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SUN-POWERED TEXTILES

Designing energy-autonomous electrotextile systems with solar cells

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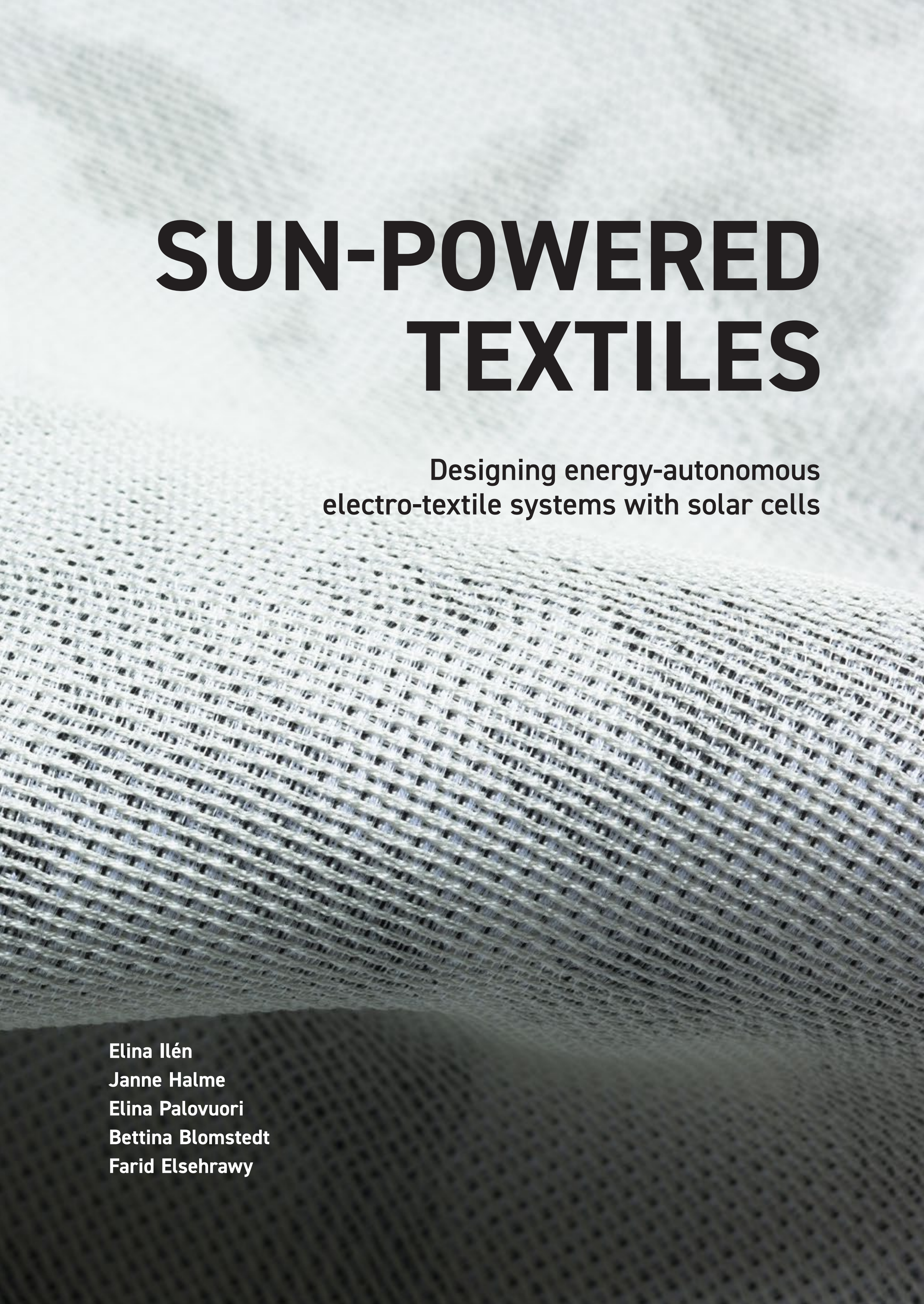

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Foreword

The great potential of wearables is well known, and wearables have a reputation of being a “game changer” in many areas of application. Nevertheless, researchers and developers in the field have not been able to tackle the many challenges of combining technologies across different industries. Electronics should meet the needs of textile products and preserve their capabilities to achieve full-scale product acceptance. Smart textiles should be washable, and electronics should be embedded reliably, unobtrusively, and invisibly into a garment. Electronics should not degrade the inherent properties of a garment. Among some of the technical challenges of electronics, is finding solar energy harvesting solutions in wearables, which have been under research for several years. The energy autonomous system with a renewable energy source, removes the need for battery replacement in a product. Now, the solar cell underneath the textile is able to gather energy from both daylight and artificial light, and thus is suitable for indoor solutions as well.

This handbook summarises the findings, learnings, and best practices of the Sun-powered Textiles project 2019–2021 in concept creation, product design prototyping and industrialisation of textile integrated solar cells. It provides concrete advice for solar cell selection and integration as well as calculations of types and numbers of solar cells required in different applications.

The research and development of wearable technology requires an interdisciplinary project team. As the project coordinators in Aalto ARTS and SCI, we’d like to thank our company partners, Lindström, the workwear producer; Foxa, the functional textile supplier; and Haltian, the sensor and software technology supplier, for a fruitful collaboration throughout our journey. We’d also like to thank our funding partner, Business Finland, for giving us the financial support we needed to work on this project.

The first chapter illustrates the principle of sun-powered textiles and envisions the potential areas for applying them. The second chapter focuses on the required properties and the inevitable electronic components of e-textile products and discusses the importance of human-centred design in the development process when designing sun-powered textiles. The third chapter introduces the characteristics of solar cells that are most important for their use as a textile electronics power source. The fourth chapter examines the performance of textile embedded solar cells and how different textile properties affect the energy harvesting capacity and visual concealment of the solar cell, and how it can be measured in practice. The fifth chapter discusses the feasibility of powering wearable electronics with textile-integrated solar cells and describes how the feasibility can be evaluated in practice. The sixth chapter introduces the alternative methods that can be used to incorporate electronics with textiles, describe their main features, and their washability and recyclability. The seventh chapter discusses the matters and issues which need to be considered when creating concepts and designing and developing textile products around solar cells. The eighth chapter discusses the sustainability aspects of producing the textile-solar cell component. The ninth chapter describes the concept of sun-powered jackets and their development process from proven idea to final working prototype. The tenth chapter describes the challenges and provides success factors for transdisciplinary projects. The final chapter concludes some of the improvements which could change the development and market of smart textiles.

We hope not only to inspire, encourage, and expand knowledge, but also to provide reliable insight into wearable solar energy today!

Background of Sun-powered Textiles project

The Sun-powered Textiles project originates from a seed funding project called Energy Textiles, that was initiated at Aalto University in 2017 by Prof. Peter Lund and Prof. Jaana Beidler. The Energy Textiles project combined, for the first time, the New energy technologies and the Fashion Textile Futures research group of Aalto University, to find new solutions to the problem of charging textile-integrated electronics. In that project, it was discovered that small commercial solar cells could be integrated invisibly underneath textiles while still producing enough electricity to power wearable electronic applications. Other persons involved in the seed project were Ilona Hyötyläinen, Kirsi Niinimäki, Tiina Aarras, Anna-Mari Leppisaari, Alpi Rimppi, Sakari Lepikko, Eveliina Ronkainen, Sandra Wirtanen, and Anni Lehtosalo.

The Sun-powered Textiles project was founded based on this idea, by Janne Halme and Elina Ilén, with the aim to study further the concept's feasibility, how different textile properties affect the energy harvesting capacity and concealment of solar cells, and how the integration of solar cells in textiles could be produced in a scalable, durable and washable way.

Sun-powered Textile project team

The following persons contributed to the Sun-powered Textiles project in various ways:

From the Department of Design (Aalto University):

- Elina Ilén, Project leader (design) (*textile technology, textile electronics design and manufacture*), co-advisor for Bettina's and Zuzana's M.A. theses
- Elina Palovuori, Coordinator, daily support of design and research (*textile materials, textile technology*)
- Bettina Blomstedt, M.A. thesis worker, research assistant (*textile design, development of knitted textiles*)
- Zuzana Zmateková, M.A. thesis worker (*textile design, development of woven textiles*),
- Maarit Salolainen, Supervisor for Bettina's and Zuzana's M.A. theses, Co-advisor for Zuzana's M.A. thesis
- Kirsi Niinimäki, Project PI (design)

From the Department of Applied Physics (Aalto University):

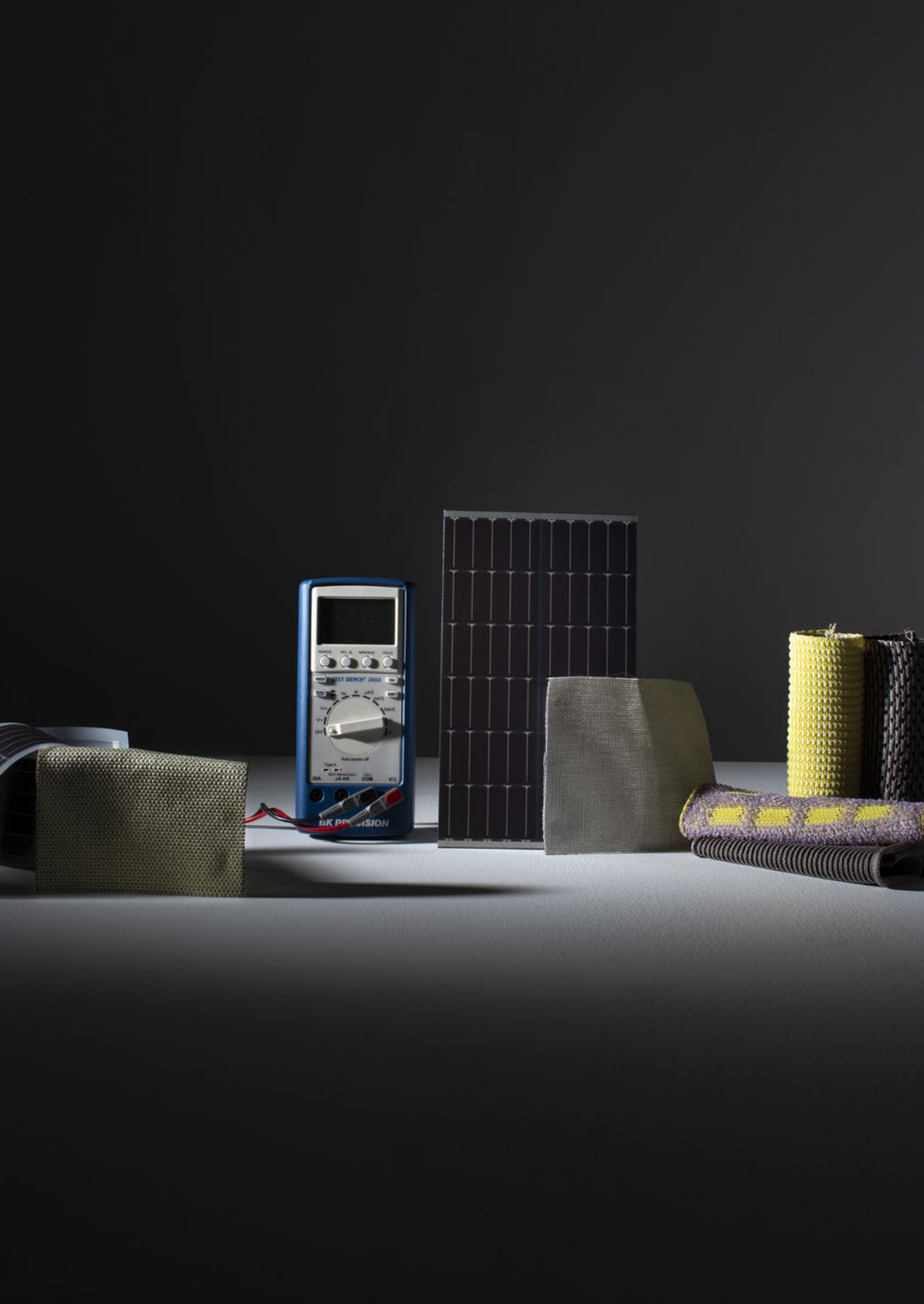
- Janne Halme, Project leader and PI (physics)
- Farid Elsehrawy, Post-doctoral researcher (*solar cell textile optics and photonics, energy harvesting electronics*)
- Linda Wederhorn, M.Sc. thesis worker (*textile - solar cell performance characterization and energy harvesting analysis*)
- Pinja Helasuo, B.Sc. thesis worker, Research assistant (*solar cell textile modelling and characterization*)
- Jaakko Eskola, B.Sc. thesis worker, Research assistant (*photographic colorimetry*)

Acknowledgements

The Sun-powered Textiles project was funded by Business Finland (project number 3666/31/2019).

