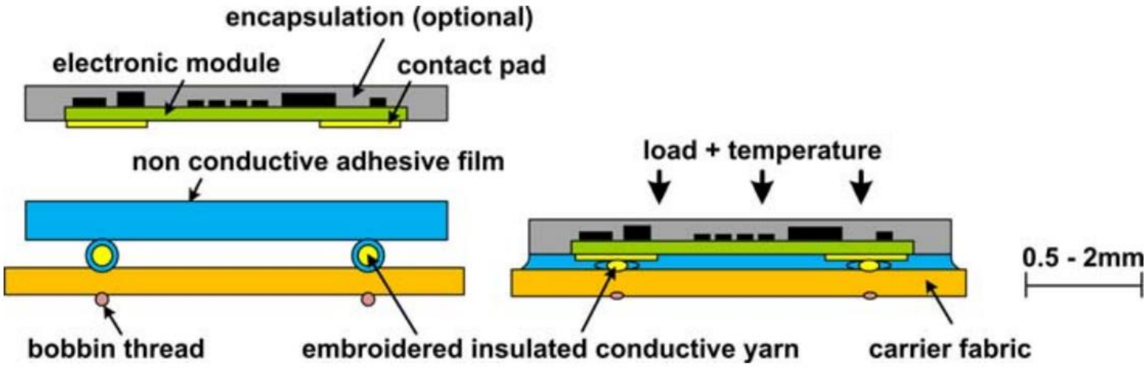


Figure 12. Illustration of the adhesive bonding process adopted for electronics-in-textiles. source: [22]

ICA and ACA are both electrically conductive adhesive (ECA) that make contacts to be connected conductive. The major differentiating factor between ICA and ECA is that ICA bonding involves the addition of conductive fillers to the adhesive material, while ACA has a much lower concentration of conductive fillers. In Figure 13, the differences between these two methods are obvious [18].

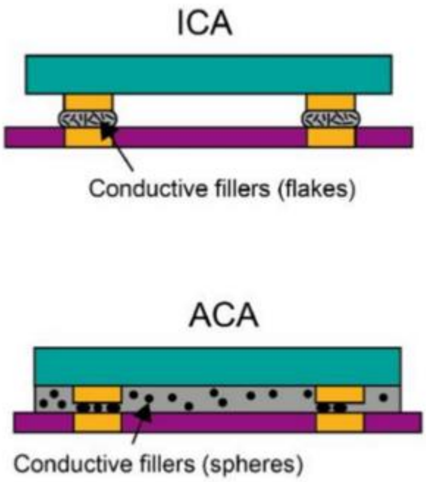


Figure 13. Detailed illustration of ICA and ACA methods. Source: [18]

Applications for ACA include flat panel displays containing thin-film ACA, glass flip chips, smart cards, and flip chip boards where soldering cannot be applied due to the thermal sensitivity of the substrate. The limitation of NCA adhesives is that they can only be used in high bond strength applications where electrical conductivity is not required [23]. Moreover, there are some drawbacks to ECA, such as sensitivity to the type and quality of component and board metallization, curing time requirements, and lack of durability in various climates [19].

2.3.3 Crimping

In electronics, crimping is the process of deforming a metal casing around a conductor to form a gas-tight permanent connection. Also known as cold soldering, crimping is a common method used in the automotive industry. Crimping is a fixed connection technique theoretically, but there are many detachable connector products that can be called crimp connectors. In this condition, a crimp terminal is used at one end to form a permanent contact with a flexible substrate and a connector such as a header at the other end [18]. The example of crimping is shown in Figure 14.

Figure 14. Example of crimping. Source: https://www.homesimprovements.net/2021/03/10/best-crimping-tool-get-it-from-wirefyshop/

The crimping approach uses standard manufacturing techniques and durable, inexpensive, and low-temperature interconnect technologies, providing opportunities for the manufacture of e-textiles. The strengths of this method are high reliability and simple-fast processing. The use of this technology in SoT has the potential to reduce the cost of producing e-textile products and thus make them competitively priced [24]. The idea of the crimping connection technique approach in e-textile is still relatively new and remains to be investigated.

2.3.4 Soldering

Soldering is a technique used to join two or more electrical or conductor contacts. It works by melting a metal, usually an alloy with a melting point lower than the melting point of the material of the contacts to be joined and applying it between the contacts. Soldering is a viable method of manufacturing e-textile circuits, and some of the conductive materials in e-textiles can be soldered. And the Figure 15 shows the example of soldering for circuits.

When it is used in e-textiles, the components are connected to a flexible substrate such as conductive wire, flexible copper wire or polyimide. Soldered connections have low contact resistance but are mechanically brittle, and in textile applications any bent or stretched connections must be reinforced to avoid breakage [18].

Figure 15. Example of soldering for circuits. Source: https://technimark-inc.com/our-blog/post/the-ultimate-guide-to-electronic-soldering

This connection technique is not suitable for temperature-sensitive textiles, as standard soldering typically requires temperatures above 200 ℃. This may mean that it is not suitable for use as a connection method for most e-textile products, as this high temperature can damage e-textile components. In addition, excessive reverse seams on trace and thread trimming can pose a challenge, and these issues can lead to electrical short circuits [19].

2.3.5 Welding

Welding is a process similar to soldering, but in welding, the metal is heated but without melted, bonded by a third alloy. Welding is known as a joining technique that achieves continuity of materials by applying heat or pressure, with or without any additional joining material. Of the various welding methods that exist today, the most common is industrial-scale welding, because the entire process can be easily automated. Among the various welding processes for the production of sensors and actuators for textile applications, ultrasonic welding, laser welding and resistance welding have the greatest potential for automation. Of these, ultrasonic welding in particular has great opportunities in the development of electronic textiles, as this welding process does not damage textiles and produces very reliable contact points [25]. Figure 16 shows how welding is applied to the production of textiles.

Figure 16. Welding in the production of fabric. Source:
https://www.leister.com/en/Solutions/Technical-Textiles

In earlier studies, e-textile transfer lines were manufactured using hot air welding technology, and the potential possibility of textile transfer lines was obtained by adding conductive yarns to the fabric through a hot air welding process. The demonstrated use of hot air welding as a convenient technique for producing reliable and durable transmission lines while maintaining the properties of textiles poses a great challenge to the field of e-textile research [26]. For instance, the hot air wedge welding diagram is shown in Figure 17.

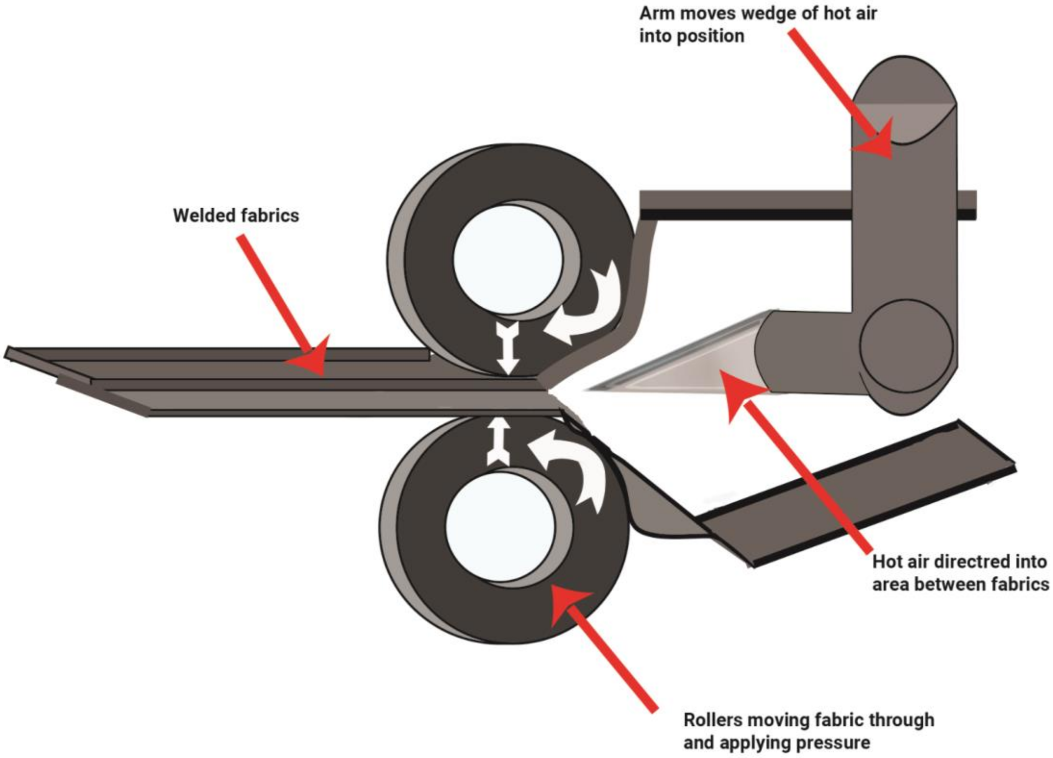


Figure 17. Hot Air wedge welding diagram. Source:
https://lightweightmanufacturing.com/uncategorized/types-of-industrial-fabric-welds/

The resistance welding method offers the possibility to draw conductive patterns of contact embroidery. In the available research investigation, a series of samples were tested for the optimization of resistance welding parameters for hybrid conductive wires crossed on textile substrates and optimized for 3 different design variables. It was shown that the resistance welding technique can achieve high quality contact structures on textile substrates. Moreover, it has been validated that, in an alternative to embroidering conductive threads directly on the fabric, the method is also applicable to embroidered contact pads for connecting conventional conductors (wires or cables) to a fabric substrate [27].

In summary, the advantage of welding connection method is that they have comparably high mechanical strength. Some welding processes do not require any filler material, and the running cost of the whole process is very low. However, temperature is a factor that cannot be ignored in the application of welding technology. When metals must be handled, welding is not a commonly used connection technique in e-textiles due to various problems associated. In the future, welding technology needs to be researched and developed to be more applicable to e-textile.

2.3.6 Tape

Tape, either conductive tape or conventional tape, can be used for the connection of e-textile components. It works well in textiles because of its flexibility to change with the movement of the textile. An example of conductive tape is shown in Figure 18, which is 3M™ 363 Conductive Aluminium Tape.

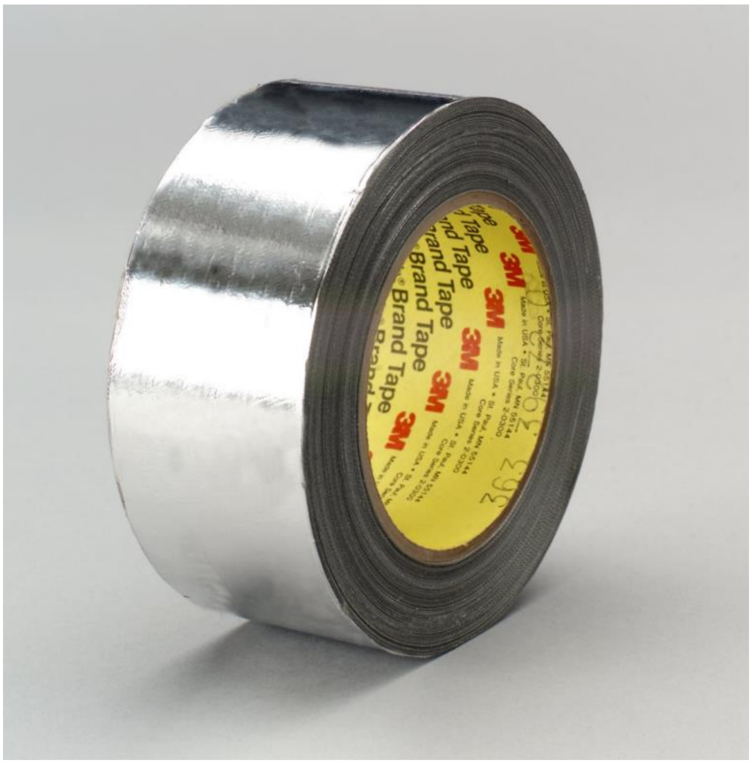


Figure 18. Conductive tape. Source: http://www.malaysia3mtape.diecut.com.my/wp-content/uploads/2017/03/3M-363-alumi_e-1.jpg

According to the research, conductive tape was applied by soldering low-resistance copper tape to the solar module contacts in solar textile. The layer structure of the textile–solar cell module is shown in Figure 19. And the results in the research have demonstrated the feasibility of this type of connection [3]. Although in that study a conductive tape was used, in principle, whether the tape is conductive or not has little to do with the effectiveness of the connection.

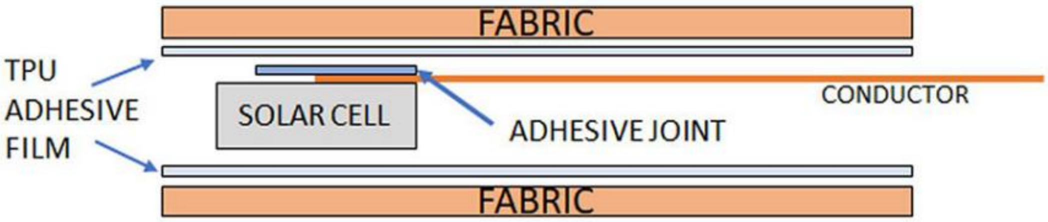


Figure 19. Layer structure of the textile–solar cell module. Source: [3]

2.3.7 Conclusion of connection techniques

The connection methods commonly used in e-textiles are soldering, welding, embroidery and sewing, adhesives, soldering, welding, crimping and tape. But these connections are only partially suitable for solar textiles. For example, welding and soldering require temperatures that are too high to damage solar cells. In addition to this, crimping method has high possibility to break solar cells.

To be concluded, this study considers 3 connection technologies achievable to connect solar cells to textile wires: tape, adhesive and stitching (sewing and embroidery). First of all, tape method is well developed in existing studies and no further improvement is considered necessary currently. In addition, stitching is regarded as a very environmentally friendly and user-friendly connection method. Moreover, there are several commercial conductive adhesives available, as well as researchers who synthesize their own flexible conductive adhesives.

2.4 Evaluation of washing durability of e-textiles and encapsulation

Cleaning and maintenance of textiles is often necessary, given that it may come into contact with human sweat, as well as environmental substances such as dust and bacteria in the air. As a member of textile family, e-textile is supposed to be washable like the majority of textiles. However, e-textile is composed of electronics with poor washability. Some e-textile product designers will ensure washability by instructing users to remove non-washable electronic components. For instance, the previous mentioned Xiaomi Mijia Cardiogram T-shirt, the electronic part is connected to the electrode button on the chest of the garment (Figure 20).

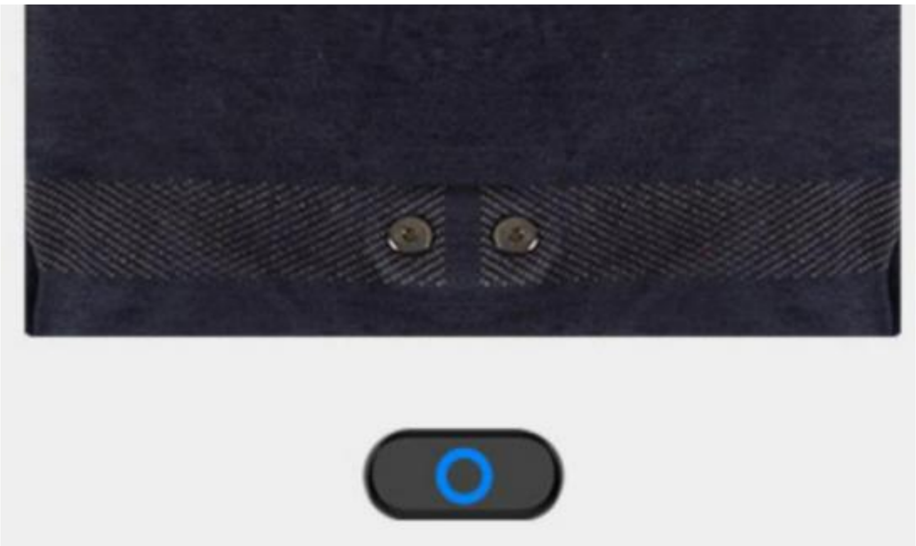


Figure 20. The detachable part of Xiaomi Mijia Cardiogram T-shirt. Source: *https://xiaomiplanets.com/xiaomi-mijia-cardiogram-t-shirt-2/*

In addition to the method of removing the non-washable parts, the encapsulation method has also been proposed to ensure that the non-washable electronic components are isolated within the waterproof thermoplastic polyurethanes (TPU) film [2]. In the study “Washable textile embedded solar cells for self-powered wearables”, recent studies on e-textile washing test methods are reviewed and a machine-washing durability test of 50 domestic machine washes at 40°C in a 55-minute program for solar cell taped with textile wires together encapsulated in TPU film and fabric model was designed. As a result, after 50 machine washings, the results showed that the performance of the solar cell elements did not significantly reduce, which means that encapsulation effectively improved the durability and washability of the elements [3].

3 Materials selection of experiments for stitching method

To make solar textile, the material selection is divided into 3 areas: solar cells, textile wires, fabrics. It is hoped that the solar textile can be produced in mass production through research, so the range of materials available in the market is affordable.

3.1 Selection of solar cells

Solar cells are the most common method of harvesting ambient energy in low-power wireless electronics applications. They offer superior power density and daily power generation potential compared to all other energy harvesting technologies imaginable with wearable electronics. Most solar cells are suitable for collecting natural light outdoors, and some have been specially developed to collect artificial light indoors [2].

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon [28]. Their energy source, electromagnetic radiation, can be visible, ultraviolet or near-infrared light. Light, on the other hand, is electromagnetic radiation consisting of photons, energy particles of light. Converting light into electricity in solar cells takes place in steps (Figure 21): When light hits a solar cell, photons are absorbed by the solar cell material, and the energy in it is transferred to electrons, forming free carriers and electron holes. To separate positive and negative charges, solar cells use layers of materials with small differences to form a built-in electric field at the interface that pushes electrons and electron holes with opposite charges to the opposite side, creating potential differences and voltages. By connecting the load, the solar cell can provide current that is used to drive electrical equipment [2].

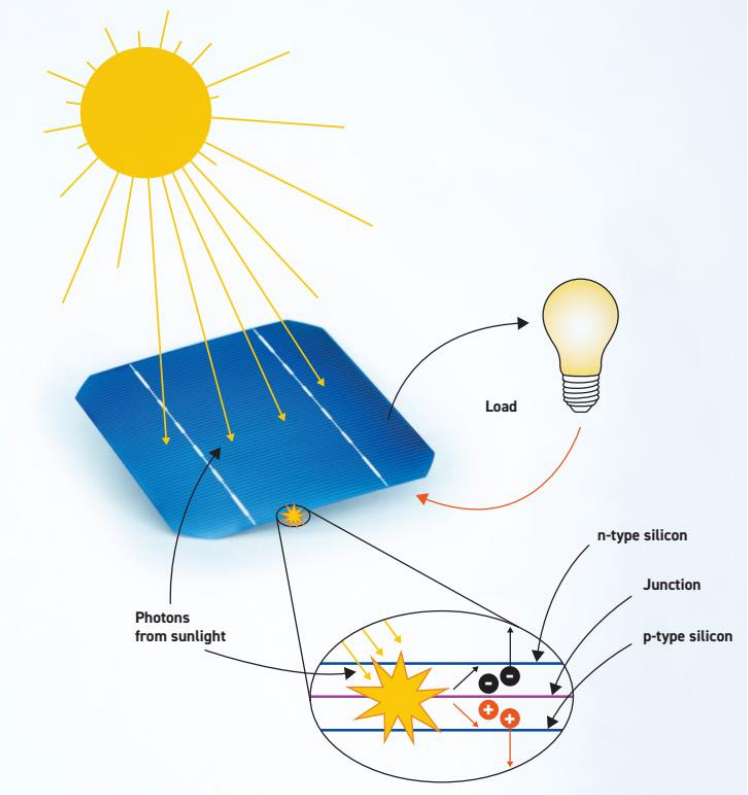


Figure 21. Solar cells convert light into electricity. Source: [2]

Commercial solar cells can be suitable for integration with textiles due to their proven technology, availability and cost-effectiveness. There is a wide variety of commercial solar cells utilizing different photovoltaic technologies, which come in different shapes and sizes. The main photovoltaic technologies in the market are monocrystalline, polysilicon and amorphous silicon solar cells [2]. Figure 22 shows examples of common solar cells with potential for solar textiles.

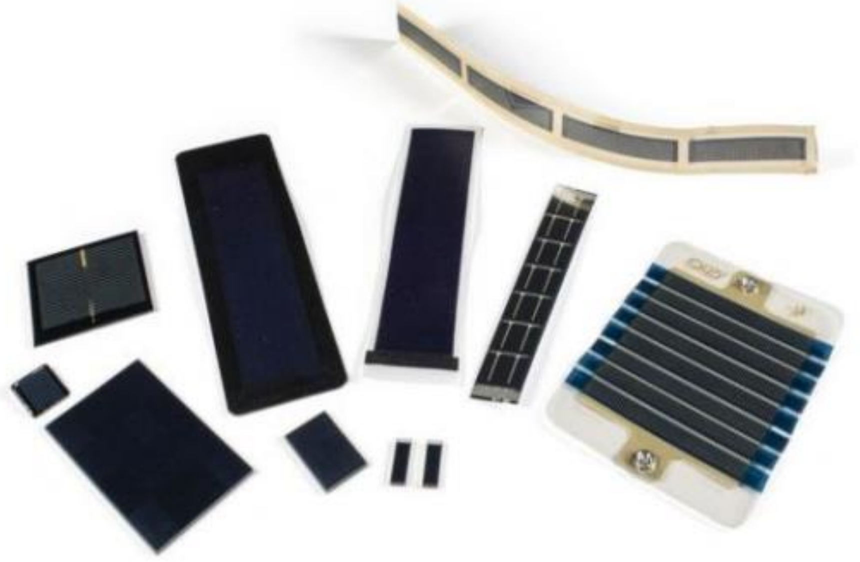


Figure 22. Examples of solar cells for solar textile. Source: [2]

Crystalline silicon solar cells absorb a wide range of spectra under different lighting conditions, while amorphous silicon cells perform better in the visible light range. Indoor light is suitable for amorphous silicon cells, while outdoor sunlight is more suitable for crystalline silicon cells. It is more complex when used on textiles, and color textiles affect amorphous silicon cells more, while crystalline silicon cells can use the near-infrared light transmitted by textiles. Textile transmittance influences the choice of light in the visible range and is suitable for different solar cell technologies. Spectral matching of lighting sources, battery types, and textile properties is an important factor in integrating solar cells into textiles, affecting power output and visibility. The need for energy in solar textile is different for different uses. For example, the energy required for electrical appliances, usually the energy provided by solar cells. If a solar cell is designed for low energy smart clothing, it is usually sufficient to have the equivalent energy of a coin cell. If it is designed for an industrial solar cell, the energy required is much larger, but without meeting the comfort requirement of garments, and a more efficient solar cell can be used [2].

At present, solar cells on the market can only supply energy in real time, which itself cannot store energy. If the storing of solar energy is needed, another energy storage device is required connected into the system. However, at present, researchers are studying solar cells that can store energy. By coordinating the energy matching between the conversion unit and the storage unit, seeking maximum power point coincidence and maximum efficiency point synchronization, the solar conversion storage efficiency of integrated photo capacitors has exceeded the milestone of 20% [29].

Various commercially available solar cells are on market, but the final selection narrowed down to two models:

1) Solid solar cell. Solid single crystal silicon solar cells by IXYS (IXOLAR SolarBIT)

2) Flexible solar cell. Flexible amorphous silicon solar cells by PowerFilm Solar (PowerFilm SP 3-37).

Both are easily available from online electronics stores in a variety of sizes, dimensions, and electrical specifications. IXYS cells are highly efficient and particularly suitable for outdoor use because they also use near-infrared light. PowerFilms are used to demonstrate flexible solar cell integration and are ideal for indoor lighting conditions, provided the covering fabric is sufficiently transparent. The total area of solar cells required for an energy autonomous electro textile system depends on the power requirements of the application and the lighting conditions under which it is used. Under the condition of the same size of light area, solid-state solar cells obtain more energy than flexible solar cells. The usable area on textiles sets an upper limit on the size of the solar cell and, in some cases, may define whether energy self-sufficiency is possible in practice.

When designing solar textile, the solar cells used are divided into flexible solar cells and solid solar cells, as shown in Figure 23. Solid solar cells have been studied to be applied to solar textiles and remain stable after 50 machine washes. Studies have proved that Solid single crystal silicon solar cells by IXYS can be washed directly for many times to maintain performance, while the flexible solar cell PowerFilm SP 3-37 has poor washability, and the same reason can be speculated that PowerFilm SP 3-37 has poor direct washing ability [3].

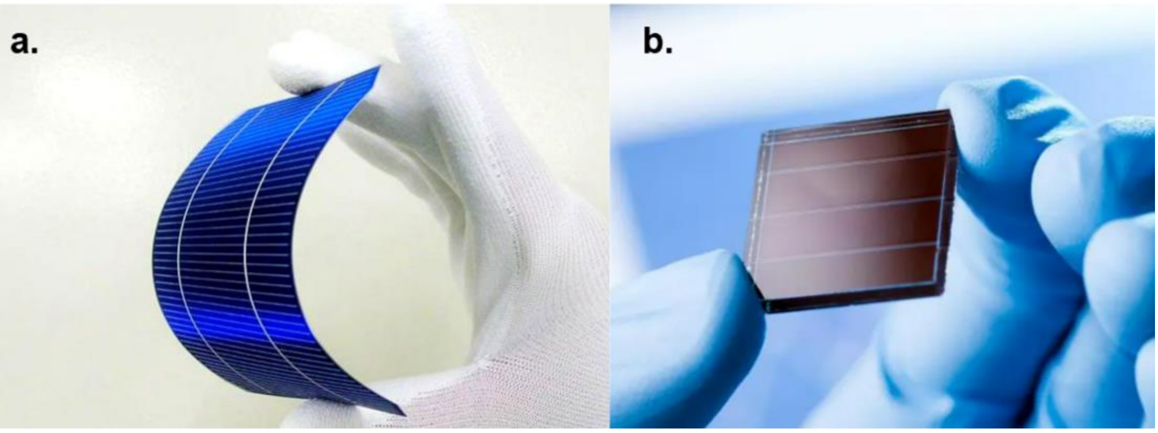


Figure 23. Flexible solar cell (a) and solid solar cell (b). Source: https://scitechdaily.com/solar-cell-efficiency-increased-with-innovative-two-dimensional-materials/

However, compared to solid solar cells, flexible solar cells are more in line with the soft characteristics of textiles, and they can bend to a certain extent as the fabric folds. It is also more suitable for solar textiles in terms of aesthetics, and the surface is flat and smooth after being covered by fabric, and there will be no obvious protrusions. In addition, both sides of the flexible solar cell can be penetrated without loss of performance. This enables the flexible solar cell connection section to be threaded like a fabric by needles, connecting the solar cell to the textile wire through a sewing machine, which is not possible with solid solar cells.

In the experiments of this study, only flexible solar cells were used. PowerFilm Solar's Flexible amorphous silicon solar cells PowerFilm SP 3-37 was used. The two sides of the back of the solar cell are custom-scraped open to form a conductive contact connection area. In the experiment, this part of the contact area was penetrated by a sewing machine, connected by stitching and textile wire contact.

3.2 Selection of textile wires

Conductive yarns often act as conductors in smart textiles, and conductive yarns act as conductors in solar textile. Wire fiber is an important component raw material for the preparation of conductive yarn, which is roughly divided into two categories. The first type of wire fiber is natural conductive fiber, such as metal fiber, carbon fiber, conjugated polymer, optical fiber, etc., generally prepared by stretching, cutting and other processes. The other one is conductive fibers obtained by combining materials with insulating properties with highly conductive materials, such as metal-based conductive materials, carbon-based conductive materials, intrinsic conductive polymers, etc., also known as composite conductive fibers [30].

In solar textile, not only conductive yarns but also conductive fabrics are used, such as braided fabrics (Figure 24). Considering that the flexible solar cell selected in this study has a narrow contact connection area at both ends, conductive yarns are more suitable than conductive fabrics.

Figure 24. Examples of conductive yarns for solar textile. Source: [2]

The conductive yarn used in this experiment is Madeira HC 12 from Shieldex company. This conductive yarn has been proven to work as a solar textile wire, and the finished sample still has high performance after multiple machine washes [3]. This yarn can be used normally by a sewing machine like a normal yarn to complete the stitching sample. It should be noted that the yarn should be placed in the lower part of the sewing machine to avoid the destruction of the silver plating caused by the yarn rubbing multiple times in the sewing machine.

3.3 Selection of fabrics

Fabric is described as “a 2-dimensional textile which is produced by knitting, weaving or non-woven technology” [2]. The numerous combinations of fibers, yarns and structures bring about the diversity of fabrics. The materials that make up a fabric are called fibers and are often classified as natural fibers and chemical fibers. Among them, natural fibers include plant fibers, such as cotton fibers, animal fibers, such as wool fibers and mineral fibers. Chemical fibers include recycled fibers, synthetic fibers and inorganic fibers. The fibers themselves are also different, even if they are made from the same raw materials. For example, polyester filaments can be woven together by a dozen or dozens of single filaments to form a fabric, while polyester fiber short yarns must be spun to form a continuous yarn after twisting and hugging between fibers to form a continuous yarn for weaving [31]. Fabrics are divided into weaving, knitting and nonwovens according to their weaving methods, as shown in Figure 25.