The authors thank the whole Sun-powered Textiles project team for their various contributions to the project, as well as all the participants in the seed project Energy Textiles. This book would not exist without the initiatives, ideas, collaboration, and the research work that produced the results. The book is a summary of the main aspects from a technical design perspective – many results from the scientific and textile design research in the project are not included but are reported elsewhere.

The authors thank the partner companies in the co-Innovation project – Foxa, Lindström and Haltian – for their invaluable input, their feedback, and materials provided during the project, and for partially funding the research, as well as, the product development team in Protex Balti As for providing appropriate production machinery for encapsulation development.



1

SUN-POWERED TEXTILES

This chapter illustrates the principle of sun-powered textiles and envisions the potential areas for applying them. It also summarises the key properties of sun-powered textiles.

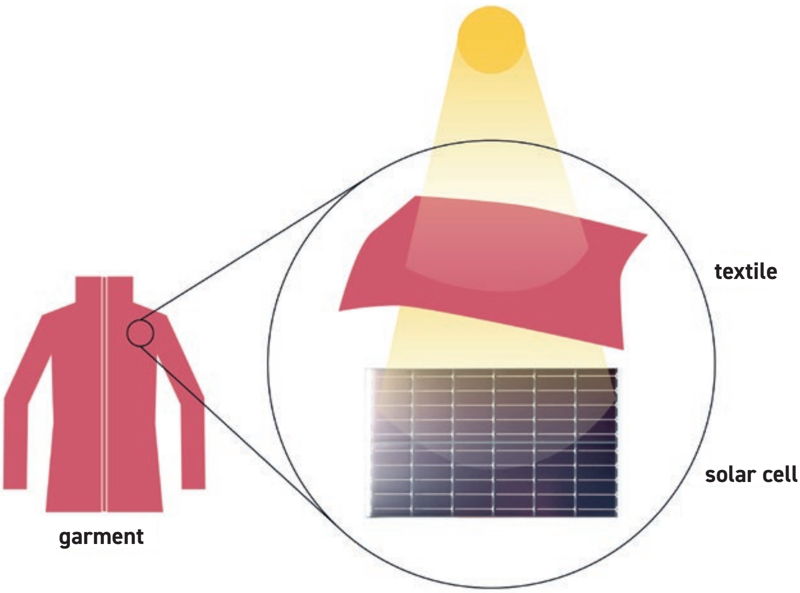
Elina Ilén and Janne Halme

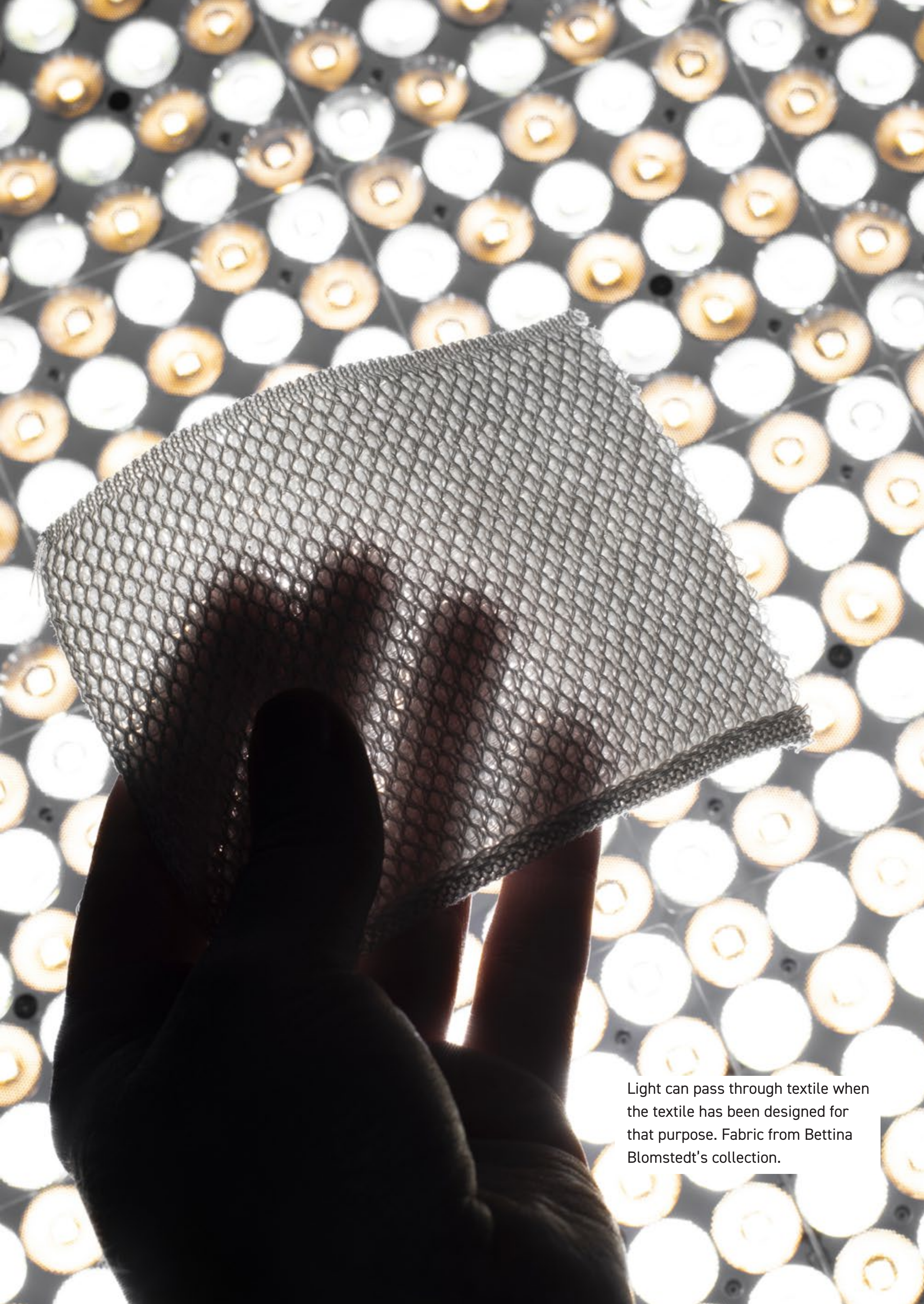
The principle of sun-powered textiles

Solar cells have a high potential as an energy source for e-textiles. Usually textile and wearable electronics along with other electronic components are powered by batteries, and need periodic replacement and recharging. Charging the battery with solar cells could make the battery replacement or recharging unnecessary.

In smart textile solutions, solar cells are usually integrated on the surface of a textile to ensure maximum energy harvesting. That significantly compromises the aesthetics: a black solar cell attached on top of a fabric dominates the look of the textile or garment. It is also prone to damages caused by hits and scratches when it is not protected. These problems can be avoided by covering the solar cell with textile.

Textile is capable of passing light through it when it is designed for that purpose. The solar cell is placed underneath the textile, and together they form a textile cell module which can generate its own energy by using light as an energy source. The fibre material, textile structure, density, colour and





Light can pass through textile when the textile has been designed for that purpose. Fabric from Bettina Blomstedt's collection.

after treatments all impact the optical properties of the textile, and hence the energy harvesting capability of the solar cell. Optimisation of these textile properties is crucial for making an effective textile-solar cell component. The hidden technology enables a broader freedom to design products according to user needs, which increases product acceptance. When solar cells are embedded into a textile by applying an encapsulation technology, electronic textile products become more durable and washable.

An aesthetic and durable textile-solar cell energy harvesting module can be widely applied to smart textiles and wearable technology solutions. They can be of particular use in the following fields and industries:

- Agriculture
- Sport and well-being
- Medicine and health
- Gaming
- Building and construction
- Automotive
- Fashion
- Professional and work wear
- Occupational health
- Robotics

Developing an effective power supply for intelligent textile products has been one of the main research areas from the get-go. Currently, most of the commercial e-textile solutions are based on a removable and rechargeable or disposable battery, as an energy source. However, batteries are sometimes perceived as a disadvantage for the usability of wearable technology. With regards to safety and protection applications, the need for battery change, or reload, is considered a safety risk, as the device becomes useless without energy. Therefore, these solutions require technology which ensures continuous energy harvesting, so that the devices can be used without interruption. Solar energy harvesting can remove the need for battery replacements, and guarantee functioning in all conditions where light is available in sufficient amounts.

Most solar cells are good for harvesting natural daylight outdoors, and some cells are developed specifically to harvest artificial light indoors. A textile-embedded commercial solar cell solution could provide a completely autonomous application, which utilises renewable energy sources to produce its own energy. It could also improve the reliability of smart workwear safety applications and decrease lifetime costs.

POTENTIAL EMBEDDING PRODUCTS

WORKWEAR

- Building constructor
- Firefighter
- Outdoor worker

OUTDOOR FABRICS

- Garden furniture textiles
- Sunshades
- Parasols

OUTDOOR AND INDOOR GARMENTS

- hats
- gloves
- belts

OUTDOOR ACTIVITY WEAR

- Alpine skiing, surfing, golf, hiking
- Sailing, fishing, gardening
- Camping

The practical challenges of textile-embedded solar cells culminate in two aspects: the energy-efficient and aesthetic integration of solar cells to textiles; and durability related to their use and care, such as going through several washing-machine cycles. The textile concealed solar cell solution, developed in the Sun-Powered Textiles project, aims to solve both challenges, as well as improving user experience by ensuring that the solar cell component does not have to be removed for washing, and is always switched on.

Solar energy is a reliable renewable energy source that is available every day throughout the world. Although the season, the time of the day, and the weather conditions affect the availability of solar energy, solar cells work tirelessly to convert even the faintest sunlight to electricity. Even artificial lighting is a source of energy for solar cells, although a weaker source: outdoor solar energy harvesting produces up to 1,000 times more energy than indoor light harvesting. Solar energy is particularly valuable in situations in which there is no access to a power grid, for example in remote rural areas, and in urban areas and indoors in locations where installing electrical wiring would be costly or impractical.