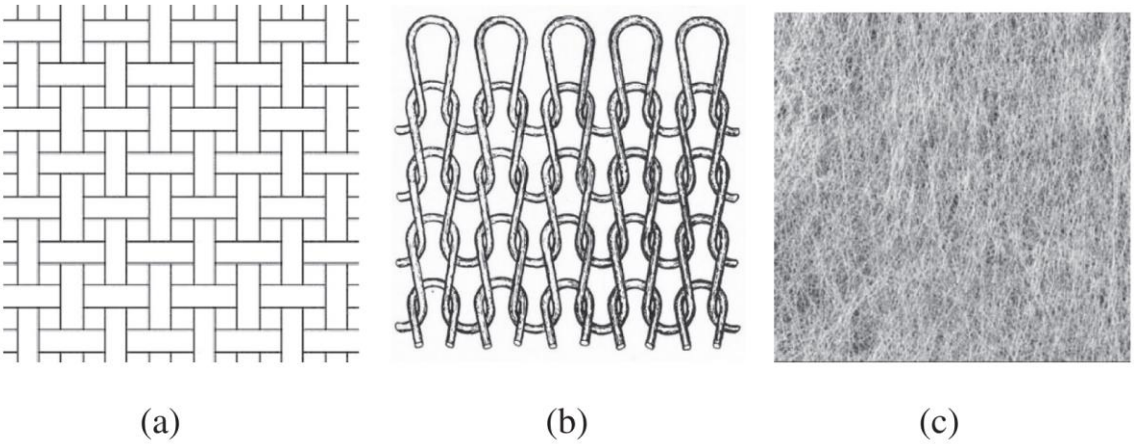


Figure 25. Detailed image of three main textile structures: a). Woven, b). Knitting, c). Non-woven. Source: [32]

When designing a solar textile, the fabric acts as a covering on the solar cell, which affects the performance of the solar cell. The light reaches the surface of the fabric, and after reflection, absorption and refraction, the refracted light can reach the solar cell covered by the fabric [2], which is shown in Figure 26. Finding a balance between transparency and coverage of textiles is a challenge in designing textiles to cover solar cells. To harvest as much energy as possible, textiles need to be transparent enough to allow light to penetrate it. But to ensure that electronic components are well concealed, textiles need to be opaque enough to cover the electronics underneath them.

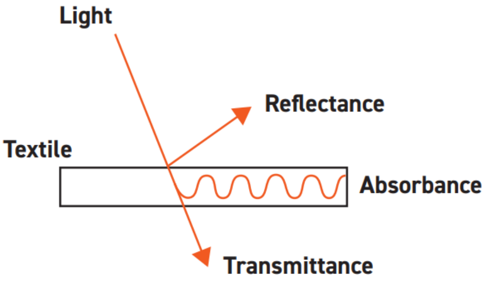


Figure 26. Light passing through the fabric. Source: [2]

In this study, the experimental part does not address the effect of fabric selection on aesthetics and light transmittance, and the fabric only serves as an outer covering for solar textile. Mainly research on the connection technology of solar cells and textile wires, the fabric used in the experiment is required to be as consistent as possible, and the impact on the light received by the solar cell is minimal, and white fabric is the first choice. The white fabric has high light transmittance and has little effect on the performance of solar cells. Non-woven fabrics are generally not suitable for machine washing, so only two kinds of fabrics, woven and knitted, and non-woven fabrics are not selected. In order to verify the effect of the fabric waterproof coating on the joining effect, coated and uncoated woven fabrics were selected, and the effect of coating on solar samples could be judged by comparing experimental data.

Based on the discussion above, 3 white fabrics were selected for the experiment in this study, as shown in Table 1.

Table 1. Experimental fabric details

Fabric	Company	Product	Type	Finishing	Structure	Composite	Weight
1	Geisa fabrics	NANDO	Warp knitting	Uncoated	plain	84 % PES / 16 % EA	220 g/m2
2	FOXA OY	Action Mistral	Woven	Coated	-	80 % PES / 20 % PU	145 g/m2
3	CARRING TON	VARESE	Woven	Uncoated	2/1 twill	64% Polyester / 33% TencelTM / 3% EOL (XLANCE®)	205gsm

4 Experiments for stitching method

The experiment procedure is shown in Figure 27.

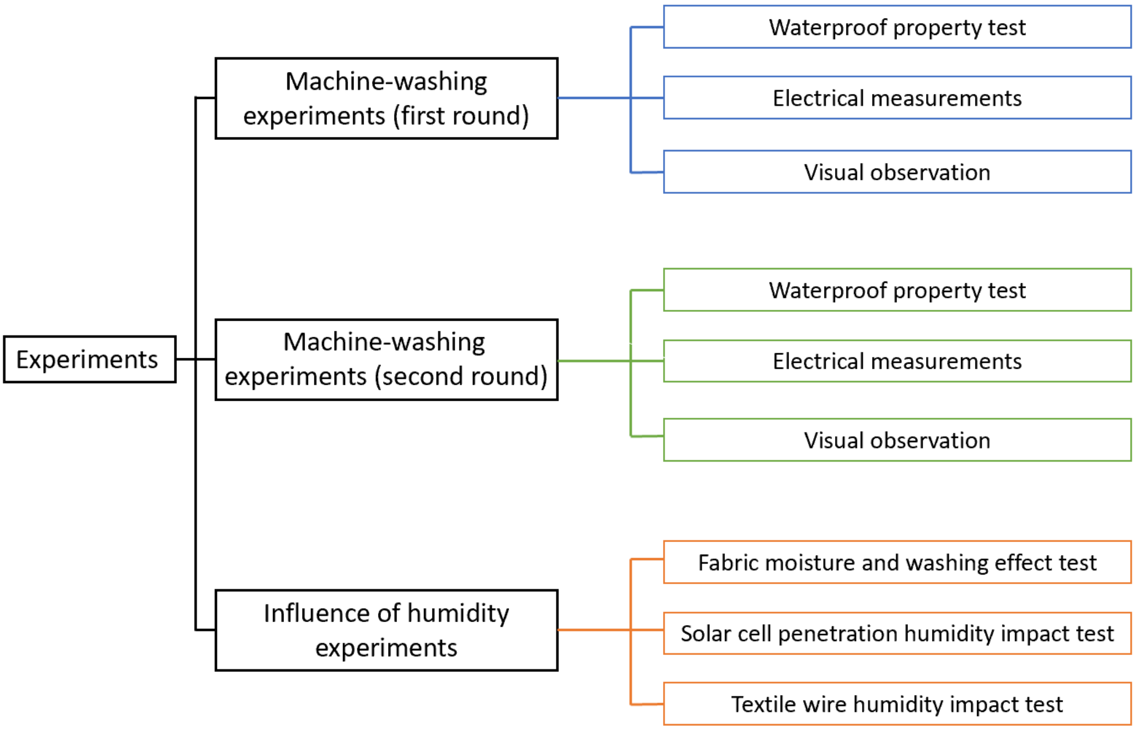


Figure 27. Experiment procedure

The flexible solar cells used in the experiment were PowerFilm Solar company's Flexible amorphous silicon solar cells PowerFilm SP 3-37. Textile wire is Madeira HC 12 from Shieldex. Sewing machine is PFAFF select^{TM} 3.2 sewing machine, the stitch selected is 301 lock stitch. The heat press used in the heat-press process is Plancha Beinsen Semiautomática from ESPIRAL.

4.1 First round of machine-washing experiments

Machine washing conditions: 40° C, 800 rmp, 52min.

Detergent: 47 g / 75 ml of household laundry detergent

Washing machine: LG Direct Drive™ F4J609WN 9Kg 1400 Spin Washing Machine

The solar textile sample was packed in a polyester laundry bag and washed with 2 kg of cotton fabric.

The washing machine and detergent for machine washing experiments are shown in Figure 28 and Figure 29 separately.

Figure 28. Domestic washing machine.

Figure 29. Domestic detergent.

The flow of the first round of machine wash testing is shown in Figure 30.

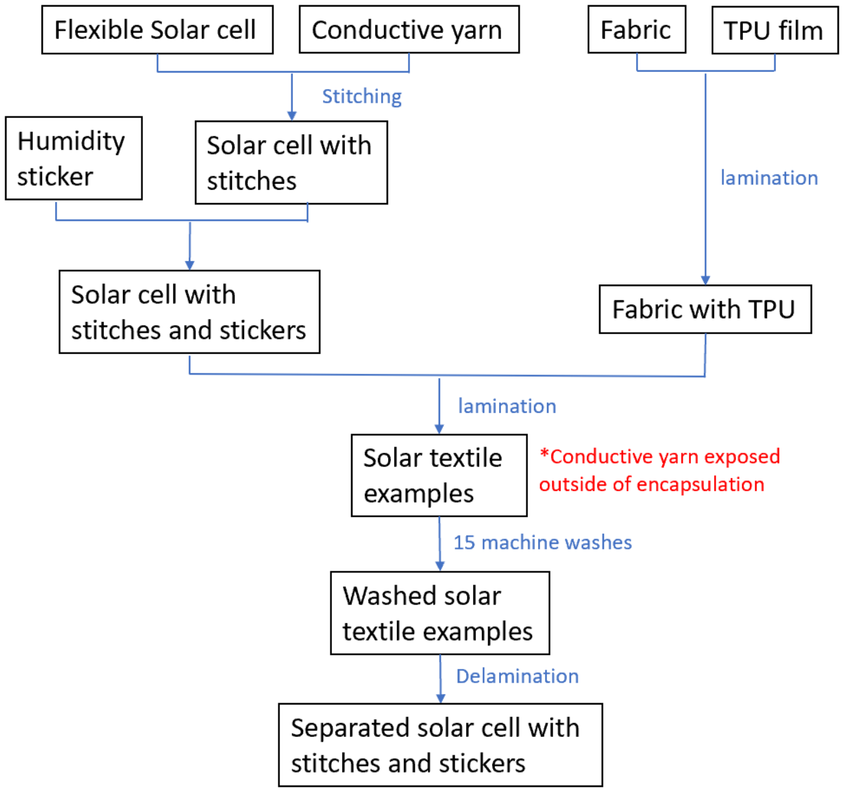


Figure 30. The experiment process of washing test (first round)

4.1.1 Samples for the first round of experiments

In this experiment, 10 solar textile samples were produced, which is shown in Table 2. In this experiment, 4 pieces of fabric 1, 3 pieces of fabric 2 and 3 pieces of fabric 3 are prepared as parallel samples for trail separately.

Table 2. Fabrics for solar textile samples (first round)

No.	Description	Composite
1	Knitted	84 % PES / 16 % EA
2		
3		
4		
5	Woven coated	80 % PES / 20 % PU
6		
7		
8	Woven	64% Polyester / 33% TencelTM / 3% EOL
9		
10		

According to the sewing and embroidery method researched in 2.3.1, the flexible solar cell and the textile wire are connected by a sewing machine with cotton spun yarn, as shown in Figure 31. Different from the stitching in Figure 10, the needle yarn is normal yarn and the bottom yarn is conductive yarn. To be detailed, the front and back of contact area on flexible solar cell with stitching are shown in Figure 32.

Figure 31. Stitching sewing for flexible solar cells.

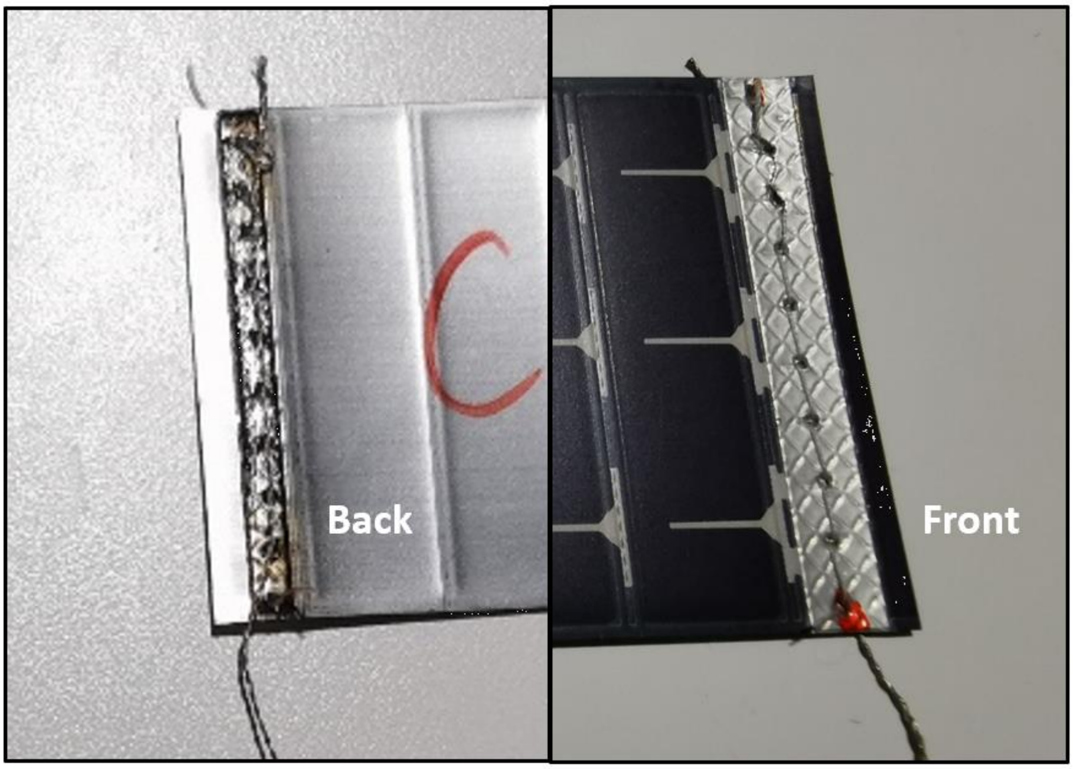


Figure 32. Stitching details on the front and back side of contact area on flexible solar cell

The layer structure of the solar textile module (first round) is shown in Figure 33. The textile wire is partially exposed outside the encapsulation for easy measurement during the experiment.

A humidity sticker is applied diagonally on the back of the flexible solar cell after stitching (Figure 34) and the fabric and TPU adhesive film are hot-pressed together for encapsulation (145° C, 20s, pressure: 3.6 bar) (Figure 35).

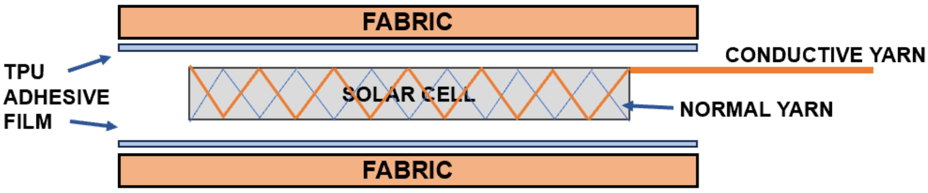


Figure 33. Layer structure of the solar textile module (first round).

Figure 34. Solar cell with humidity sticker (first round).

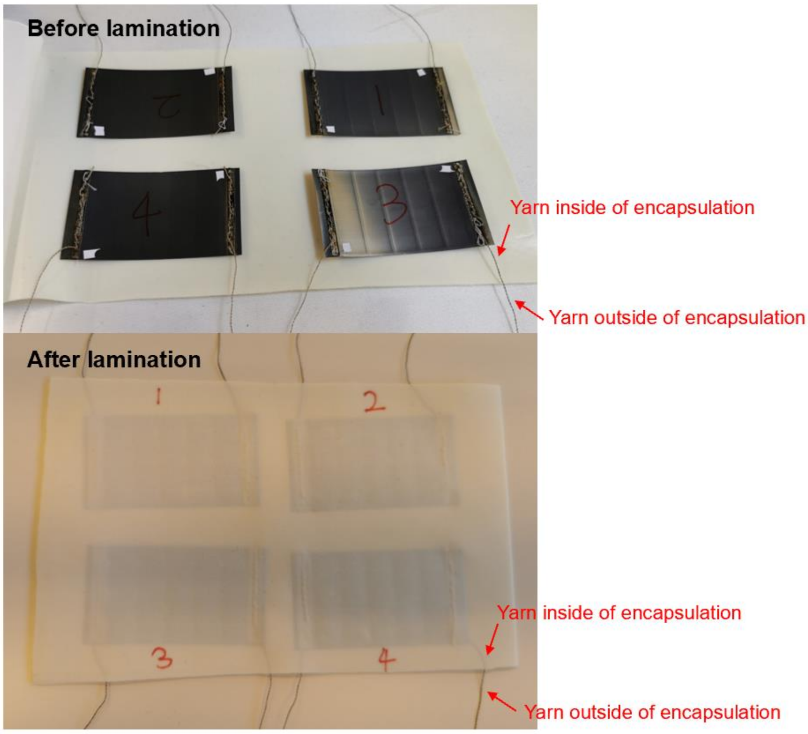


Figure 35. Sample before and after lamination (first round).

4.1.2 Waterproof property test

The surface of the humidity sticker is white, and when it encounters water, the surface of the sticker turns red. Stick a humidity sticker on the bottom left and top right of the back of the solar cell. By observing the reddening of the humidity sticker after washing, the degree of waterproof of the sample was judged.

4.1.3 Electrical measurements

The electrical measurement process for the first round of machine-washing test is illustrated in Figure 36. The direct current (DC) voltage of each sample is tested using a multimeter AMPROBE (Figure 37) after stitching and the schematic diagram of electric test is illustrated in Figure 38. Then the flexible solar cell after stitching is packaged, and the DC voltage is tested on the packaged fabric sample. The solar textile sample is tested for DC voltage before machine washing, dried at room temperature after every 5 washes, observed for damage in appearance, whether the sticker turns red, and detects the DC voltage between textile wires exposed to the fabric. Until after 15 washes, disassemble the fabric and observe if the sticker turns red and the solar cells, wires and connections are not broken. Next, solar textile samples were delamination, where TPU and fabric were removed from the surface of the solar cell and the voltage across the textile wire was tested. Test the DC voltage between the wires that were once inside the package and measure the DC voltage across the exposed wires outside the package and compare it.

After the solar cell ends are stitched with textile yarn, the measurement is between two conductive yarns. It is important to note that simply testing the yarn exposed outside the encapsulation is not enough to demonstrate a change in solar cell performance. After all, yarns exposed outside the encapsulation may be damaged by the washing process. Therefore, after the washing experiment is completed, the encapsulated sample needs to be disassembled and the ends of the yarn wrapped in the encapsulation measured.

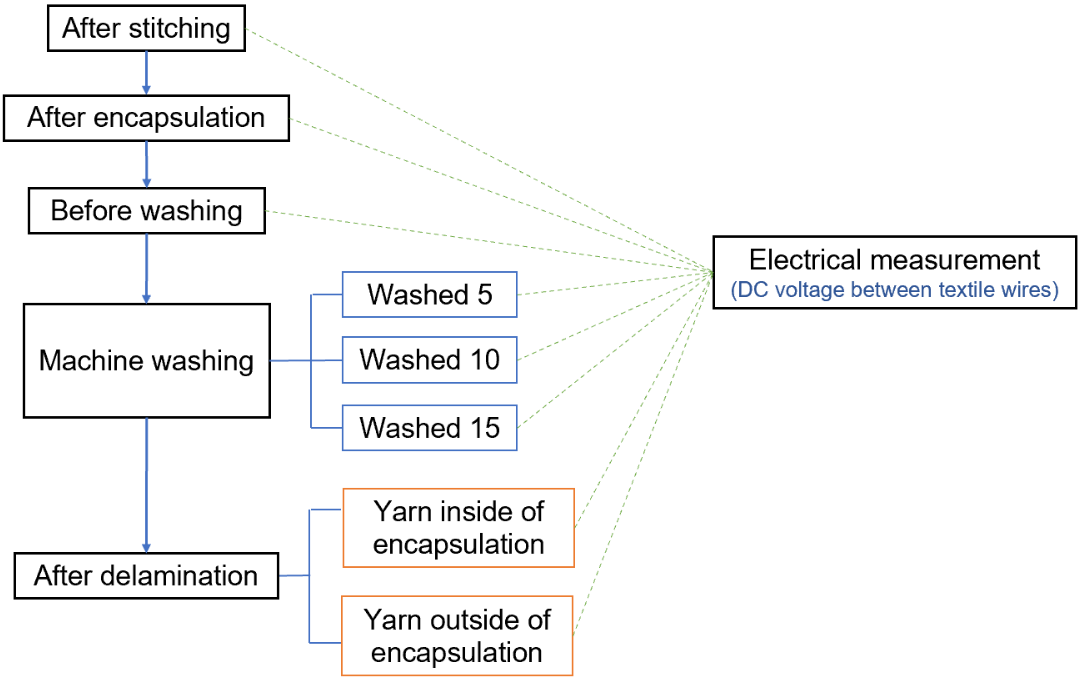


Figure 36. The measurement process of textile solar samples (first round).

Figure 37. Multimeter.

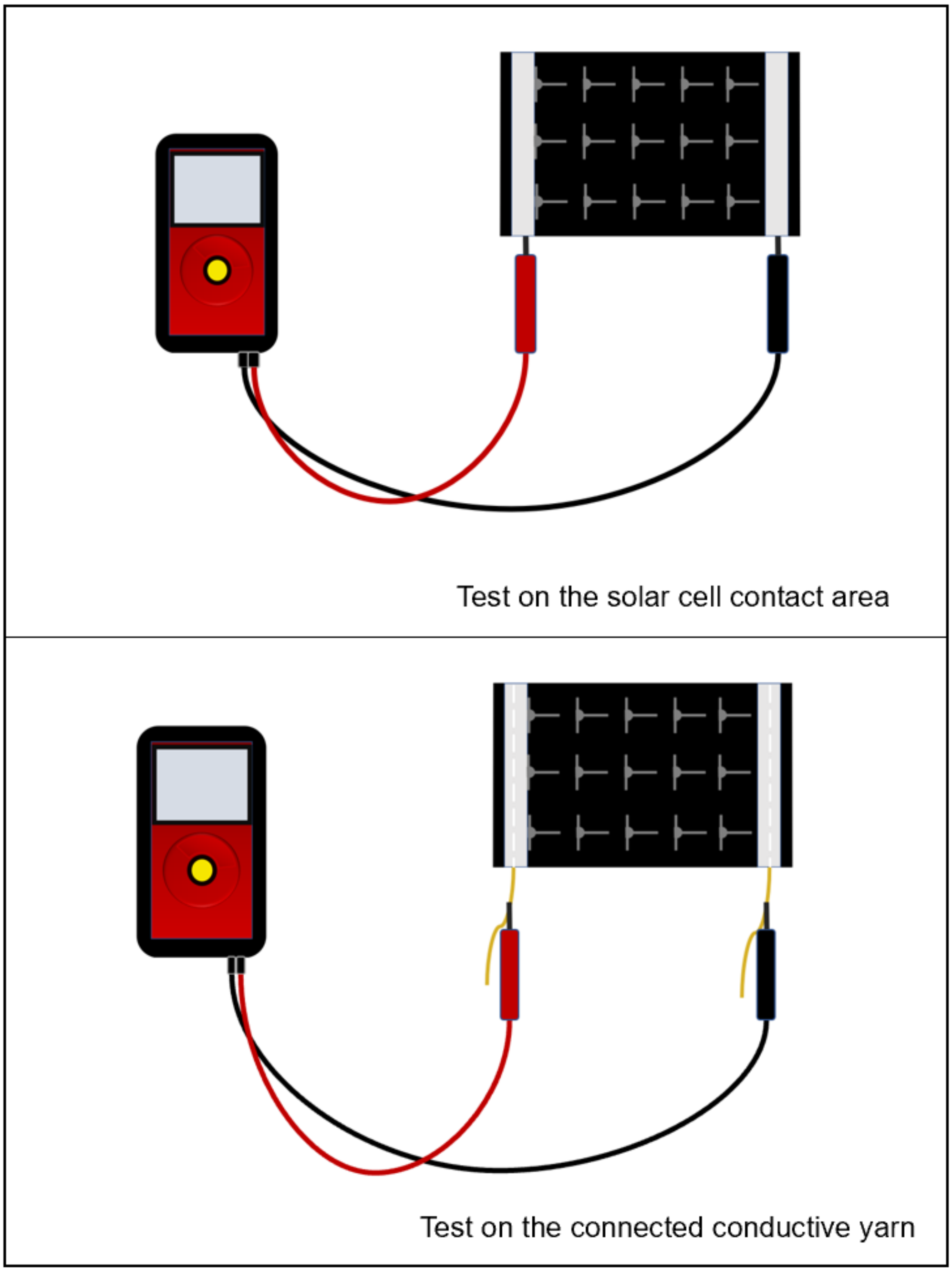


Figure 38. Schematic diagram of electric test.

4.1.4 Visual observation

Contrast the visual changes at all stages of the solar textile. To check if the solar cell crack.

4.2 Second round of machine-washing experiments

After the first round of testing, the experimental results were scattered and no reliable conclusions could be drawn. Therefore, a second round of experiments was designed to test the conjecture based on the results of the first round (Figure 39). The sample production and testing methods of the first round of experiments were optimized, and the test of the influence of solar cell pores and humidity on the performance of conductive yarns was supplemented. In the machine wash test portion of the second round of experiments, solar textile samples were made in a similar way to the first round of experiments, but the conductive yarns were designed not to be exposed outside the fabric, and an experimental group of no wires was added to verify the effect of solar cell penetration on performance.

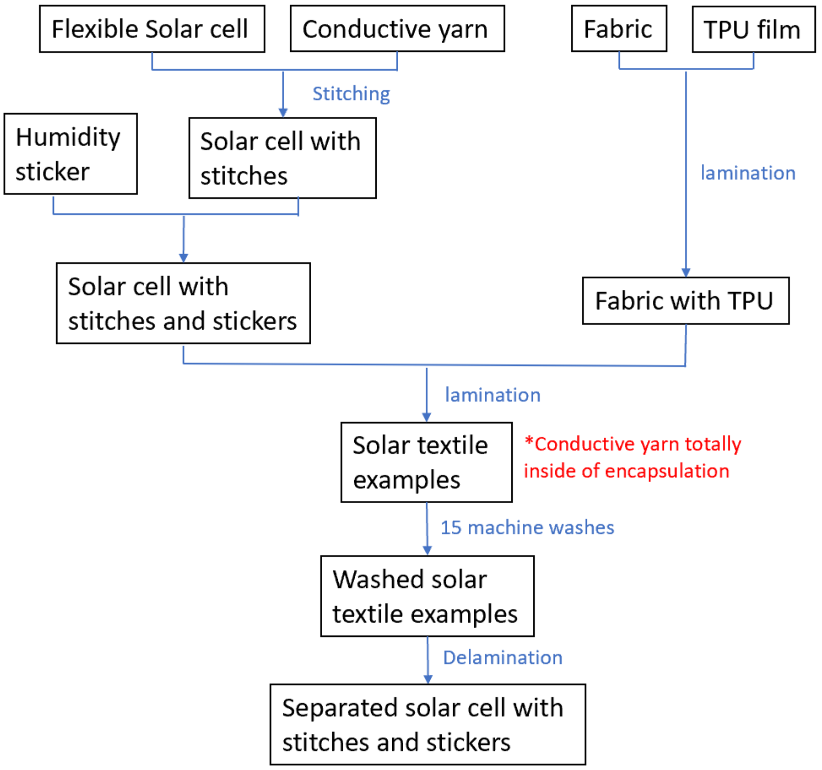


Figure 39. The experiment process of washing test for samples with stitches (second round).

The machine wash conditions of the second machine wash test remain the same. The covering fabric used in the second round of machine wash experiments was uncoated knitted fabric (84 % PES / 16 % EA).

After encapsulation, the solar cells and yarn are completely wrapped inside the encapsulation and no longer have textile wires exposed to the fabric. It cannot be tested after packaging, nor after 5 washes, only after 15 washes. So, it is not known if the sample after encapsulation is damaged until delamination.

To verify the resistance of encapsulation to machine washing of flexible solar cells, solar textile samples with holes in the contact area but without textile wires were produced. The experimental procedure is shown in Figure 40.

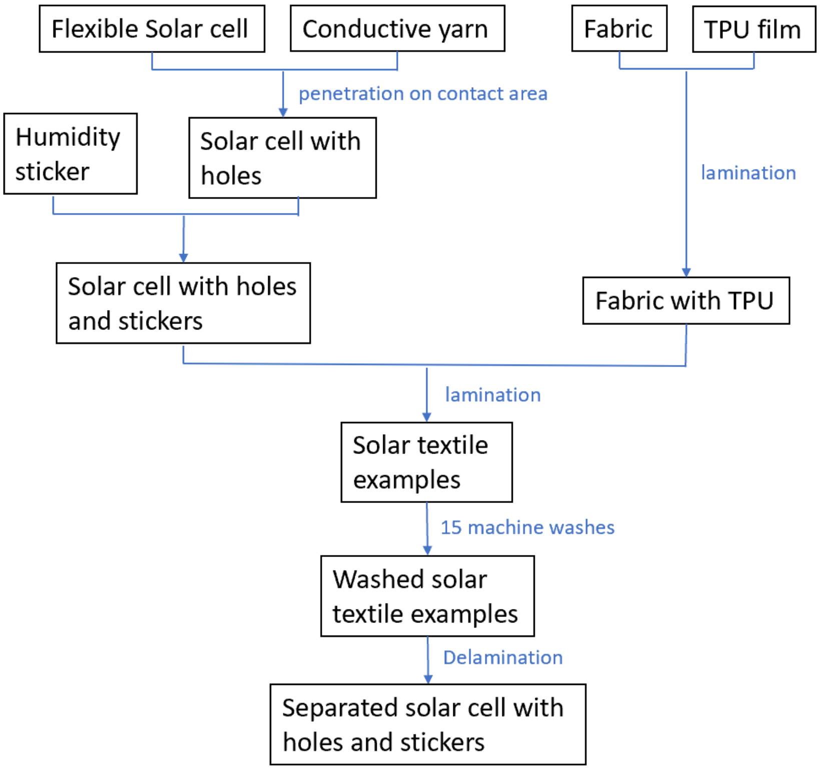


Figure 40. The experiment process of washing test for samples without yarns (second round).

4.2.1 Samples for the second round of experiments

In this experiment, 6 solar textile samples were made (6 experimental groups: 3 stitching and 3 penetration-only, and 2 control groups without encapsulation process: 1 stitching and 1 penetration-only). The layer structure of the solar textile module (second round) is shown in Figure 41.