Textiles are also widely used in places where they constantly are exposed to sunlight. Outdoors, textiles are found in boats, sails, outdoor furniture, sunshades, curtains, tents, and other camping equipment, and of course in outdoor clothing. Indoors, textiles are found everywhere. In fact, wherever you can *see* a textile there is also *light* for the solar cells to capture and convert to electricity.

VISIONING THE APPLICATIONS FOR SUN-POWERED TEXTILES

Solar energy for lightning

LEDs are effective sources of light and consume a relatively low amount of energy. LED lights used to illuminate the interior lining of bags could make it easier to find items in a dark urban setting, as well as in dark rural environments, such as while camping. In professional or occupational wear, it could improve visibility – for mailmen for instance, or construction workers. In shelters and tents, integrated LED lights would bring comfort and safety. LEDs could also be used in neon signs, for example they could be integrated into the textile roof of a street food cart.

Solar energy for body sensing

Wearables are one of the obvious applications for solar energy. Garment is a natural textile-based platform for body monitoring. Many biosensors, such as humidity, temperature, heart rate, muscle activity or movement sensors, could be powered by solar cells. Children and the elderly could be located by integrating cells, location (GPS), and textile antennae to the garment.

Solar energy for cooling or heating

Large outdoor textiles are useful places for solar panels. For example, solar cells could be integrated into the sails of a yacht and used for keeping groceries cool or providing energy for lighting at night. Cyclists could benefit from textile cooling bags that are attached to their bikes. In the garden, an awning could collect solar energy and provide a warmer, cosier environment at night. A cooling hat could also provide a cooling spot on one's forehead which would create a nice cooling sensation.

Solar energy for mechanical movements

In home interiors, window blinds can cover a large area and be exposed to sunlight. Solar panels integrated into the blinds could provide energy for closing and opening, or harvest energy for other devices in the room. Sun-powered energy could also be used to turn on a fan to create a sensation of cooling, rather than actual thermal cooling.

→ **NOTE:** The abovementioned use ideas are given only for inspiration. To confirm whether an idea for a solar-powered electronic textile application is feasible, requires a careful technical analysis, which is the topic of the section, 'Feasibility for energy autonomous operation'.

Whenever needed, the storing of sun-powered textiles is simple. The folding of the product into smaller form saves space. Sun-powered textiles are a portable and lightweight solution in comparison to conventional solar cell applications.

Key properties of the Sun-powered Textiles solution

Integrating solar cells underneath a textile has the following advantages and disadvantages, compared to the traditional way of placing them over the textile:

Aesthetics: Underneath a textile, the solar cells are hidden from the direct view of the observer, either completely or partially. This allows the solar cells to blend into the overall visual surface design of the textile product. The textile can be coloured and patterned independently from the colour and shape of the solar cells.

Best of both worlds: Because the aesthetic and power-generation functions in this solution are separated into different material components, i.e., aesthetics to textiles and power-generation to solar cells, they can be selected independently to optimise the overall performance, durability, textile-functionality, and cost.

Commercially ready: The Sun-powered Textiles solution is based on commercially available solar cells, and it uses industrial textile manufacturing processes. A solar textile manufacturer can therefore use any solar cell product that is available on the market at suitable volumes. They are not tied to only one solar cell technology or manufacturer, which helps to mitigate risks in building the business.

Durability: The textile layer in front of the solar cell protects the solar cell from mechanical wear and tear.

Fabrics from Zuzana Zmateková's collection.

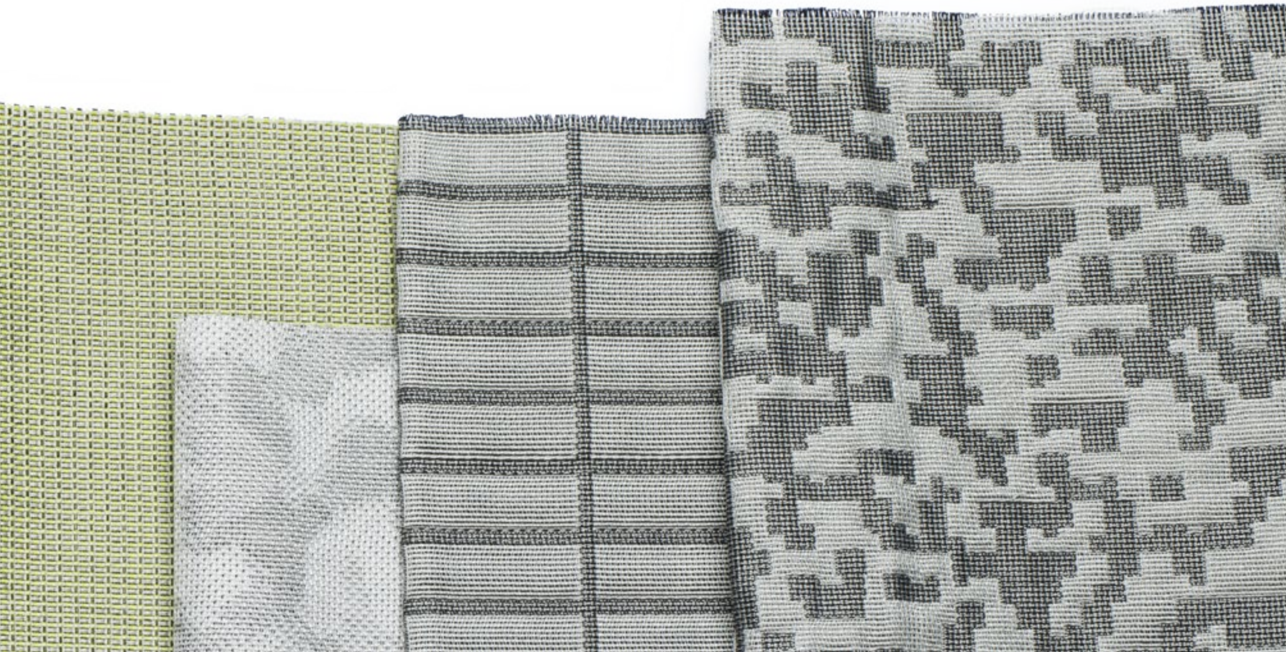
Encapsulation: There is no need to thread electrical conductors through the textile material: all the non-textile components (solar cells, electrical wires, energy storage, and other electronics) can be placed on the back of the textile. As a result, the product can be continuous (seamless), which improves the aesthetics, feel, and durability, and lowers the manufacturing costs.

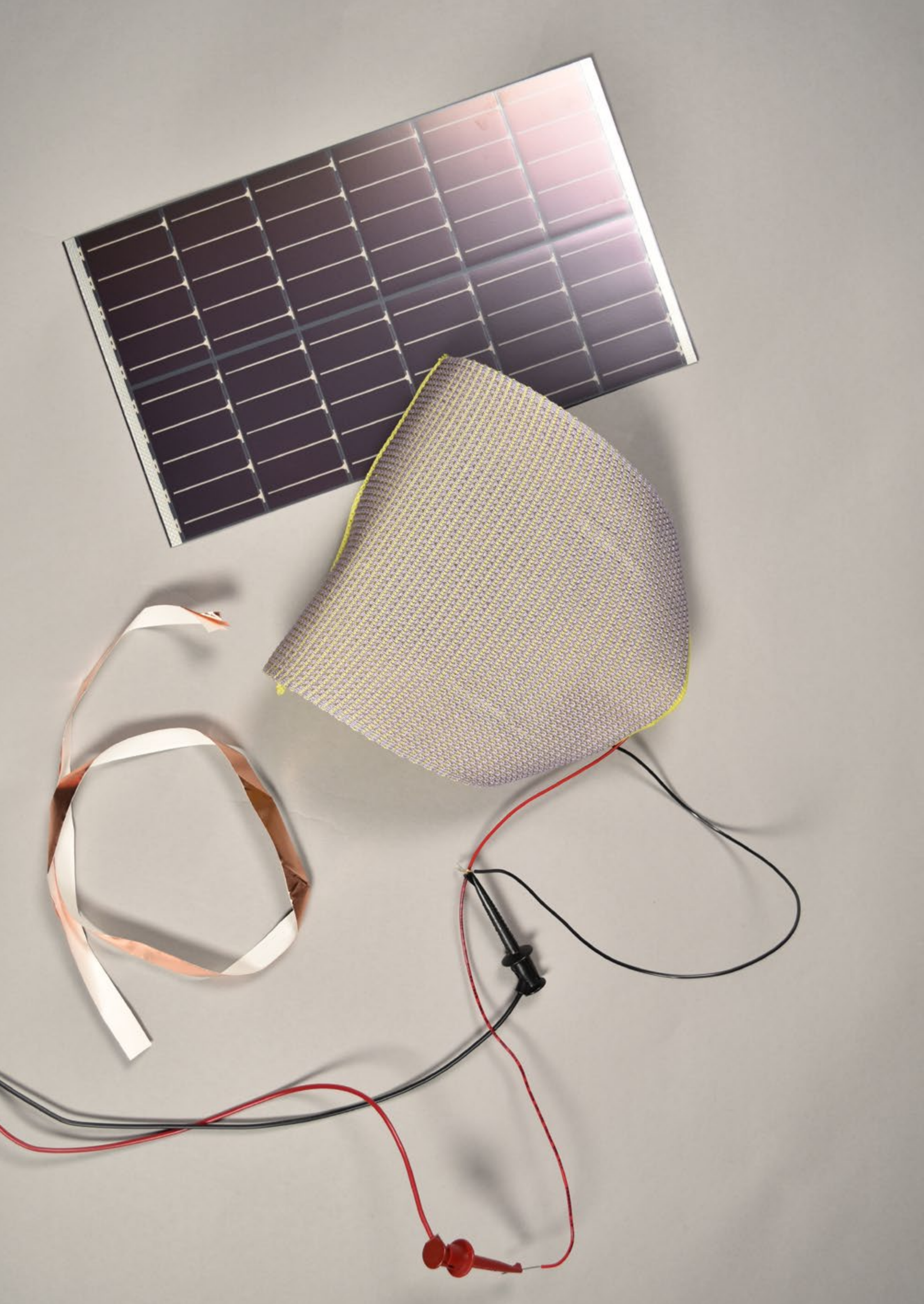
Energy: Thanks to their aesthetic advantage, sun-powered textile garments with hidden solar cells may end up being used for a longer time, and therefore produce more energy over their product lifetime.

Size: If a solar cell is covered by a semi-transparent textile, it receives less light. Therefore, for it to produce the same amount of energy as an uncovered cell, it needs to be bigger. On the other hand, if the electronic application consumes only a little power, a small textile-covered cell can remain small. A larger solar cell costs more than a smaller one. Depending on the application, the higher cost can still be a small fraction of the overall product cost, and therefore be acceptable thanks to the other advantages it provides.

Technological readiness: The solution can be realized with crystalline or amorphous silicon solar cells that are proven and efficient technologies. Colourful dye-sensitised solar cells and organic solar cells have been proposed for textile-integration, but they are less efficient and durable, have a limited range of colour options, and are still in the earlier stages of technological development.

Washability: The component manufactured by textile encapsulation is proven to tolerate 50 machine-wash cycles in 40°C with a 55-minute programme.





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REQUIREMENTS OF E-TEXTILES AND WEARABLES

This chapter takes a look at the required properties and the inevitable electronic components of e-textile products and discusses the importance of human-centred design approach in designing sun-powered textiles.