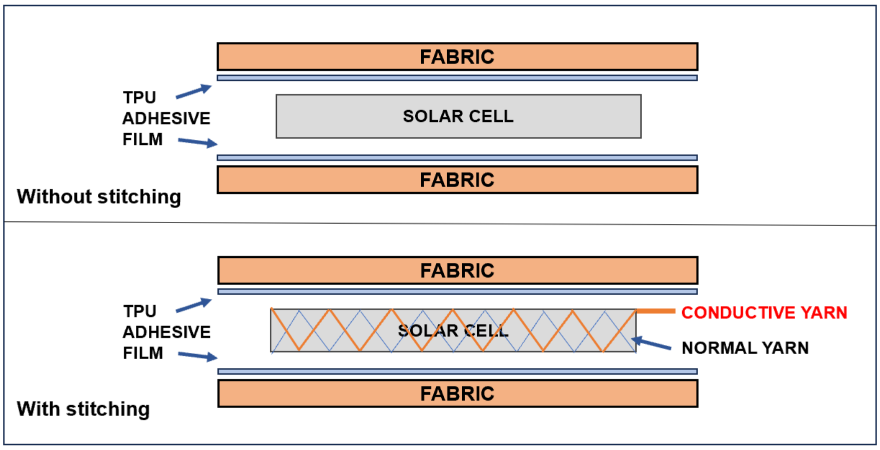


Figure 41. Layer structure of the solar textile module (second round).

4 solar cells with stitching connection technology were fabricated in the same way as in first round test, and 4 solar cells with contact area uniformly penetrated through and small holes appears (Figure 42). With humidity stickers affixed to the front and back of solar cells and TPU film attached to fabrics, the samples are made by lamination (145°C, 20s, pressure: 3.5 bar).

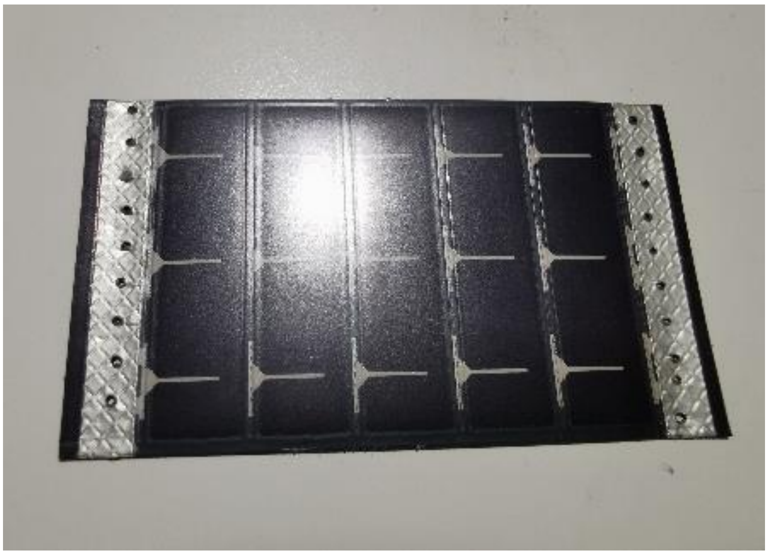


Figure 42. Flexible solar cell with holes at contact area.

4.2.2 Waterproof property test

Observe the redness of the humidity sticker after washing to determine the degree of waterproof of the sample. After the improvement, the stickers attached to each sample were changed from 2 to 10, not only on the back of the solar cell, but also on the front. Put 10 humidity sensor stickers on every solar cell (Figure 43) and there are 5 on the front and 5 on the back.

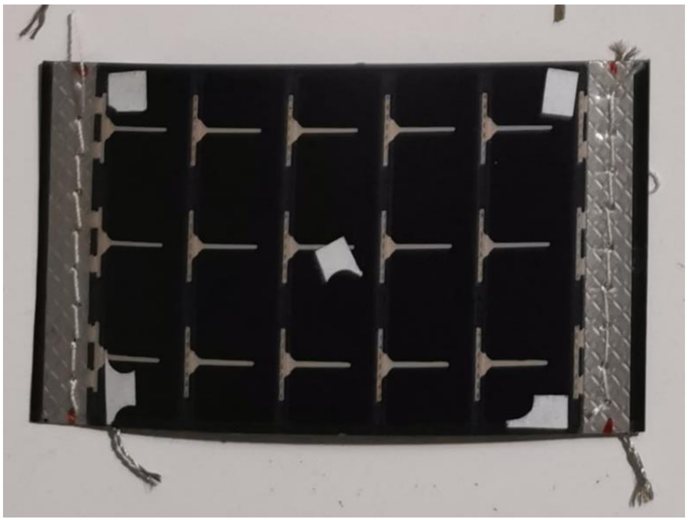


Figure 43. Solar cell with humidity stickers (second round).

4.2.3 Electrical measurements

The measurement process of textile solar samples for second round machine washing test is shown in Figure 44. After the improvement, the original measurement voltage was changed to measure DC current. Because the current is directly proportional to light intensity, and it is more sensitive measurement. Use a multimeter to measure the DC current across the solar cells contact areas. At the time of the first experimental test, the light conditions were relatively unstable. Even according to the ratio of samples and references, the accuracy of these tests is still not guaranteed. After all, the combination of natural light and light in the laboratory is unstable. Therefore, in the second experiment, the light conditions were also improved during the measurement. All tests were carried out with only one stable IKEA table lamp as the light source and in the same light position as shown in Figure 45. For each measurement, the density of light is measured with a luxmeter, which is Luxómetro RS PRO ILM1332A (Figure 46). Measurements were made under the relevant same lighting conditions and are not repeated.

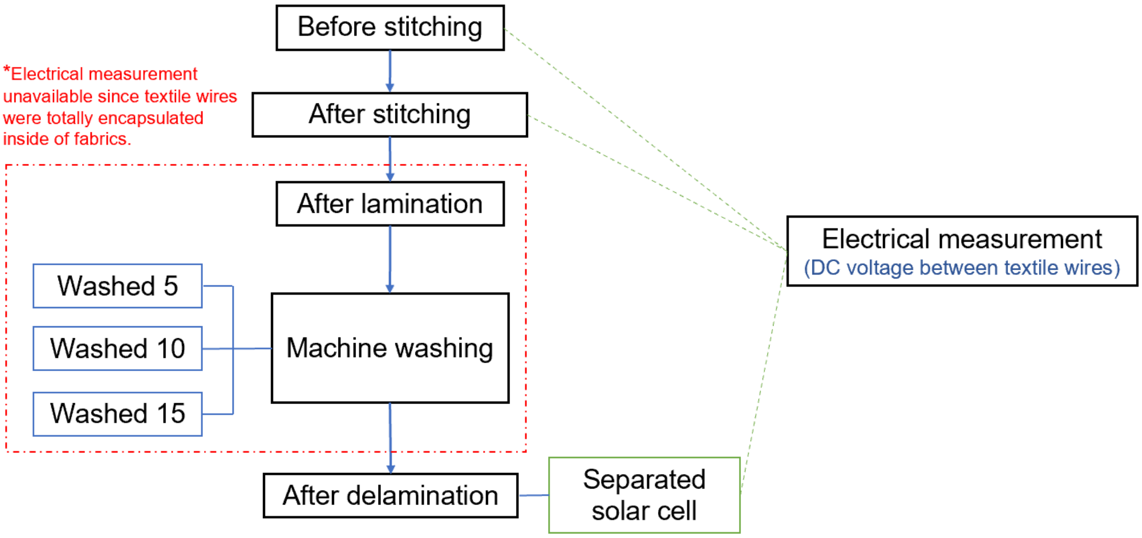


Figure 44. The measurement process of textile solar samples (second round).

Figure 45. Stable IKEA table lamp.

Figure 46. Luxmeter. Source: https://es.rs-online.com/web/p/luxometros/1232360?gb=s

4.2.4 Visual observation

Observe the appearance of the sample at different stages and compare the changes in each stage of the sample.

4.3 Influence of humidity to the harvesting capability experiments

After the failure of the first round of machine-washing experiments, it is speculated that humidity influences the performance of the sample. Water from the washing process may enter the solar textile sample through the wicking phenomenon of the textile wire, affecting performance. The process of influence of humidity experiments is illustrated in Figure 47.

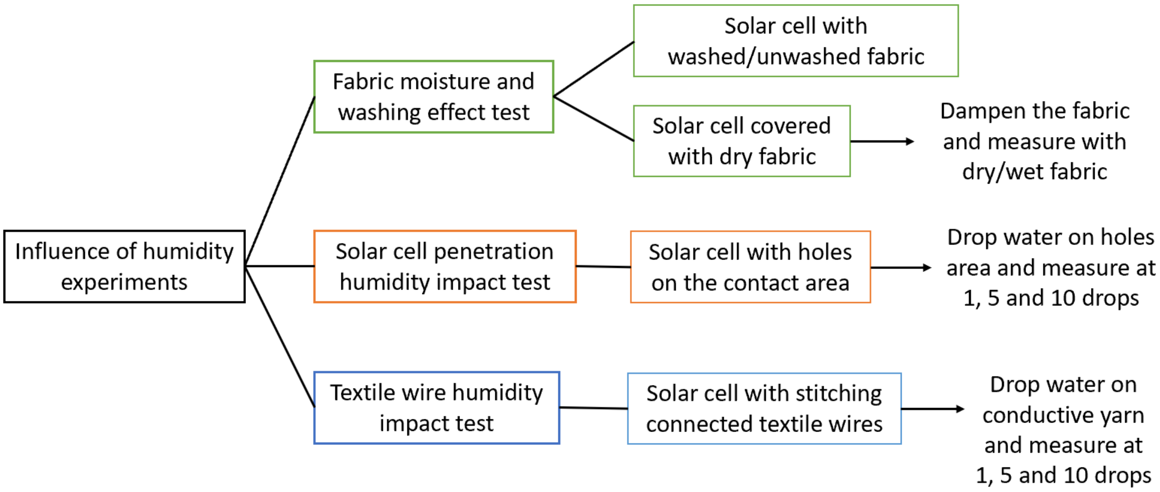


Figure 47. The process of influence of humidity experiments.

4.3.1 Fabric moisture and washing effect test

This experiment requires verification of whether fabric moisture and washing affects the test results. Test solar cell samples measure the DC current through both ends of the solar cell through a multimeter.

After the first round of experiments, the fabric on the sample is dismantled and cut into squares of corresponding size by control solar cells to serve as covering fabrics for washing 15 times. Samples 1-4 of fabric 1 and 8-10 of fabric 3 from the first round of washing test are used. Make unwashed fabric 1 and fabric 3 reference separately. Another 3 pieces of unwashed fabric 1 and 3 pieces of unwashed fabric 3 are used to complete the humidity effect test. Flexible solar cells that have not undergone any treatment are used.

- Prepare 1 flexible solar cell, test without fabric as reference. Cover it with unwashed fabric and test the current at both ends of the solar cells. Take off the unwashed fabric, cover the solar cell with fabric washed 15 times, and measure the current at both ends of the solar cell. For example, the measurement of solar cell covered with fabric 3 washed 15 times is illustrated in Figure 48.

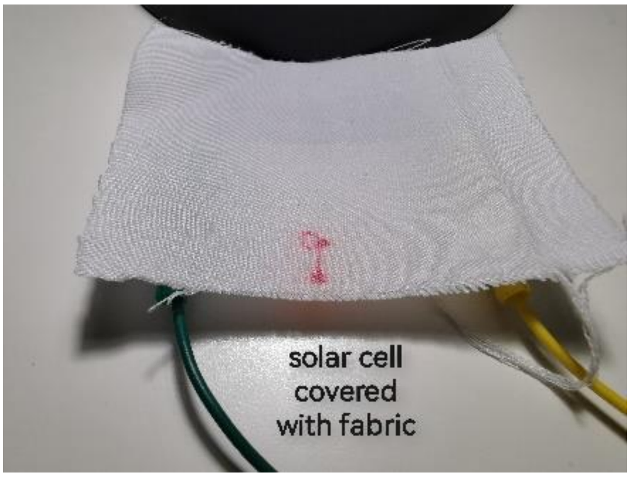


Figure 48. The measurement of solar cell covered with fabric 3 washed 15 times.

Prepare 3 pieces of dry fabric 1 and 3 pieces of dry fabric 3.

- Test the solar cell without fabric. Place the dry fabric 1 and test the DC current. Replace the other fabric 1 and test the DC current though solar cell. Test the dry fabric 3 in the same way and test the wet fabric 1 and wet fabric 3 in the same way. The fabrics are dampened and dipped for 30s in water.

4.3.2 Solar cell penetration humidity impact test

In this experiment, it was necessary to verify the influence of humidity on the perforated solar cell performance test results. Test solar cell samples measure the DC current through both ends of the solar cell through a multimeter.

Prepare 3 flexible solar cells, thread through with a sewing machine, no wires. The solar cell performance was measured with dropping drops (1, 5 and 10 drops) of water for 30s on different locations of the solar cell sample using a dropper, as shown in Figure 49. Test the DC current across the solar cell at each stage.

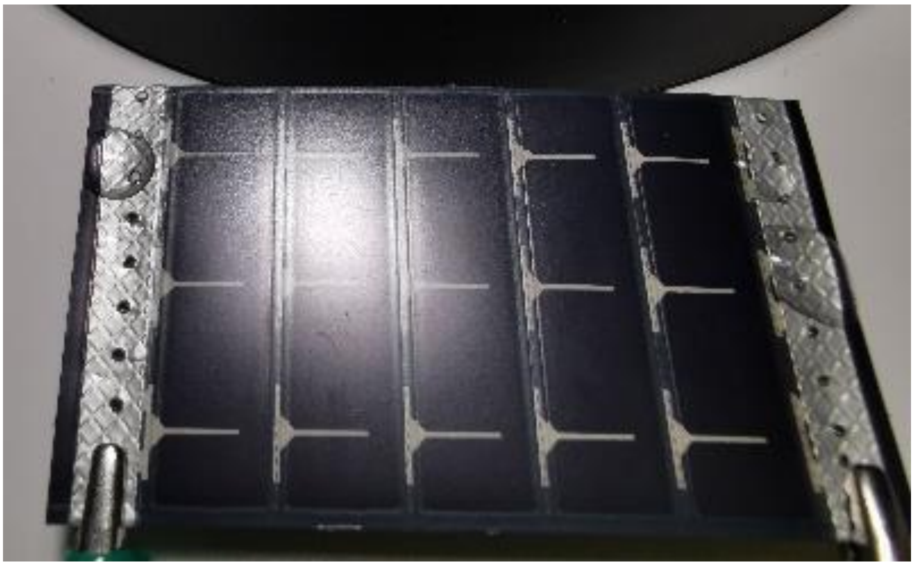


Figure 49. Solar cell with penetrations with water droplets

4.3.3 Textile wire humidity impact test

In this experiment, it is necessary to verify whether the humidity of textile wires affects the performance test results of solar cells after stitching. Test solar cell samples measure the DC current through the textile wires at both ends of the solar cell by means of a multimeter.

Prepare 4 flexible solar cells, thread through with a sewing machine, with textile wires. The solar cell performance was measured with dropping drops of water on textile wires using a dropper, as shown in Figure 50. Test the DC current across the solar cell at each stage.

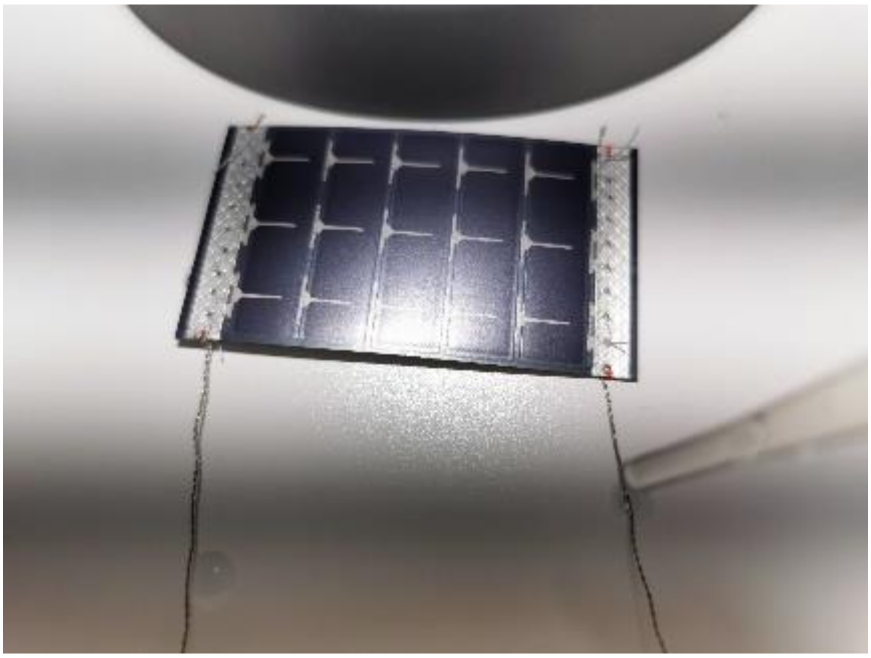


Figure 50.Textile wires of sample with water droplets

5 Experiment results and analysis for stitching method

5.1 First round of machine-washing experiments

5.1.1 Waterproof property test

The color variations of the humidity sticker are shown in Table 3. From the experimental results, samples 2, 9 and 10 have poor water resistance, samples 4 and 8 have poor water resistance, and there is no problem with the water resistance of other samples.

Table 3. Color change of humidity stickers (first round).

	Sample	Left-down	Right-top
Knitted	1		
	2	🟥	▨
	3		
	4	▨	
Woven coated	5		
	6		
	7		
Woven	8	🟥	
	9	▨	🟥
	10	🟥	🟥

🟥 moist
▨ slightly moist
⬜ dry

5.1.2 Electrical measurements

The voltage test results for the washing phase are shown in Figure 51. The test results for the voltage across the sample performance change after 15 washes and delamination are shown in Figure 52.

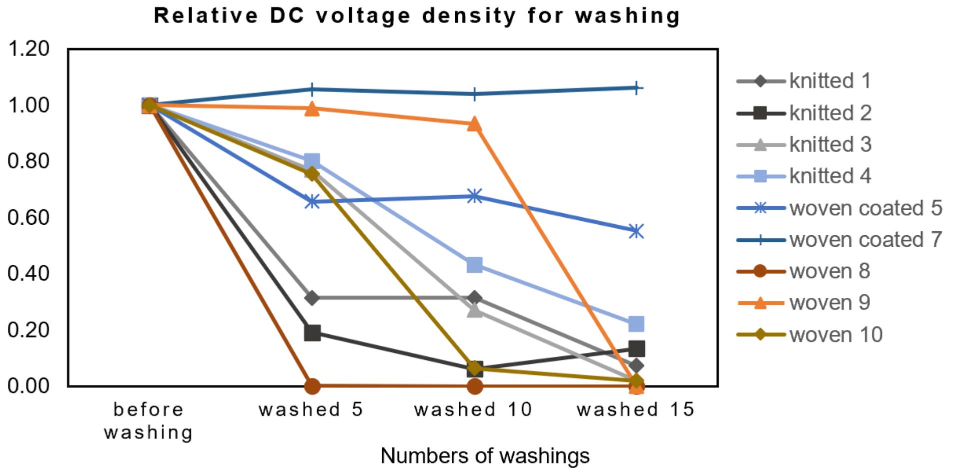


Figure 51. Evolution of the relative output voltage in the washing test (first round).

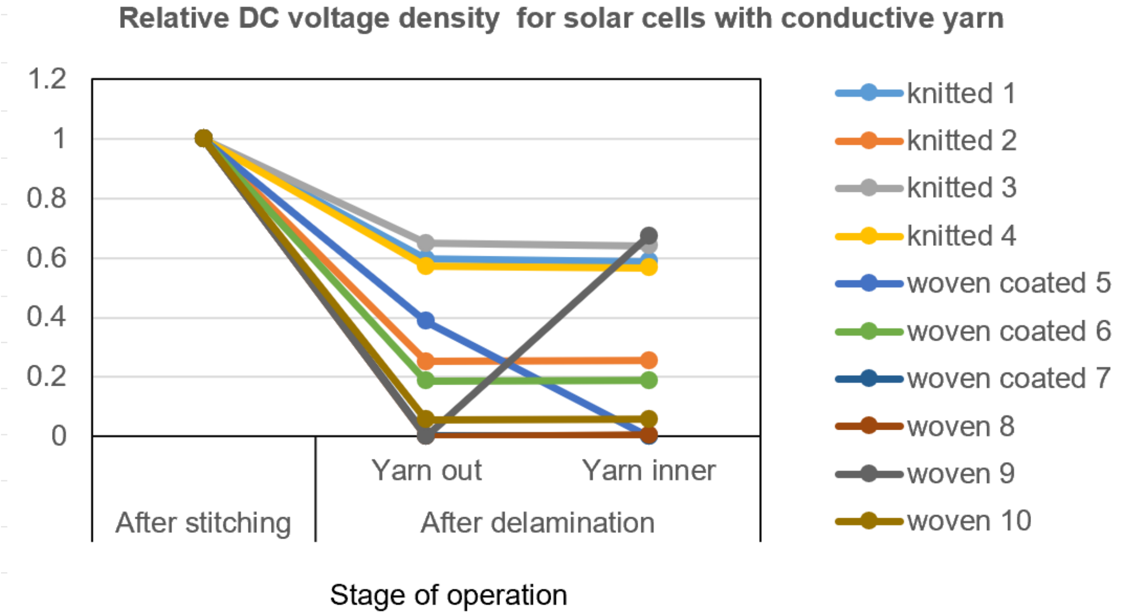


Figure 52. Changes in performance of samples after 15 washes and delamination (first round).

Electrical measurements of the first round of experiments cannot be verified. Because the test conditions are not standardized, and the lighting conditions may be different for different tests. Nevertheless, the solar textile samples with fabric 2 maintain good performance after 15 washes compared to the general degradation in performance with other samples. Fabric 2 is a coated fabric, and the solar textile samples produced have stable performance, and the solar textile designed with this fabric has the potential to have high durability. But because this sample is too strong, it is difficult to separate the fabric, TPU, textile wires or solar cells when delamination. Consequently, sample 6 is scrapped after delamination, as shown in Figure 53. Although samples made from this fabric remain performing well, it is not suitable for solar textile product recycling.

Figure 53. Damaged solar cell in sample 6.

In view of the fact that the reliability of stitching connection technology cannot be verified by experimental data, a second round of experiments was designed to optimize the sample production process and test process. Through the failure of the first round of experiments, 3 factors, the humidity and washing of the fabric, the humidity of textile wires and the influence of humidity on perforated solar cells, were suspected to affect the experimental results. To test this conjecture, a group of influence factor tests were designed to verify the correlation of the three factors of fabric humidity and washing, textile wire humidity and humidity on perforated solar cells, respectively.

5.1.3 Visual observation

The solar textile samples produced were not visible before and after washing. After delamination, the solar cells are difficult to strip from the TPU film, and obviously cannot be compared with the original solar cells. When the first machine wash test sample was made, the pressure of the heat press was 3.6 bar. Considering that too much pressure could make it difficult to peel off the solar cells, the pressure of the heat press was reduced to 3.5 bar during the second round of experimental sample production.

5.2 Second round machine wash experiments

5.2.1 Waterproof property test

According to the results of the humidity sticker experiment in Table 4, each wired sample had a red sticker, and the wireless sample did not turn red. This indicates that there is water ingress inside each wired sample, which may also be the reason for the reduced performance of the wired sample after washing. Even if the preliminary experimental judgment of humidity has little effect on performance, laundry detergent solution may have an impact on the performance of solar cells or yarns.

Table 4. Color change of humidity stickers (second round)

Solar cell	Condition	Front 1	Front 2	Front 3	Front 4	Front 5	Back 1	Back 2	Back 3	Back 4	Back 5
1	no wire	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
2		⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
3		⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
4	with wire	⬜	🟥	⬜	⬜	⬜	🟥	🟥	⬜	⬜	⬜
5		⬜	⬜	⬜	⬜	🟥	⬜	🟥	⬜	⬜	⬜
6		⬜	⬜	⬜	🟥	🟥	⬜	🟥	⬜	⬜	⬜

🟥	moist
▨	slightly moist
⬜	dry

5.2.2 Electrical measurements

The cause of water ingress inside the wired sample remains to be studied. At present, it is speculated that it may be due to the presence of yarn, which makes the surface of the solar cell uneven, which in turn leads to gaps in the TPU package. During the washing process, the laundry detergent solution enters the wired sample through the gap, corroding the yarn and solar cells. In order to optimize this problem, finer yarns should be selected, or flat sewing stitches should be selected to make the surface of the solar cell after sewing flatter.

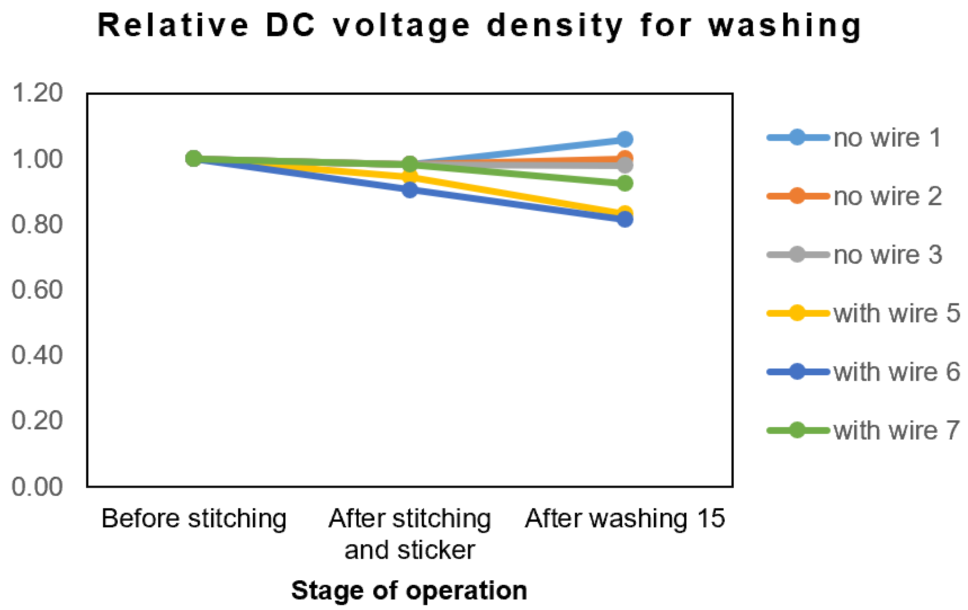


Figure 54. Evolution of the relative output voltage in the washing test (second round).

As far as the results of the current second round of 15 machine washes (Figure 54) are concerned, although the performance of solar cells is reduced, the proportion of decline is very low, and the performance is still good. Compared with the results of the first round of 15 machine washes, which also used fabric 1 knit as the covering fabric, the performance of the second round sample was much better than that of the first round. This shows that textile wires exposed to the package are indeed more susceptible to corrosion by washing powder. It may even be possible because of the wicking phenomenon unique to textiles entering the package and corroding the inside of the sample. In the first round of experiments, the end of the textile wire was designed to be exposed outside the package so that the sample could be measured after 5 washes. If the textile wire is fully encapsulated, as in the second round of experiments, it cannot be tested before delamination after lamination. If the sample is damaged, it is not known where the problem occurred. There was no sample damage in this round of experiments.

5.2.3 Visual observation

After the machine wash test, the sample is delamination, and the solar cells are manually removed from the package. For operational reasons, some solar cells are crimped and even have creases. It is more difficult to peel off solar cells with wires than in groups without wires. The solar cell is perforated at both ends and may have been damaged by the yarn force. In addition, the combination of yarn and TPU is more difficult to separate. Therefore, when the solar cell is stripped, it is easy to damage the solar cell.

The visual compare of separated solar cell from delamination of solar textile samples is taken, and the results for samples with stitching and without stitching are illustrated in Figure 55 and Figure 56 separately.

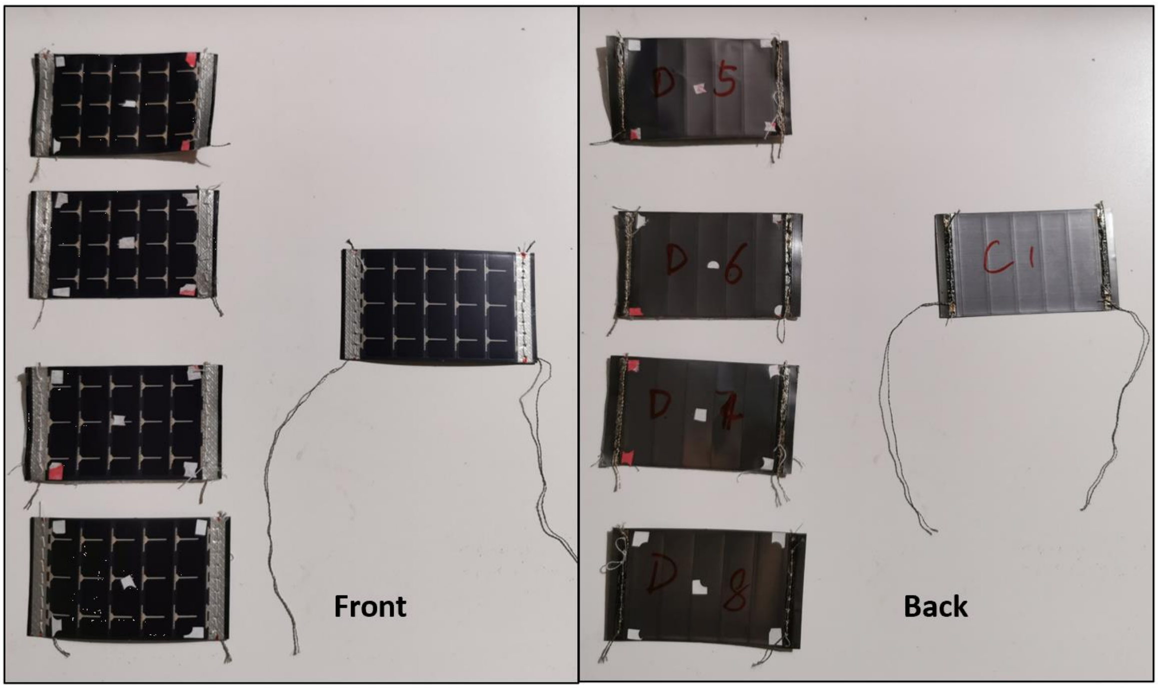


Figure 55. Visual observation of separated solar cell from delamination (with stitching).