Elina Ilén

Characteristics of e-textiles

Electronic textiles and wearables are functional textile materials which interact actively with their environment. This means that they respond or adapt to changes in the environment. The engineering of electronic textiles and wearables has progressed significantly, giving rise to several global start-ups in the field of sports and leisure clothing. The main advancement in this development has been the integration of "smart components" into textiles, without compromising the user experience and the usability of the garments.

The textile-based wearable technology is deeply interdisciplinary. It combines textile and clothing technology with information technology and electronics and applies design practice, aided by human and social sciences. Textile materials are a natural platform for wearable technology, because their soft, flexible, lightweight, air-permeable, elastic, and stretchy characteristics are adaptive to the shapes and movements of the human body.

Textile products endure a wide range of environmental and weather conditions when protecting the wearer, but also handling caused by random human behaviour, i.e., the textile product can be folded or hanged, stored for a long time, stuffed in a backpack, dropped on the floor, someone can sit on it, it can be left outdoors, food or chemicals can be spilled on it, and it can be washed.

The challenge of designing textile-based wearable technology is to meet the demands of ordinary clothing in terms of acceptance, usability, and care. E-textiles should not significantly compromise superior textile characteristics. Hence, all electronic components, such as solar cells, that are integrated into textiles must meet the demands of the garment or textile product. They have to allow as much flexing, stretching, and washing as the corresponding ordinary textile products. Weakening the soft feel, breathability, adaptability, and usability would decrease the e-textile user acceptance. The wearers of e-textiles often experience them as heavy and uncomfortable and perceive them as masculine and robotic. Sometimes the negative user experience originates from hard, fragile, garment-inadequate electronics that might break unexpectedly.

Fabrics from Bettina Blomstedt's collection.

Even though textile-based wearables have gone through over 30 years of development, even now the 'smart' in smart textiles also means adding stiffness, heaviness, and lack of usability and aesthetics to the textiles. The best and inherently wearable characteristics of textile materials are still sacrificed to ensure the functions of hard technology. This is probably due to the fact that there are not enough textile engineering and textile design experts in e-textile research groups who would focus on meeting the demands of the textile product.

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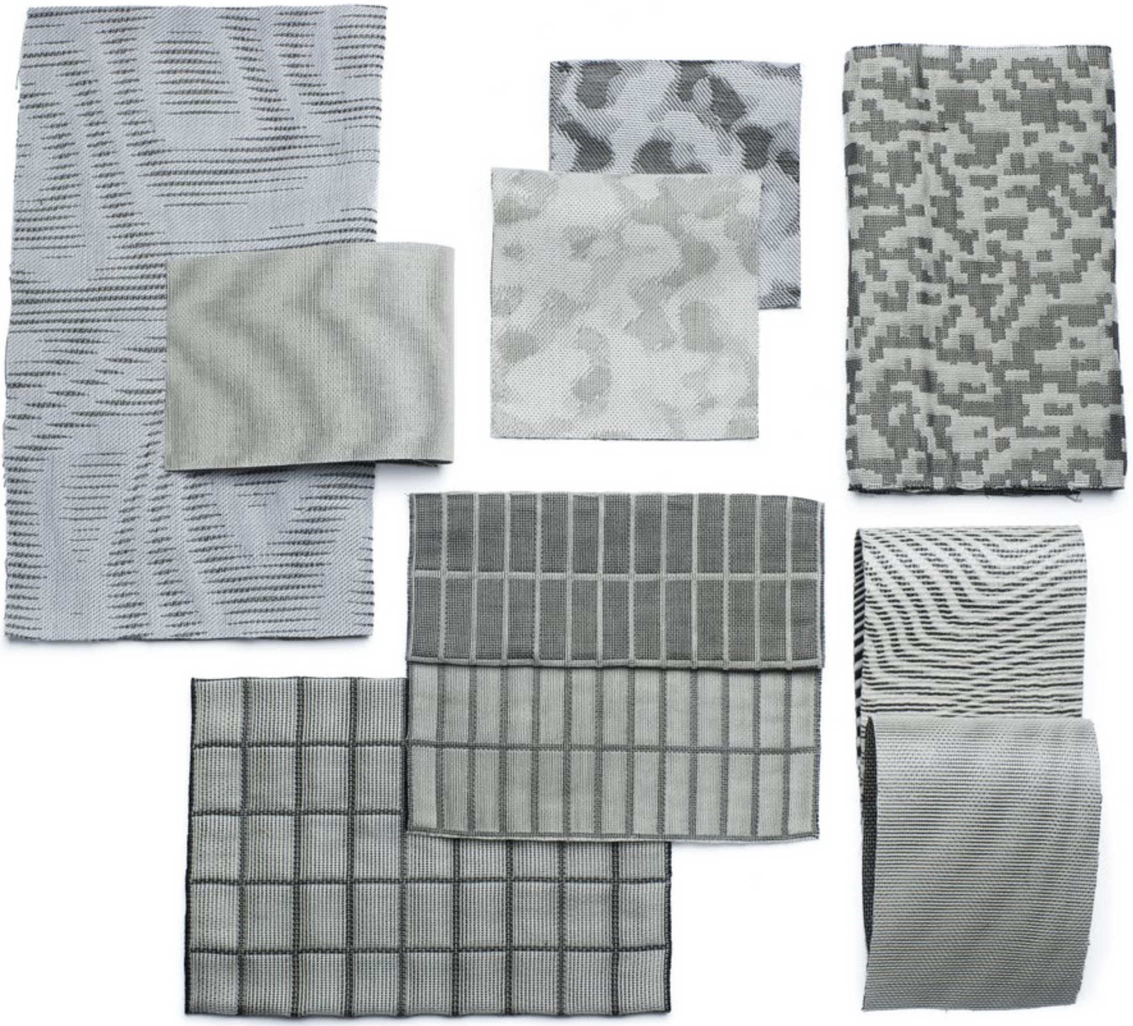
GLOSSARY

Wearable technology, wearables or wristables: Electronic products which are used by wearing them (body worn), and where there is no need for textiles to be involved, such as smart watches or wristables.

Smart or intelligent textiles, or materials, or fibres are able to react to external impulses and stimuli, e.g., heat, light, pressure, or electricity. Application areas are not limited for wearable solutions. To put it simply, smart textiles combine intelligence and textile.

Textile electronics, electronic textiles, e-textiles: Every product where the electronics are combined, integrated or embedded into textiles to add value for the user. Application areas: sport, health care, work wear, automotive industry, construction, and fashion.

Conductive textile: Electrical conductivity of the textile material is used for sensoring, monitoring, heating, and data transferring. A part or a component in an electronic device.



Textile: The term for all fibre-based materials. It covers all the fibre and yarn processing technologies such as knitted, woven and non-woven fabrics, laces, braids, and knitted and woven narrow bands. Except for fabrics, the component is ready for use and only needs to be cut to correct length.

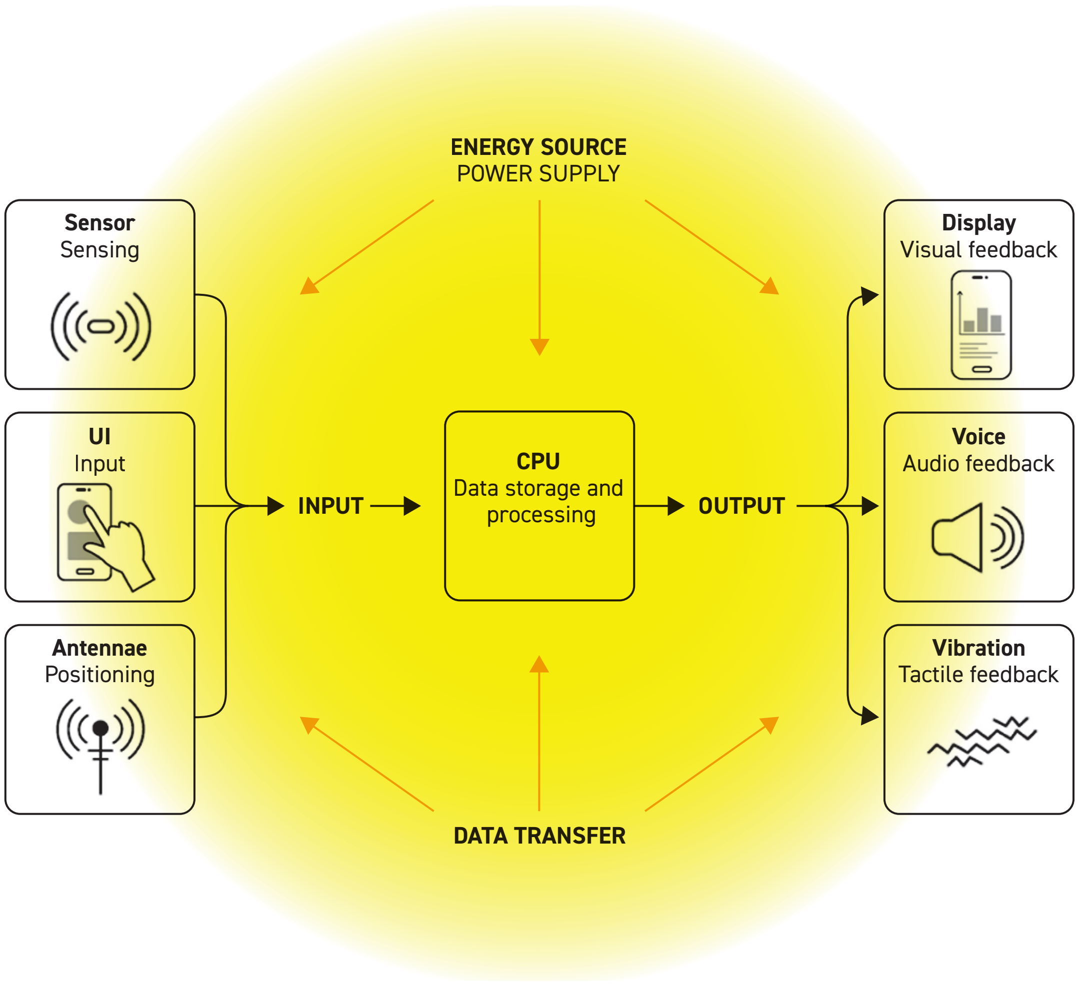
Fabric: a 2-dimensional textile which is produced by knitting, weaving or non-woven technology. A component is cut from fabric into the required size and shape.

↑ Fabrics from Zuzana Zmateková's collection.

The role of the energy source in an electronic textile system

The input device, the sensor, such as a textile sensor, or a textile-embedded sensor, gathers the input signal, e.g., heart rate or muscle activity in body monitoring. The user interface (UI) device such as a phone, or a watch, or antennae can also input the signal to the system. The signal is transmitted to the central processing unit (CPU) for data processing. The output device, the visual (a phone, or watch), audio, or tactile feedback, displays the processed data. Data from input device to CPU and from CPU to output device is transferred either via a wireless connection (Bluetooth Low Energy, BLE) or conventional cables. All these components in the system require energy for an operation. The application determines how much energy is required and data needs to be transmitted between the different components.