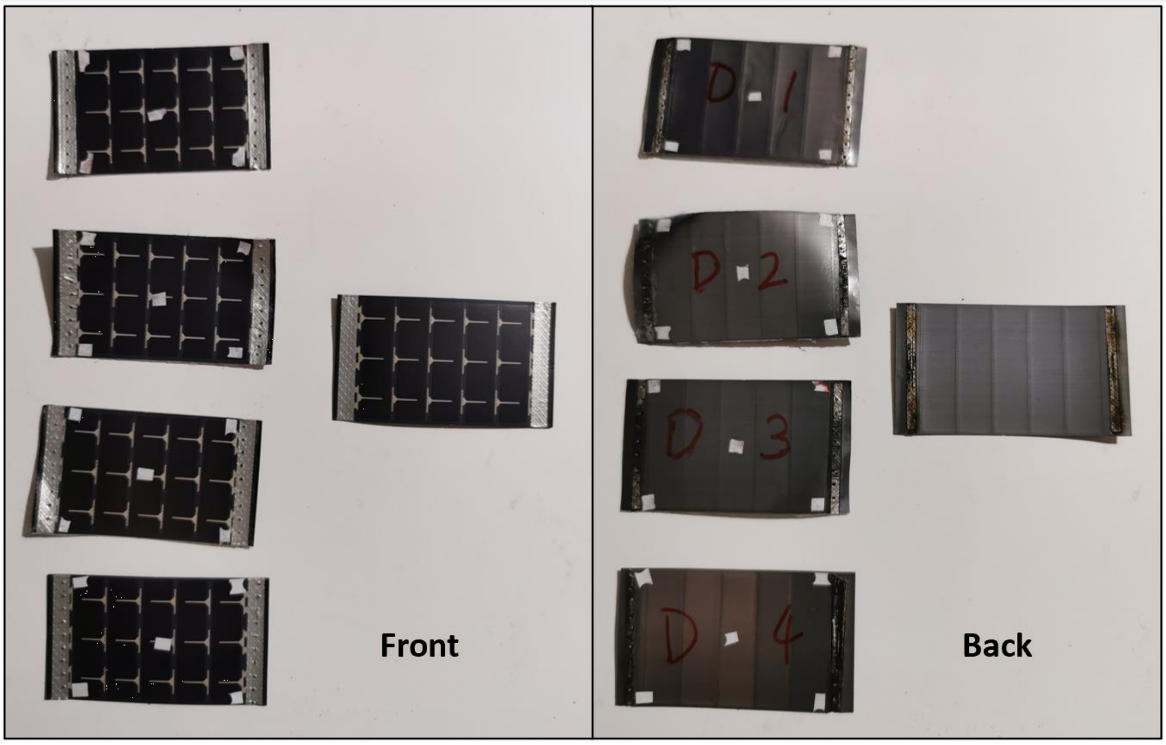


Figure 56. Visual observation of separated solar cell from delamination (without stitching).

5.3 Influence of humidity on harvesting capacity experiments

The results show that the humidity of the holes on the solar cells and the humidity of the textile wires do not affect the performance of the solar cells. However, the humidity and washing of the fabric have an effect on the performance of the solar cell. Compared to the unwashed fabric, the fabric with 15 washes made the performance of the solar cell slightly degraded. The wet fabric gives increased performance compared to the dry fabric. Fabric 3 (uncoated woven fabric) was affected to a greater extent than fabric 1 (uncoated knitted fabric).

5.3.1 Fabric moisture and washing effect test

Figure 57 and Figure 58 show the humidity influence of the covered fabric 1 and fabric 3 to the performance of the solar cell samples separately. The wet fabric gives increased performance compared to the dry fabric. Fabric 3 (uncoated woven fabric) was affected to a greater extent than fabric 1 (uncoated knitted fabric).

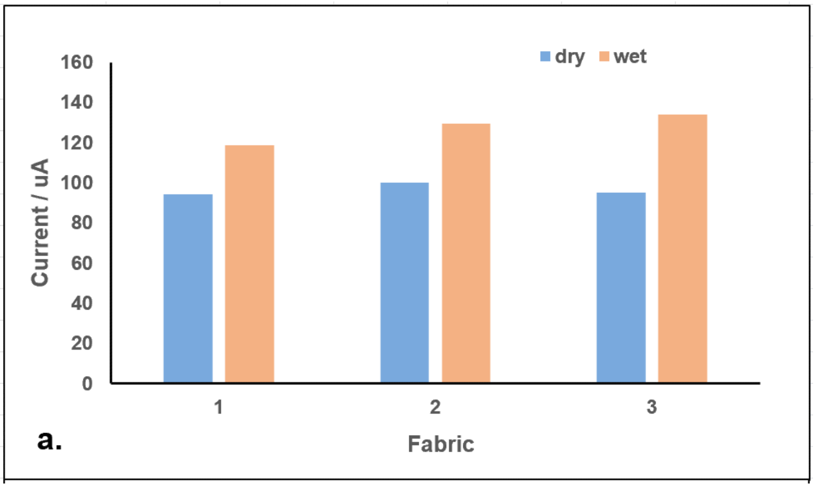


Figure 57. Evolution of the effect of wet and dry covering fabrics on the performance of solar cell samples in comparison (fabric 1)

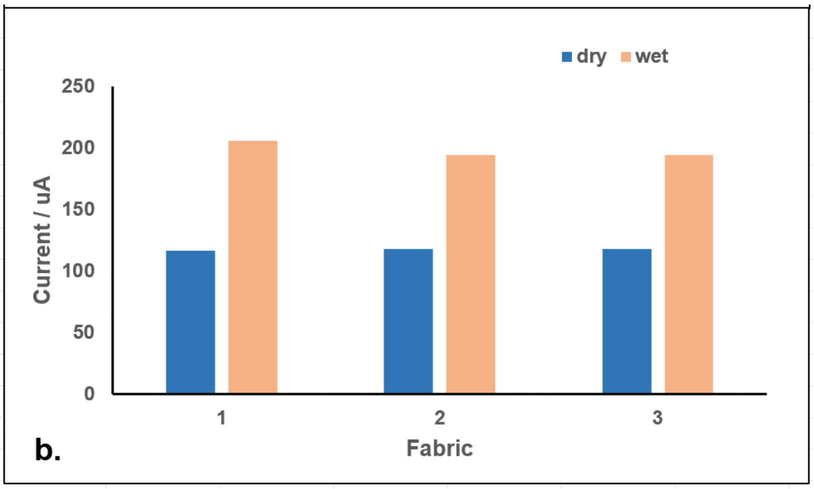


Figure 58. Evolution of the effect of wet and dry covering fabrics on the performance of solar cell samples in comparison (fabric 3)

As shown in Figure 59 and Figure 60, the difference in test results is not significant compared to unwashed fabric 1 and fabric 3 after 15 washes separately. Compared to the unwashed fabric, the fabric with 15 washes made the performance of the solar cell slightly degraded. This means that the fabric after 15 washes has light effect on the energy harvested by the solar cell.

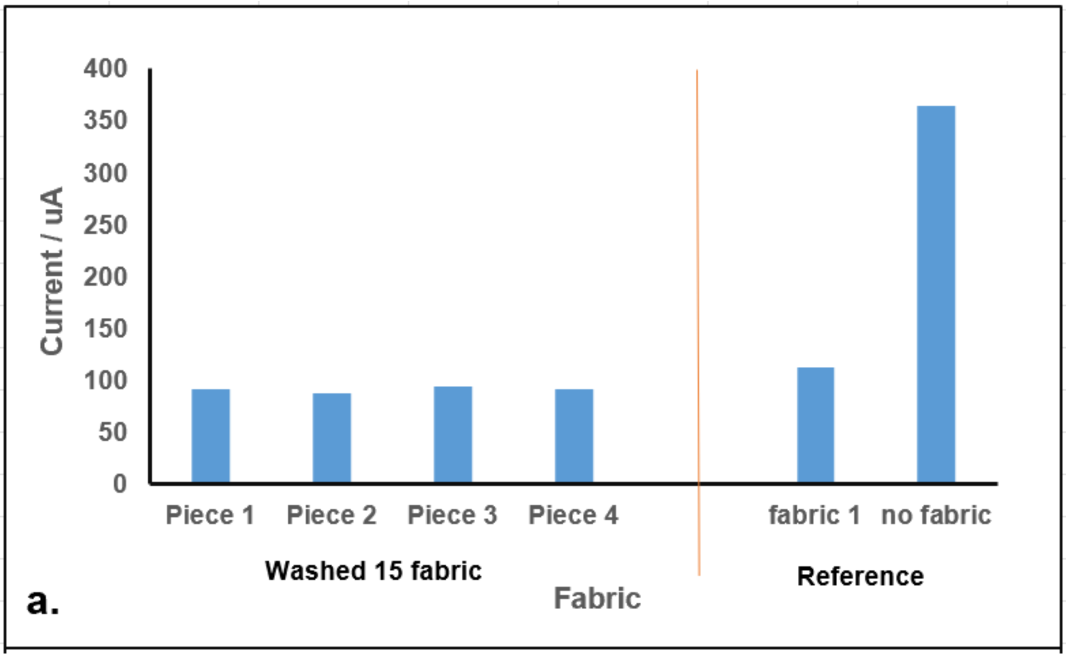


Figure 59. Evolution of the effect of washing influence of covering fabrics on the performance of solar cell samples in comparison (fabric 1)

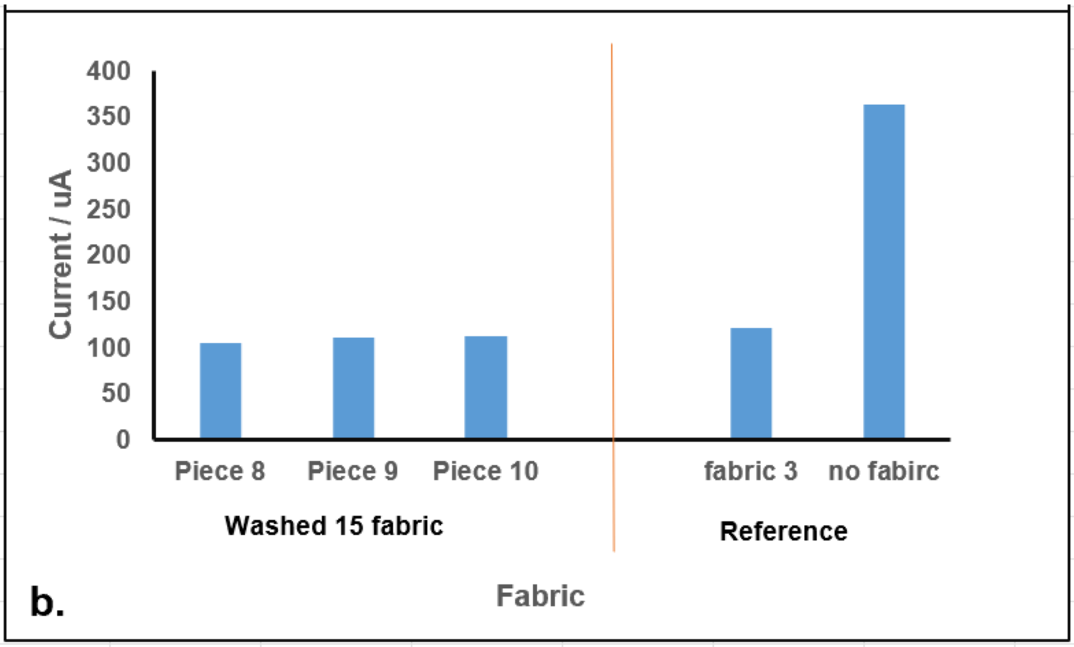


Figure 60. Evolution of the effect of washing influence of covering fabrics on the performance of solar cell samples in comparison (fabric 3)

5.3.2 Solar cell penetration humidity impact test

As shown in Figure 61, humidity has little effect on solar cell performance after perforation.

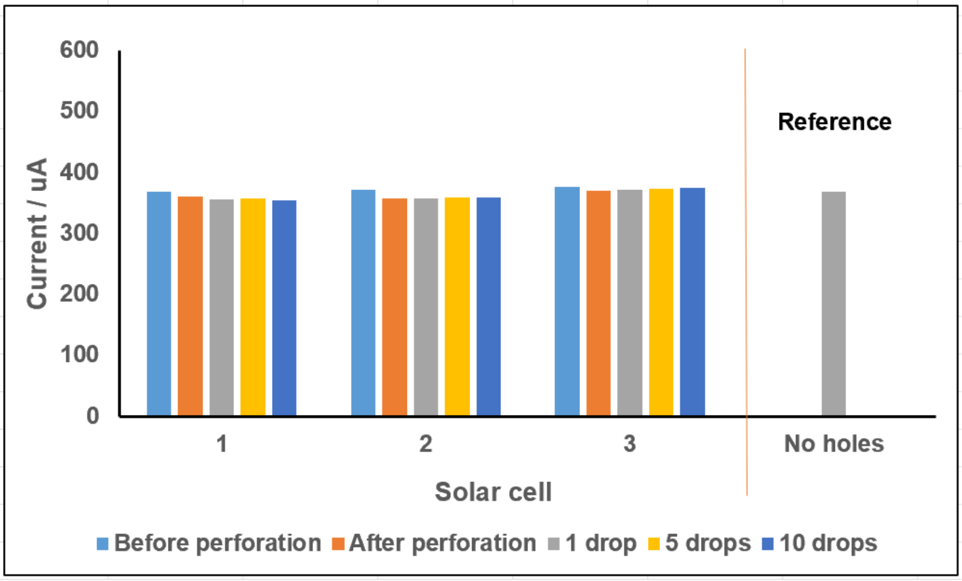


Figure 61. Evolution of the effect of wet and dry of perforated solar cell on the performance of solar cell samples in comparison.

5.3.3 Textile wire humidity impact test

As shown in Figure 62, the humidity of the textile wire has little effect on the performance of the sample.

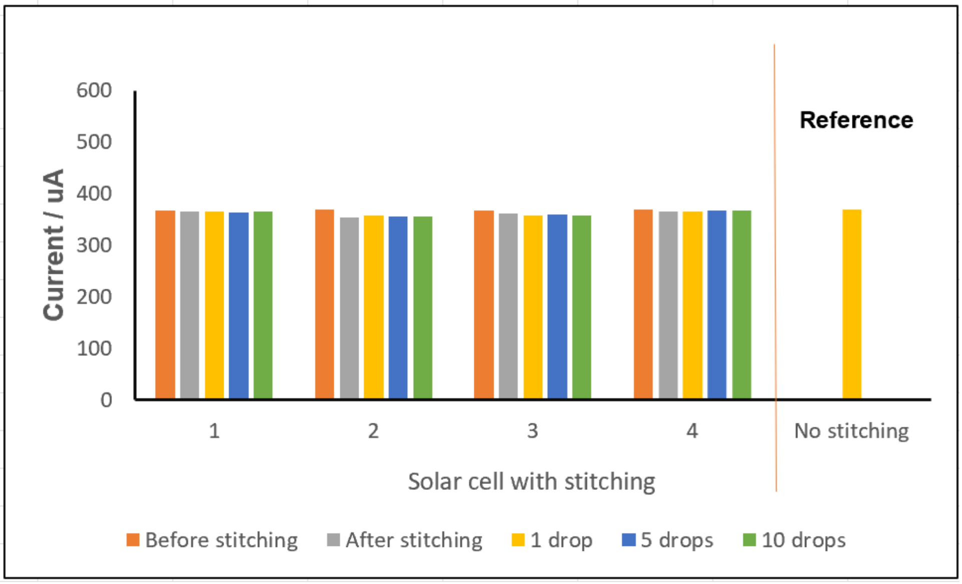


Figure 62. Evolution of the effect of wet and dry textile wires on the performance of solar cell samples in comparison.

6 Results and analysis for tape and adhesive method

6.1 Tape

Single-sided adhesive tapes are used to attach textile wires to the connection area of solar cells and have been shown to maintain good performance. In order to have a better conductive effect, the contacts were made by soldering low-resistance copper tape to the solar module contacts [3]. This method is applicable to both flexible and rigid solar cells. The conductivity of the tape is not necessary, after all, the tape does not actually touch the connection area, but fixes the textile wire in the appropriate position to play a connecting role.

Although this method does not require high requirements for joining materials, it requires manual and delicate operation, which means that when mass production, errors are easy to generate. If the process of tape application can be optimized and automated production can be realized, it is also a connection technology that can be put into mass production.

6.2 Potential adhesives for solar cells

Through the method of adhesives as a connection technique, laboratory synthetic adhesives and the purchase of commercial adhesives are considered. In e-textile, in order to bond electronic components and textiles, many studies have attempted to synthesize flexible conductive adhesives. A polyurethane based ECA is developed to meet all the requirements of flexible interconnects, including an ultralow bulk resistivity that is maintained during bending, rolling, and compressing, good adhesion to various flexible substrates, and facile processing [33]. Transparent, adhesive, stretchable and tough hydrogels via semi-interpenetrating network (SIPN) strategy, which consists of linear poly(3,4-ethylene dioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) and chemically cross-linked poly(acrylamide-co-methacrylic acid), was developed [34]. A stretchable conductive adhesive consisting of silver particles with carbon nanotube as an auxiliary filler in silicone adhesives was proposed. Based on strong adhesion to a stretchable substrate, the gel-free dry adhesive printed on elastic bandages for ECG monitoring showed extremely stable performance during subject movement, even after multiple separation-bonding and machine washing [35].

In addition, there are many conductive adhesives on the market that can be applied to electronic products, but few are suitable for combining electronic components with textiles. Most conductive adhesives for electronic components can be applied if flexibility is not a concern. However, because textiles are soft and foldable, flexible conductive adhesives are often required when connected to electronic components. This is also the difficulty of finding a suitable conductive adhesive, soft conductive adhesive has a higher price. In addition, the use of conductive adhesives usually requires heating. Since (flexible) solar cells are not resistant to high temperatures, the maximum temperature is only 150°C, which makes there are fewer flexible conductive adhesives available on the market. The available conductive adhesives on the market are shown in Table 5.

Table 5. Adhesives for connecting textile wires and solar cells

NO.	Description	Type	Company	Product Name	Assessment of flexibility	Hardness	Curing Condition
1	Electrically Conductive Adhesive (ECA) silver epoxy	ECA	SunRay Scientific	S-CEP7-SF5	flexible	-	Less than 2 min @ 130°C down/10 min @ 110°C
2	Two component, room temperature curing epoxy for bonding, sealing and coating	ECA	Master Bond	EP79	stiff	-	overnight at room temperature followed by a post cure of 1-2 hours at 150-200°F
3	bonding heat-sensitive components, bonding flexible circuits	ICA	Panacol	Elecolit® 3036	Medium flexible	Hardness shore D: 70-80	at room temperature or more rapidly with heat （25 ℃ - 150 ℃）
4	LCD bonding, bonding flexible conductors	ACA	Panacol	Elecolit® 3063	High flexibility	Hardness shore A: 60-70	UV + pressure, VIS + pressure
5	Flexible Electrically Conductive Silver Epoxy, Thermally Conductive Adhesive Solder Replace	ECA	ConductiveX	Electro-Bond 16	High flexibility	Hardness shore D: 64	24 hours @ Room Temp/ 2 to 4 hours @ 60°C
6	Flexible Highly Conductive Pure Silver Epoxy Elecrically Conductive Adhesive 1 to 1 Mix D	ECA	ConductiveX	Electro-Bond 17	High flexibility	Hardness shore D: 63	24 hours @ Room Temp/ 2 to 4 hours @ 60°C
7	Flexible Nickel Epoxy Electrically Condutive Conductivity Nickel Filled Adhesive EMI RFI	ECA	ConductiveX	Electro-Bond F3	High flexibility	Hardness shore D: 65	24 hours @ Room Temp/ 2 to 4 hours @ 60°C

Despite the high price, according to testing studies, SunRay Scientific's ECA conductive adhesive is considered to be the most suitable flexible conductive adhesive product. It is proven to be suitable for the combination of textiles and electronic components, with low operating temperatures, good connection quality and very flexible [36]. Forms are optional flexible conductive adhesives. In principle, these glues can be used as a connection technology to connect solar cells (whether flexible or rigid) and textile wires. However, this study does not confirm whether any conductive adhesive is suitable for solar textile.

However, this method of conductive adhesive has a disadvantage, that is, adhesive as a chemical reagent remains a problem for recycle without sacrificing the environment. Whether or not the use of the adhesive connection technique for textile wires to solar cells will affect the environment needs to be followed up and investigated to determine.

7 Budget summary

The budget of this study is about cost of desk research work, materials, and equipment.

Budget about desk research work:

Items	Quantity	Price	Cost
Desk research work			€ 8,320.00
Author working	450 h	10 €/h	€ 4,500.00
Tutor advice	100 h	35 €/h	€ 3,500.00
Energy consumption for desk work	-	-	€ 320.00

Budget about experiment:

Items	Quantity	Price	Cost
Materials			€ 65.95
64% Polyester / 33% TencelTM / 3% EOL woven uncoated fabric	0.5 kg	4 €/kg	€ 2.00
80 % PES / 20 % PU woven coated fabric	0.5 kg	3 €/kg	€ 1.50
84 % PES / 16 % EA knitted fabric	1 kg	5 €/kg	€ 5.00
Conductive yarn	0.15 kg	270 €/kg	€ 40.50
Normal yarn	0.05 kg	1 €/kg	€ 0.05
TPU film	0.3 kg	4 €/kg	€ 1.20
Flexible solar cell	0.2kg	75 €/kg	€ 15.00
Detergent	0.35 kg	2 €/kg	€ 0.70
Equipment			€ 140.00
Heat press machine	5 h	4 €/h	€ 20.00
Sewing machine	2 h	15 €/h	€ 30.00
Washing machine	30 h	3 €/h	€ 90.00
Multimeter	5 h	3 €/h	€ 15.00
Luxmeter	5 h	4 €/h	€ 20.00

Budget summary:

Items	Cost
TOTAL	€ 8,525.95
Desk research work	€ 8,320.00
Materials	€ 65.95
Equipment	€ 140.00

8 Analysis and assessment of environmental and social implications

Environmental and social implications are critical to product design in e-textile. With reasonable design, solar textiles can effectively utilize clean energy, reduce the consumption of secondary energy such as oil, and be conducive to environmental protection.

From the perspective of environmental protection, there are high expectation for the stitching method. Stitching connection method is considered environmentally friendly, without chemicals involved, and enables complete separation and recycling of individual components. This connection technique returns to the traditional production method of textiles, with low requirements for the machine and simple operation. After all, sewing machines are common and basic instruments in the textile industry. From a sustainable point of view, the raw materials used in this connection method are usually commonly used yarns such as cotton spun yarn, which is clean and environmentally friendly. At the end of its life, the yarn used in connection can be completely removed and sorted for recycling, leaving no residue on solar cells and textile wires.

Conductive adhesive is suspected of being an environmentally unfriendly connection technology. Chemical agents in adhesive method are required, which leaves it a problem to completely separate and recycle the components after the end of the product cycle. Tape joining technology and electrically conductive adhesives have similar problems, there are potential chemical residues, but separation and recycling can be achieved. However, existing studies have not proved the negative environmental and social impacts of tape and adhesive methods. Further investigations and studies are needed to judge the assessment of the effects of separated components and chemical residues in the adhesive and tape connection methods.

9 Conclusions

The study proposes 3 connection techniques to connect solar cells and textile wires in a solar textile. The feasibility of tape and adhesive methods was analyzed by literature review. The feasibility of stitching connection technology for flexible solar cell and textile wire connection is verified by experiments. The study successfully used a sewing machine to sew textile wires into contact areas on both sides of flexible solar cells, and encapsulation was made into solar textile samples. Through 15 machine wash experiments, the performance of the solar cells remained almost unchanged, there was no water inside the sample, and it was easy to disassemble the individual components. In addition, the humidity of the fabric was preliminarily judged to affect the test results of the sample, but the number of fabric washes, the humidity of perforated solar cells and the humidity of textile wires had no effect on the test results of the samples.

Stitching is more suitable for mass production than tape and adhesive methods based on literature view and experiments. It is a reliable method that is both effective and scalable, and it does not require new investment in factories when assembled in garment factories.

The limitation of the final solution of this study is that it is not processed to verify the feasibility of the tape and adhesive connection methods experimentally and compare the 3 proposed connection techniques.

Given that flexible solar cells are more in line with the characteristics of textile flexibility than solid solar cells, stitching, which is suitable for flexible solar cell connections, should be further studied. In future work, the connection technology can be optimized by comparing the connection effects of different stitching stitches, replacing different flexible solar cells, and replacing different textile wires. In addition, 15 washes are not enough to meet solar textile expectations, and 50 washes can be designed in the future to verify the washability of samples.

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11 Appendix

The raw data for the experimental part of the experiment are as follows.

First round of machine-washing test

Table 1. Solar cell performance at every stage (1)

Sample		Voltage（V）						
		After stitching	After en-capsulation	Before washing	Washed 5	Washed 10	Washed 15	After de-lamination
Knitted	1	3.560	2.309	1.989	0.626	0.628	0.145	1.756
	2	3.019	2.953	2.489	0.478	0.157	0.335	1.747
	3	3.638	3.319	2.932	2.257	0.798	0.054	1.717
	4	3.627	3.345	2.962	2.375	1.281	0.659	2.293
Woven coated	5	3.617	3.107	2.236	1.472	1.515	1.236	-
	6	3.652	2.974	0.322	0.407	0.655	0.033	0.776
	7	3.557	2.034	1.429	1.510	1.486	1.518	-
Woven	8	3.631	3.390	2.866	0.005	0.001	0.001	0.128
	9	3.610	3.297	2.309	2.286	2.159	0.001	2.107
	10	3.515	3.088	2.643	1.997	0.173	0.053	0.564
Refer-ence	R1	3.209	3.310	2.118	2.215	2.101	2.118	3.308
	R2	3.632						

Table 2. Solar cell performance at beginning and end

Sample		Voltage（V）		
		After stitching	After delamination	
			Yarn out	Yarn inner
Knitted	1	3.560	1.023	1.019
	2	3.019	0.367	0.374
	3	3.638	1.139	1.133
	4	3.627	0.998	1.002
Woven coated	5	3.617	0.675	0.002
	6	3.652	0.328	0.336
	7	3.557	0.004	0.005
Woven	8	3.631	0.000	0.010
	9	3.610	0.000	1.184
	10	3.515	0.096	0.101
Reference		3.209	1.545	1.561

Second round of machine-washing test

Table 3. Solar cell performance at every stage (2)

Condition	Current (μA)			
	Solar cell	Before stitching	After stitching and sticker	After washing 15
Solar textile sample without wire	1	354.8	347.9	375.8
	2	351.8	345.8	352.1
	3	359.2	353.2	351.3
Reference solar cell without wire	4	362.7	346.8	354.8
Solar textile sample with wire	5	351.6	332.1	292.7
	6	363.1	328.4	295.5
	7	357.2	350.4	330.4
Reference solar cell with wire	8	354.5	328.6	357.6
Light condition (lux)		1247	1250	1271

Influence factor experiments

Table 4. Solar cell performance with washed / unwashed fabric

Sample	Washed fabric				Unwashed fabric 1	Reference without fabric
Fabric 1	Piece 1	Piece 2	Piece 3	Piece 4		
Current (μA)	91.6	87.7	93.9	90.7	112.2	363.8
Lux	1274	1277	1278	1280	1281	1281

Sample	Washed fabric			Unwashed fabric 3	Reference without fabric
Fabric 3	Piece 8	Piece 9	Piece 10		
Current (μA)	104.4	110.9	112.2	121.1	363.5
Lux	1301	1302	1301	1300	1299

Table 5. Solar cell performance with wet / dry fabric

Fabric 1 (84 % PES / 16 % EA knitted)

Sample	1		2		3		Reference without fabric
	Dry	Wet	Dry	Wet	Dry	Wet	
Weight (g)	0.78	1.66	0.78	1.77	0.78	1.82	-
Water content (%)	112.8205		126.9231		133.3333		-
Current (μA)	94.5	118.6	100.1	129.7	95.1	133.9	357.3
Lux	1306	1305	1304	1305	1304	1304	1302

Fabric 3 (64% Polyester / 33% TencelTM / 3% EOL woven uncoated)

Sample	1		2		3		Reference without fabric
	Dry	Wet	Dry	Wet	Dry	Wet	
Weight (g)	0.8	1.48	0.68	1.31	0.8	1.55	-
Water content (%)	85		92.64706		93.75		-
Current (μA)	116.4	205.7	117.9	194.2	117.5	192.8	359.1
Lux	1306	1303	1305	1305	1306	1305	1303

Table 6. Solar cell performance with humidity on perforated solar cell

Solar cell	Current (μA)					
	Before perforation	After perforation	1 drop	5 drops	10 drops	Lux
1	368.7	360.5	356.6	357.3	355.1	1310
2	372.1	357.5	357.4	358.9	359.7	1308
3	376.4	370.1	371.3	373.4	375.7	1309
Reference	368.9	-				
Lux	1298	-				

Table 7. Solar cell performance with humidity on textile wires

Solar cell	Current (μA)					
	Before stitching	After stitching	1 drop	5 drops	10 drops	Lux
1	366.8	365.4	364.4	363.5	364.7	1302
2	369.1	354.4	358.1	355.8	354.8	1301
3	367.4	361.2	357.9	359.1	358.2	1300
4	368.9	365.1	365.3	366.4	368.1	1299
Reference	369.4	-				
Lux	1303	-				