Currently, the most challenging part in the system is the undeniable need of a power source. No electronic device can function without electricity. If an electronic textile is stationary, the power can be sourced directly through a plug in the wall. However, mobile electronic textiles, such as garments, need to be powered by a mobile power source, i.e., a battery. In fact, removable batteries are usually used in such wearable systems. Yet, there are many reasons why this is not the best solution. Batteries need to be changed occasionally, which makes them unreliable in terms of protection and safety. The textile-integrated solar energy system eliminates the need for changing or recharging the battery, or removing it before washing. Even though, waterproof battery covers are available, they are often too expensive. In addition, the battery is usually in the same case as the electronics, so waterproofness may also be compromised when the case is opened for battery replacing. Modern electronics and sensors are small in size, and the main contributor to the size and weight of textile-integrated electronics is the battery. To reduce weight and bulkiness, it is possible to shift into an energy-autonomous solution and eliminate the need for a battery. It may also be more environmentally friendly to reduce the need for constant battery replacements. An autonomic system, where the energy is harvested from solar energy, would guarantee that the system functions in all use conditions.



The e-textile system architecture always covers the signal input, such as textile electrodes on the body, and output devices, such as a mobile phone, control processing unit and the energy source for data processing and transferring between all these elements.

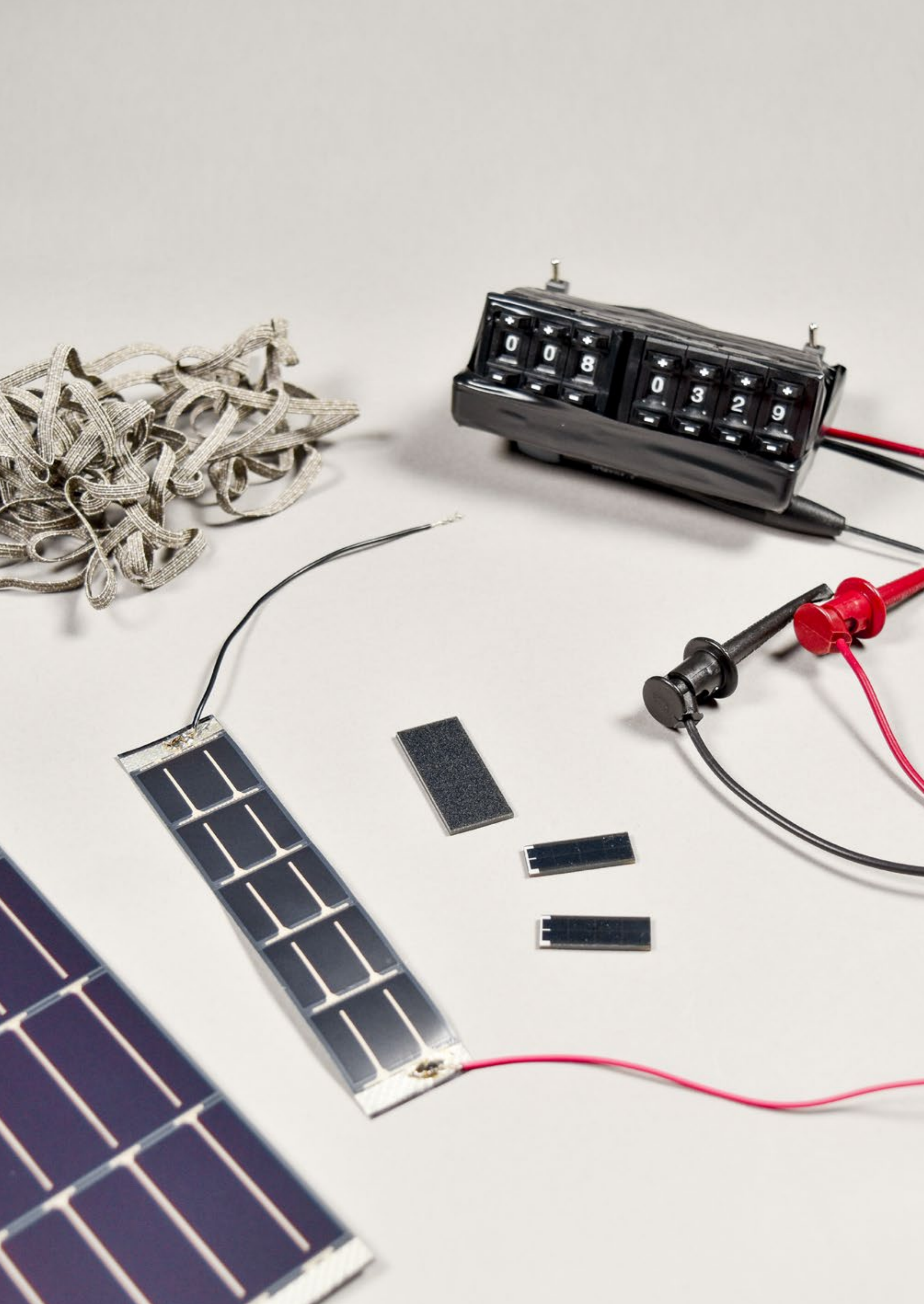
Human-centred design as a game changer for Wearables

The groundbreaking developments in electronics are the driving force in the development of wearable technology. E-textile garment applications have been discussed for decades, but the creation of meaningful wearable solutions has not been possible without the development of fast and effective wireless networks for communication with low energy usage, such as BLE (bluetooth low energy) technology and the miniaturisation of electronic components and exponential growth of smartphones and tablets. With this in place, the components can now be integrated into clothing or textile structures, and there is no more need for, or challenge to integrate displays into textiles.

Smart clothing is an obvious part of IoT, especially in applications in which either the user's body or condition or close-environment is under detection. The ITC technology readiness is no longer a limiting factor, but it is also challenging to find beneficial and value-added properties for smart textile products because not everything needs to be textile-based. In fact, mobile phones, wrist computers and smart watches have reduced the need for certain applications such as textile displays, playing music, etc.

As the major technological barriers are removed, human centred design is turning into an essential approach in research and development of smart textile-based wearable solutions. People's distrust of emerging technology, including wearable and portable electronics, has gradually decreased, but at the same time people are more concerned with safety, reliability, and real usefulness of the products. This is most probably at least partly due to the massive increase of electronic devices. When the number of electronic devices increases, people's fears and doubts surface. This has to be considered because experiences and emotions play an important role in user acceptance. An important aspect of development is that the product should not be frightening but desirable and necessary. Otherwise, there is no point in developing it.

The product design process of e-textile solutions is often technology-driven, and developed through an approach in which various electronic components are combined into a new product, including visibly. In the traditional approach to integrate solar cells into textiles, a solar cell is attached to the front surface of the textile, because common sense suggests that in that position the solar cell should be able to harvest the maximum amount of light for it to work sufficiently. However, if the solar cell is positioned in that way, the aesthetics of the textile product are significantly compromised, because the black or dark solar cells are easily distinguishable. Solar cells dominate the product surface, which limits the design possibilities. On the other hand, if the solar cells are visually concealed with textile, they become more deeply integrated, and therefore unobtrusive, enabling broader freedom for the product and textile design, so that textile products can be tailored for different contexts and for various visual needs of the user. For instance, thanks to the invisibly embedded technology, it is possible to design products for any gender or age group. Human-centred approach is important in design in order to make valuable and beneficial products for the users.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SOLAR CELLS FOR ENERGY HARVESTING TEXTILES

Solar cells are semiconductor devices that convert light into electrical energy. Their source of energy, electromagnetic radiation, may be visible light, ultraviolet radiation, or near-infrared light. How efficiently the solar cell is able to utilise different wavelengths of light and what other properties it has, depends on the type of solar cell, its materials, and the way it is manufactured. This chapter takes a look at the characteristics of solar cells that are most important for their use as a textile electronics power source.

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What is a solar cell?

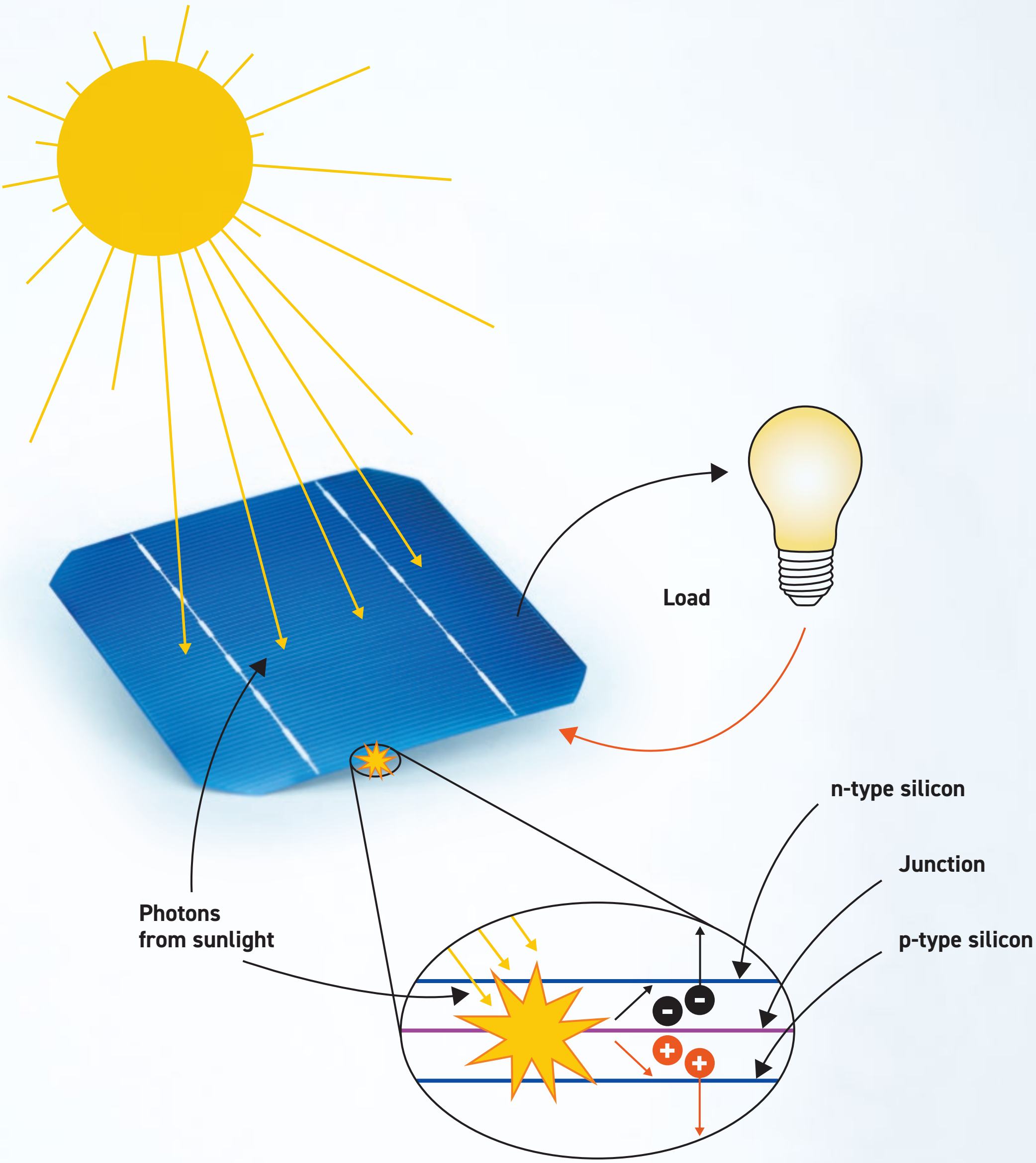
Solar cells are the most common method of harvesting ambient energy for low-power wireless electronics applications. They provide superior power density and daily energy generation potential compared to all the other energy harvesting technologies conceivable for wearable electronics. But what is a solar cell and how does it work?

A solar cell is an electronic device that generates electricity from sunlight. 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:

Absorption of light: When light hits the solar cell, its photons are absorbed into the material of the solar cell. In this process, the photon disappears, and its entire energy is transferred into one of the electrons in the chemical bonds between the atoms in solar cell material.

Creation of free charge carriers: The energy received from the photon can release the electron from the chemical bond, so that it can move around in the material. The released electron leaves behind an empty place in the chemical bonds. This empty slot in the bond is called an electron hole, and it can also move, as an electron from an adjacent bond can move in to fill the empty place. In effect, the hole then moves to the opposite direction, like switching seats. The released electron carries negative electric charge, and the free hole behaves like a positive charge carrier. At this stage, however, electricity has not yet been generated. To generate voltage and current, the negative electrons and positive holes must be separated.

Separating the positive and negative charges: To do this, the solar cell is built from two slightly different layers of material with a built-in electric field at the material interface between them. Under the influence of this electric field, the oppositely charged electrons and holes get pushed to opposite sides of the



In crystalline silicon solar cell, the electrons and the electron holes produced by light absorption in the silicon are separated to different sides of the cell by a built-in electric field at an interface between p- and n-type silicon – the pn-junction. The p-type and n-type refer to different chemical impurity atoms introduced to the different layers (phosphorous in n-type and boron in p-type) with the purpose of forming the electric field.

interface, creating an electrical potential difference, i.e., voltage, between the opposite layers and electrical contacts connected to them.

Delivering current to an electric load: The light-induced voltage is a sign that the solar cell is able to do electrical work: When wires are connected to the cell, electrons can flow out, driven by this voltage, and charge a battery or power up an electric load, like a wearable sensor.

In this way, the solar cell converts sunlight into electricity silently and reliably, without any moving parts or chemical changes in its materials. The same operating principle applies to almost all commercially available solar cell varieties although they may be made from different materials.

Energy harvesting

Energy harvesting means collecting freely available energy from the environment and converting it into electrical energy for various small electrical appliances, such as wearable electronics. Energy harvesting can be used to fully satisfy the energy demand of the device, or just to extend its battery life – the approach depends on the energy consumption of the device and the availability of energy in the environment. The amount of energy that can be harvested depends to a large extent on which product the energy harvester is connected to, under what conditions or in what way the product is used, and on the efficiency of the energy conversion technique.

In the environment where textile products are used, ambient energy can be available for energy harvesting in a variety of forms and sources, for example:

1. light energy from natural light outdoors or artificial lighting indoors
2. kinetic energy from the environment, e.g., wind, movement or vibration of equipment, or acoustic vibration
3. thermal energy from the environment, e.g., waste heat from electrical appliances
4. human-generated muscle work or kinetic energy e.g., walking, limb movements, breathing, heartbeats, and conscious acts such as pushing a button
5. thermal energy produced by the human body (body heat)
6. electromagnetic energy from ambient radio-frequency (RF) waves of wireless telecommunication

When comparing the typical power densities of these different energy sources (see table below), it can be seen that light harvested with solar cells is by far the most abundant ambient energy source, especially if the textile product is used outdoors in daylight: Even a short moment outdoors can produce significantly more electricity by solar cells than could be collected from the same surface area with other techniques throughout the day. For this reason, solar cells are an excellent energy harvesting technology for powering energy self-sufficient textile electronics.

TYPICAL ELECTRIC POWER GENERATION AVAILABLE FROM VARIOUS AMBIENT ENERGY SOURCES BY DIFFERENT ENERGY HARVESTING METHODS.

The values in this table represent typical maximum **power** (Watts, W), namely the temporary energy flow (Joules per second, J/s), attainable by each method. It would be more useful to know how much **energy** (Joules, J, or Watt-hours, Wh) could be produced within a certain time period, for example during one typical day when the textile electronic product is used, as this could be directly compared to daily energy need of the product. The same amount of energy can be produced with high power in a short time or with low power over a long time. Comparing different energy harvesting methods can therefore be complicated. Fortunately, solar cells are simple: they produce relatively high power whenever they are exposed to light, as textiles often are.

ENERGY SOURCE	TYPE	METHOD	POWER DENSITY
Radiant	Solar	Photovoltaic (outdoors)	15 000 μW/cm^2
		Photovoltaic (indoors)	< 15 μW/cm^2
	Radio frequency	Electromagnetic	0.1 μW/cm^2 (GSM)
		Electromagnetic	0.01 μW/cm^2 (WiFi)
Mechanical	Wind flow & hydro	Electromechanical	16 μW/cm^3 (*)
	Acoustic noise	Piezoelectric	0.96 μW/cm^3 (*)
	Motion	Piezoelectric	330 μW/cm^3 (*)
Thermal	Body heat	Thermoelectric	40 μW/cm^2

(*) Note that these three values are per device volume (/cm^3), whereas the others are per device area. Converted to per-area-units (/cm^2), the values become much smaller if the device is thin, which is often a prerequisite for textile-integration. The Table is adapted from Kofi Sarpong Adu-Manu et al. "Energy-Harvesting Wireless Sensor Networks (EH-WSNs): A Review". In: ACM Transactions on Sensor Networks 14.2 (July 2018), pp. 1–50. doi: 10.1145/3183338.

Different types of solar cells

Commercial solar cells can be suitable for integration with textiles due to their mature technology, availability, and cost-effectiveness. There is a wide range of commercial solar cells that utilise different photovoltaic technologies, and they come in different shapes and sizes. The main photovoltaic technologies available on the market are single-crystal silicon, multi-crystalline silicon, and amorphous silicon solar cells.

Single-crystal silicon solar cells, also called monocrystalline silicon solar cells, are formed by sawing a silicon crystal grown from liquid silicon into thin slices called silicon wafers, and these wafers are then processed into solar cells. They provide high efficiency at a high cost. **Multi-crystalline silicon solar cells**, also called polycrystalline silicon solar cells, are otherwise similar but sawed from a chunk of polycrystalline silicon. They are cheaper to produce but give slightly lower efficiency. Both single-crystal and multi-crystalline silicon solar cells are usually thick and rigid because they are encapsulated with a thick glass or plastic sheets to prevent the brittle silicon wafers from cracking which could happen if the solar cell is bent. **Amorphous silicon solar cells** are also commercially available and promising for textile integration due to their low cost and flexibility, despite their lower efficiency. The amorphous silicon cells owe their flexibility to the light absorbing material, amorphous

GLOSSARY

Silicon (Si) is a natural element used as the light-absorbing semiconductor material in most solar cells. It is the second most abundant element in the Earth's crust (28% by mass), where it is bound to oxygen (the most abundant element) in the rock-forming minerals called silicates. (Don't confuse silicon with silicone, the substance used for making oils and rubber!)

Crystalline silicon solar cell is made of crystalline form of silicon. Extracting pure silicon from silicate rocks (quartz) by melting takes a lot of energy, but it gives an excellent material for making solar cells and electronics in general. The required energy could be produced by solar cells, by the way.

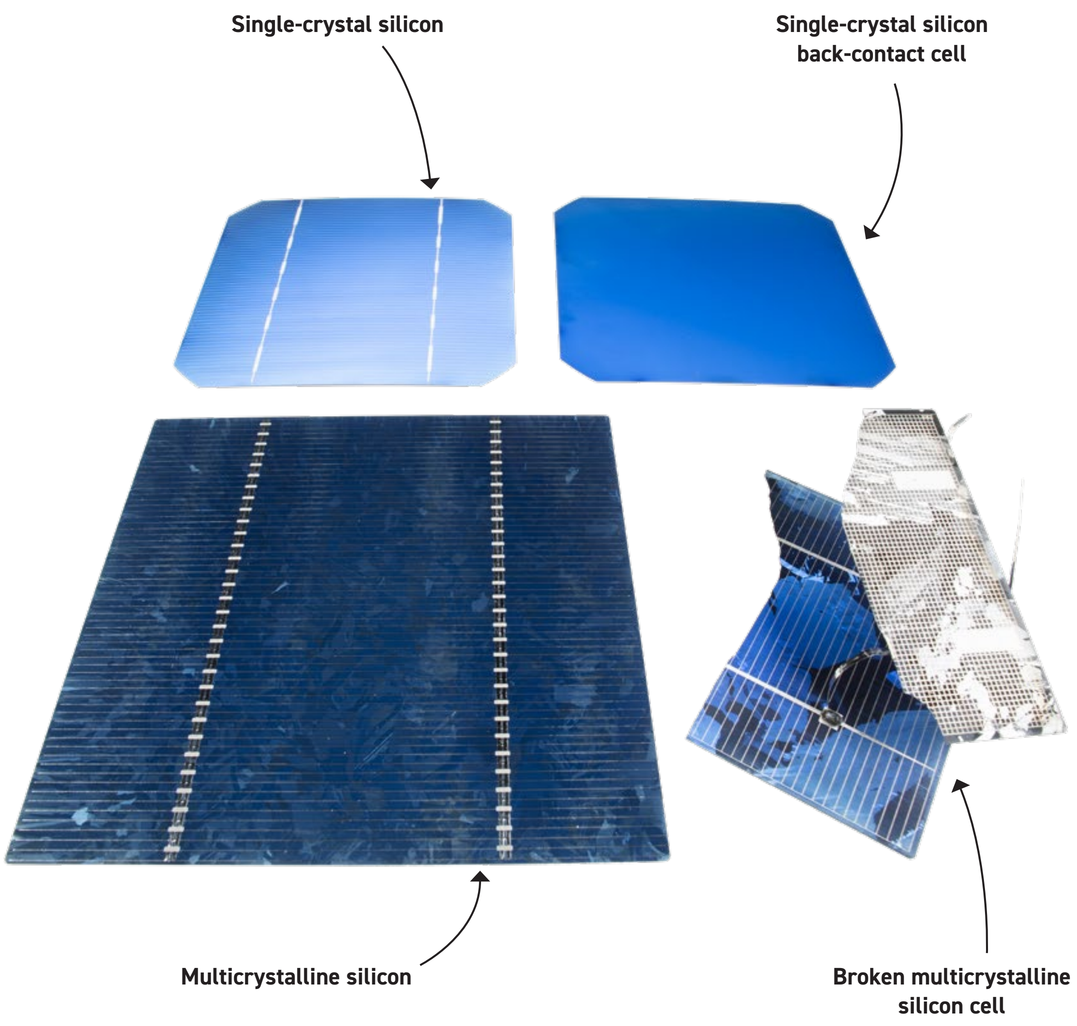
Single-crystal silicon solar cell (also known as monocrystalline silicon solar cell) is made of a slice of one big silicon crystal. A single semiconductor crystal gives the solar cell very good electronic properties (electrons can move well in it because there are no crystal boundaries). On the other hand, crystallinity makes it hard and brittle, so it breaks easily if bent too much.

Thin-film solar cells are thinner and non-crystalline, so they don't break as easily as crystalline silicon solar cells when bent, and can therefore be made thinner, lighter, and more flexible.

Multicrystalline silicon (also known as polycrystalline silicon) consists of many interconnected small crystals. The individual crystals are often visible because different orientations of the crystals reflect light differently. Nevertheless, the crystals are much wider than the silicon slice is thick, so the borders between the neighbouring crystals affect electron movement only a little.

Amorphous silicon solar cell is a thin film solar cell made of the non-crystalline form of silicon. Amorphous means that there is no long-range order in how the Si atoms are positioned in the material, which makes electron movement more difficult. Luckily, amorphous silicon absorbs light very efficiently, which is why only a thin film is needed. In addition to solar cells, it is used in thin-film transistors and liquid-crystal displays.

Thin film solar cells are a large group of different solar cell types where the solar cell material is so effective in absorbing light that only a thin film is needed. This makes it possible to apply it as a coating on various substrate materials that can be flexible like plastic and metal foils, and even on textiles. These cells are thin which is why they can be more flexible than crystalline silicon solar cells that are thicker and need more sturdy mechanical protection.



Silicon is grey by nature. The blue colour of single-crystal (top left) and multi-crystalline silicon (bottom left) solar cells comes from an anti-reflection coating which is used to capture more light. Although visible in the bare solar cells, the blue colour turns darker when the cells are manufactured into solar panels by encapsulating in clear sealant polymer underneath a protective glass sheet. On the front side, thin screen-printed silver lines and thicker silver 'bus bars' are prominent. They collect the electric current generated by light in the silicon. On the backside, a denser silver print serves as the other electrical contact. In an advanced cell design (top right), called the back-contact cell (right), both positive and negative contacts are placed behind the cell. This prevents them from shading the cell, which improves the efficiency and gives the cell a uniform appearance often preferred in solar architecture and integration into products. Unprotected, the crystalline silicon cells are prone to cracking when bent (bottom right).

silicon. It is so effective at absorbing light that it can be applied as a thin layer over various substrates, including flexible metal or polymer foils. There is also a range of other thin film solar cell technologies with different efficiency, durability, cost, technical maturity, and commercial availability, such as cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and gallium arsenide (GaAs), as well as organic and dye-sensitized solar cells.

Solar cells, solar modules, solar panels

Solar cells are almost always sold in the form of solar panels which are also called solar modules. Solar panels consist of multiple electrically interconnected solar cells. A single solar cell provides a relatively low voltage, however, connecting a number of cells in electrical series augments the voltage, making it more suitable for practical applications. On the other hand, connecting solar cells electrically in parallel adds up their current. Finally, making a solar cell or solar panel larger increases its output power proportionally to its surface area. It is therefore common for the solar panel manufacturers to offer a broad range of product models with different size (area), dimensions (length, width), and electrical configurations (nominal current, voltage, and power). The designer of an electro-textile system with solar cells may therefore have several solar module models from which to choose. The choice should be made based on the requirements of the electronic application.

→ **NOTE:** In this handbook, we call both single solar cells and the solar panels of multiple cells, simply solar cells, unless otherwise mentioned.

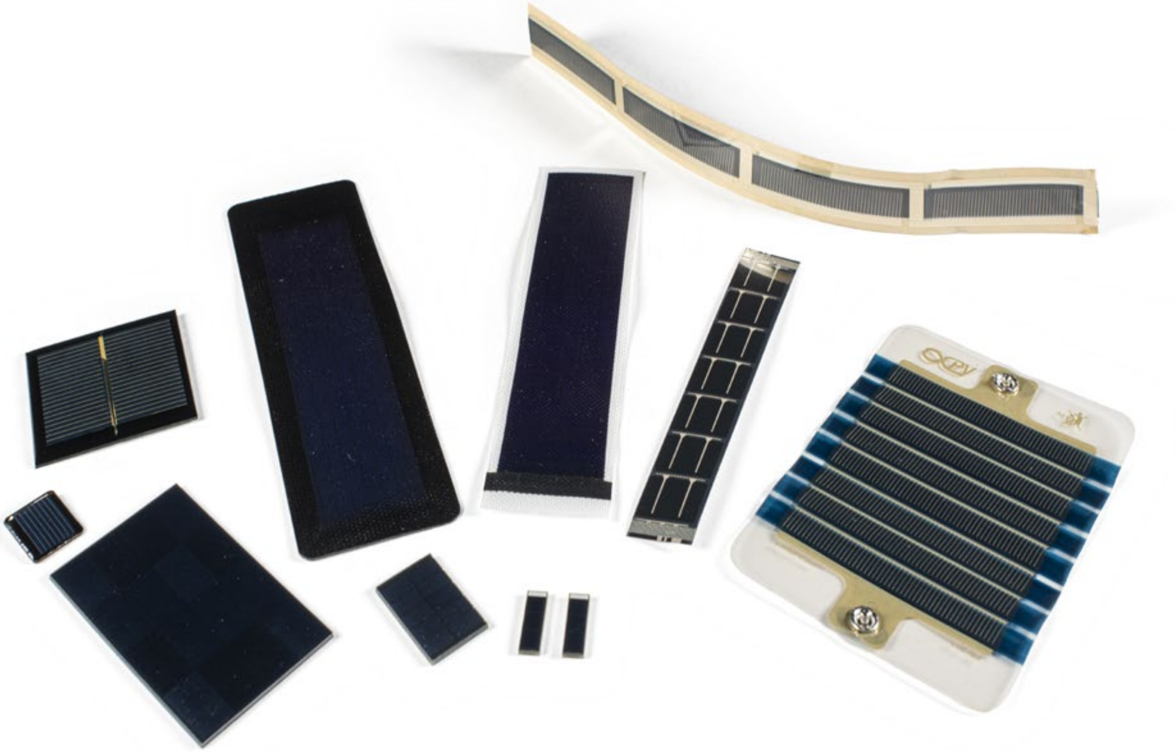
Size

The total area of the solar cells needed for an energy autonomous electro-textile system depends on the power requirements of the application and the illumination conditions where it is used. Fortunately, solar cells are usually available in a wide range of sizes, from as small as a centimetre to several metres, in both rigid and flexible configurations. This results in high design flexibility for textile-integrated solar cells. Naturally, the available area on the textile product sets an upper limit for the size of the solar cell, and may in some cases define whether energy self-sufficiency is possible in practice. Estimating the solar area needed for a given application is therefore a central design problem and is discussed in detail in a later section of this handbook.

The current and voltage of the solar cells depends on how many individual solar cells are in the same solar cell device, called solar panel or module, what type of cells they are, and how they are connected electrically, in series or in parallel. In small solar panels, all the cells are usually series-connected, because that way more voltage can be produced, whereas more current can be simply produced by making the individual cells larger.

Encapsulation

Solar cells are also available in a variety of encapsulations. Rigid solar cells are commonly encapsulated with epoxy resin, as it provides strong resistance to environmental factors. Another common encapsulant in rigid commercial solar cells is glass, which is durable and effective in prolonging the solar cell lifetime even if it can be prone to scratches or cracking in harsh conditions. Rigid encapsulation provides strong protection against external factors, but it is at the expense of flexibility and ease of integration. On the other hand, the active material in flexible solar cells is encapsulated with polymer films, which are transparent and cost-effective, but less durable, and may be prone to delamination at high temperature, for example in washing. Flexible amorphous silicon solar cells are commonly encapsulated with such materials. In addition to their flexibility, polymer films are also very light and thin, making them ideal for product-integration at the expense of long-term durability.



↑ Solar cells suitable for textile integration are commercially available with various technologies, sizes, shapes, weight, thickness, and flexibility. The figure shows examples of two square-shaped rigid multicrystalline silicon solar cells with epoxy sealing (top left), four rigid monocrystalline silicon cells with hard plastic encapsulation (bottom left), three flexible amorphous silicon solar cells from different manufacturers (middle), a flexible organic solar cell (right), and an organic solar cell tape that can be cut to desired length and attached to a surface (top right).

Flexibility

In practice, the flexibility of the solar cell, namely its stiffness and how tightly it can be bent without damaging it, depends also on how it is encapsulated – a sturdier encapsulation makes the cell thicker, less flexible, and also heavier. Note that practically all flexible solar cells can be bent only in one direction at a time, in other words, they can be wrapped around a stick, but not around a ball. This is because, unlike most fabrics, solar cells are not stretchable but only bendable. This is important to keep in mind when designing the placement of solar cells for example on a garment.

Effect of shading and current mismatch

The performance of electrically series-connected solar cells can be significantly affected by partial shading. In the context of textile integration, partial shading can happen if a series of solar cells (or a large solar panel) are placed underneath a fabric that has a colour pattern or structure that shadows some of the underlying solar cells more than the others. This would cause a mismatch

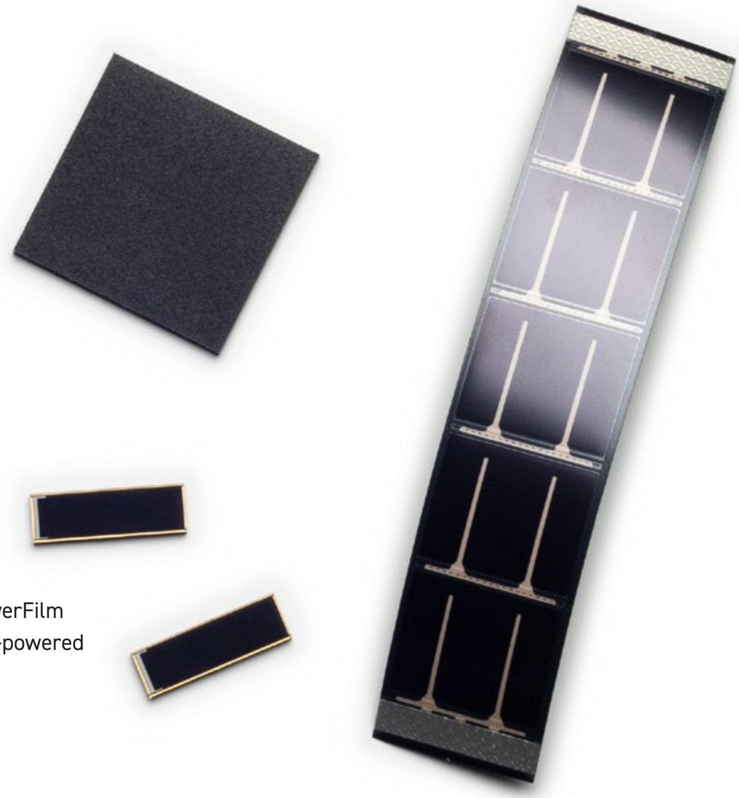
Partial or uneven shading of solar cells by textile can lead to low current production in the whole device. The best solution is to place the cells underneath a textile area that has uniform transparency.

of the output currents: because the current through series-connected electrical components is always equal, the current of all the cells would drop to the same level as in the most shaded cell. In other words, shading just one cell in the series restricts the power output from the other cells too. It is therefore advisable to place the solar cells underneath textile regions that have similar transparency so that they receive roughly the same amount of light. If this is not possible, it is better to add more solar cells through parallel connection, or to add a bypass diode to each solar cell to allow the current of the other cells pass by the shaded cells. Likewise, when connecting multiple solar cells in series, they should all be of the same model, or more specifically, have equal current rating. Correspondingly, if the multiple cells are connected in parallel, they should have the same voltage rating. Otherwise, energy losses from the current or voltage mismatch may occur.

Spectral response of solar cells

In terms of functionality at different illumination conditions, crystalline silicon solar cells are able to absorb a wide range of the solar spectrum. Amorphous silicon solar cells, however, have a limited absorption spectrum, which is strongest in the visible light spectral range. This allows amorphous silicon cells to be more efficient for indoor light (i.e. artificial lighting), while crystalline silicon cells are more efficient for outdoor light (i.e. sunlight). As for textile-covered solar cells, the situation becomes more complex. Coloured textiles absorb light in the visible spectrum, which impacts amorphous silicon cells more than crystalline silicon cells. On the other hand, crystalline silicon cells can absorb light in the near-infrared range, which is usually transmitted through textiles. However, textiles can also be selected based on their transmittance in the visible range to allow using various solar cell technologies.

The spectral matching between the source of illumination, the type of solar cell, and the properties of the textile, is an important factor in the textile integration of solar cells, as it affects both the power output of the solar cell at different use conditions, and its visibility through the textile. The next chapter will therefore dive deeper into this topic.



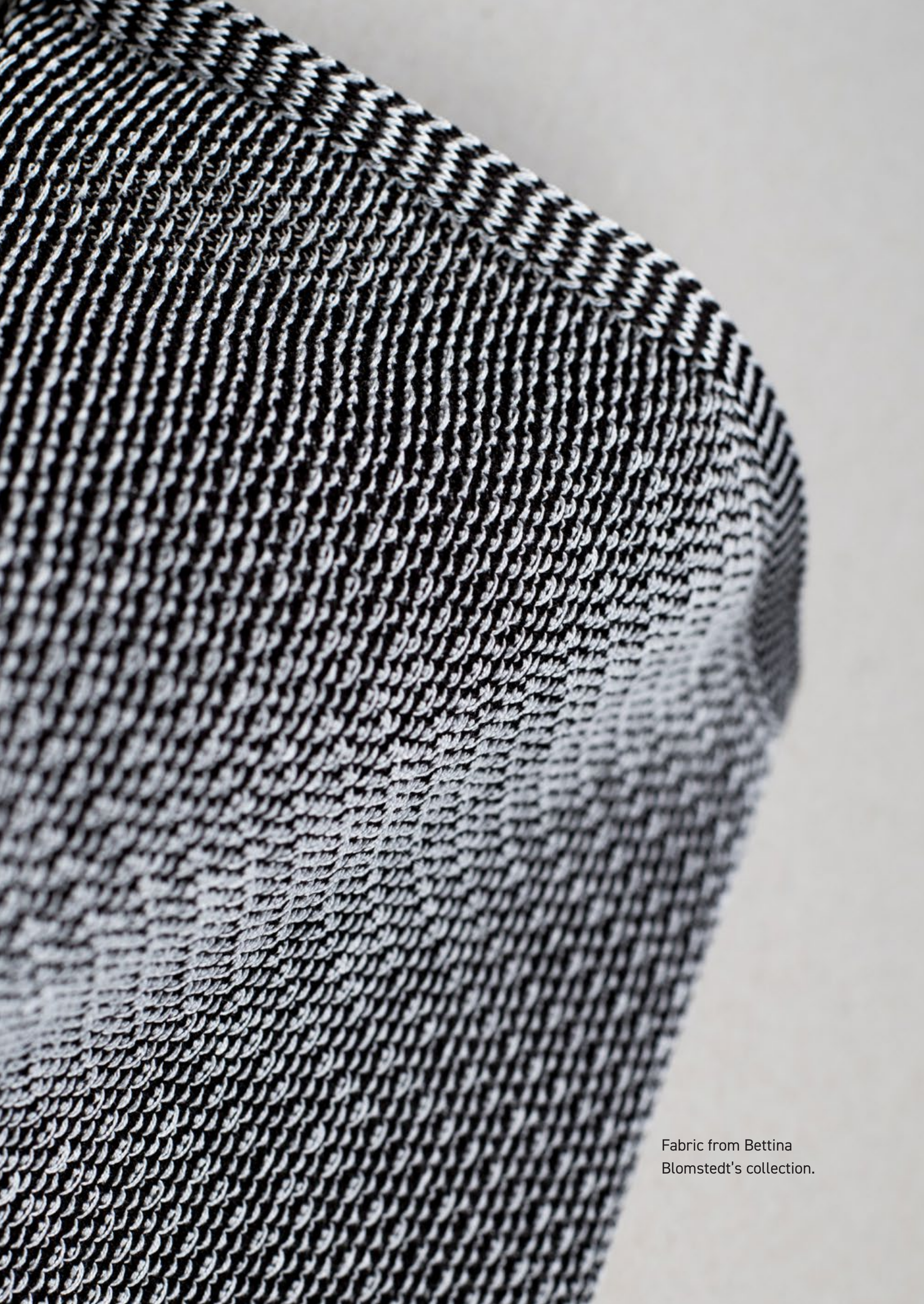
Rigid IXYS and flexible PowerFilm solar cells used in the Sun-powered Textiles project

SOLAR CELLS SELECTED FOR THE SUN-POWERED TEXTILES

Various commercially available solar cells were tested during the project, but the final selection narrowed down to two models:

1) Rigid single crystal silicon solar cells by IXYS (IXOLAR SolarBIT) and
2) Flexible amorphous silicon solar cells by PowerFilm Solar (Electronic Component Solar Panels).

Both were readily available from online electronic stores in various sizes, dimensions, and electrical specifications. The IXYS cells have high efficiency and are particularly suitable for outdoor use because they also use near-infrared light. The PowerFilms were used for demonstrating flexible solar cell integration and were a good choice for indoor lighting conditions provided that the cover textile was transparent enough. In the feasibility calculations, also rigid amorphous silicon solar cells by Panasonic (Amorton) were used. Nevertheless, because an extensive comparison of different manufactures and models was not carried out, other good choices may exist on the market. Organic and dye-sensitised solar cells were ruled out due to their low or uncertain durability, low efficiency, and limited commercial availability.



Fabric from Bettina Blomstedt's collection.

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PERFORMANCE OF TEXTILE-EMBEDDED SOLAR CELLS

When a solar cell is covered with a textile layer, it decreases the amount of light the solar cell receives. How much electric power the solar cell can still produce depends on the source of illumination, the type of the solar cell, and the optical properties of the textile. This chapter explains how these three factors play together and allow the solar cell to work, even when it is visually concealed by the textile, and how different textile properties affect the energy harvesting capacity and visual concealment of the solar cell, and how it can be measured in practice.

Janne Halme

Operating principle of textile-covered solar cells

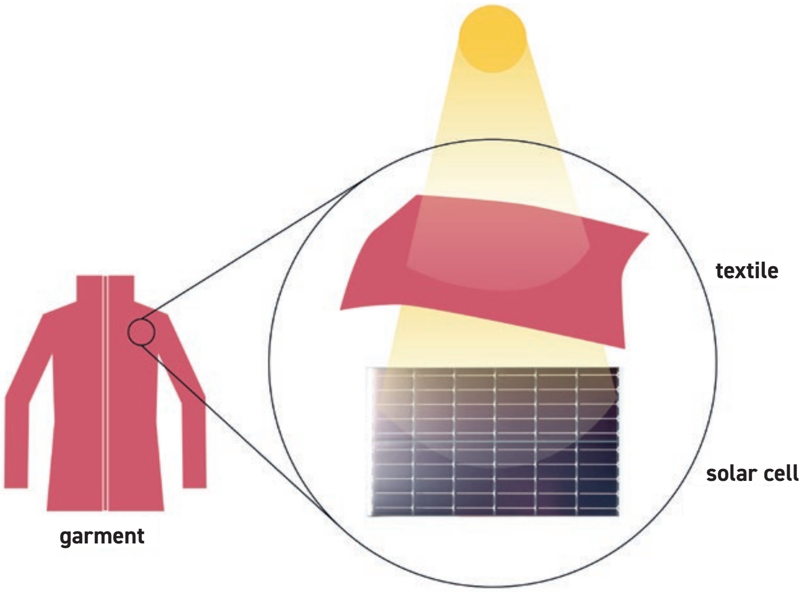
Textile-coated solar cells work like solar cells covered with any coloured film, filter, or coating. Some of the light passes through the optical cover, which in this case is the fabric, and is absorbed into the solar cell beneath it. The same principle is also used in building-integrated photovoltaics (BIPV), where optical coatings, patterns or prints of different colours are used to make black solar panels more suitable for a building façade or otherwise architecturally more appealing. In solar panels meant for building-integration, a coloured coating is applied, for example to the front or back surface of the panel's front glass, or a coloured reflective film is installed between the glass and the solar cells. In solar cells integrated into textiles, the textile itself acts as a coloured optical coating for the cells.

The solar cell behind the optical cover can even be completely hidden visually, but still perform relatively well. Some of the light in the visible wavelength range is reflected from the textile surface, producing the perception of the colour – the more light that is reflected, the lighter the colour of the fabric. Light that is not reflected is either absorbed into, or transmitted through, the fabric. The light absorbed into the fabric is wasted in the sense that it is neither reflected towards the viewer nor does it end up in the solar cell, but, instead, it is converted into heat in the fabric. Ideally, the fabric would absorb light as little as possible and strongly reflect light at visible wavelengths, forming colour, and transmitting the remaining light to the solar cell, which would generate electricity from it.

The following sections discuss the various factors that affect how much electricity a textile-coated solar cell produces. We will first learn about the efficiency of a solar cell and its electrical operation.

HOW IMPORTANT IS SOLAR CELL EFFICIENCY FOR TEXTILE INTEGRATION?

It depends on how much power is needed and how much area is available on the textile product. If a solar cell has lower efficiency, it needs to be bigger than a higher efficiency cell to produce the same amount of power, or else more cells need to be used. If larger solar cell area is not a problem, lower efficiency cells may be fine, and may even be a good choice economically if their cost per rated power is lower (€/W_p). On the other hand, if there is limited space to install the cells, higher efficiency may be a priority over cost. In the case of textile-covered solar cells, it is usually wise to look for the most efficient cells, because the cover textile lowers the power output (efficiency), which increases the area need.



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Power conversion efficiency

Solar cells produce electric power in direct proportion to their size and the amount of light they receive. This proportionality is called power conversion efficiency, PCE, or simply efficiency. The power conversion efficiency tells us how big a fraction of the incoming light the solar cell can convert into electrical power, and it is defined as:

$$\mathrm{PCE} = \frac{P_{\mathrm{max}}}{P_{\mathrm{in}}}$$

where P_{max} is the maximum output power per unit area (W/m^2) produced by the cell and P_{in} is the power intensity of the solar radiation on its surface at that moment, also expressed in W/m^2. The efficiency is a useful quantity for estimating how much power a solar cell might produce under solar illumination.

For example, a small crystalline silicon solar cell might have 15% efficiency. This means that under bright sunlight on a clear blue sky – which has a power intensity of roughly 1000 Watts per square metre (W/m^2) – the solar cell could produce at most 150 W/m^2, or in more practical units for small cells: fifteen milliwatts per square-centimetre, 15 mW/cm^2. This means that, if the solar cell were 2 cm wide and 5 cm long, for example, and therefore had an area of 10 cm^2, the maximum power it could deliver under this illumination would be 150 mW. Maximum means when it would be faced directly to the light and operated with an optimal load (See section Current – voltage curve).

On the other hand, if the same solar cell were measured on an overcast day, receiving 1/10 of the sunlight power compared to the clear sky situation, the solar cell would correspondingly produce only 1/10 of the output power, i.e., 15 mW. In principle, it is as simple as that.

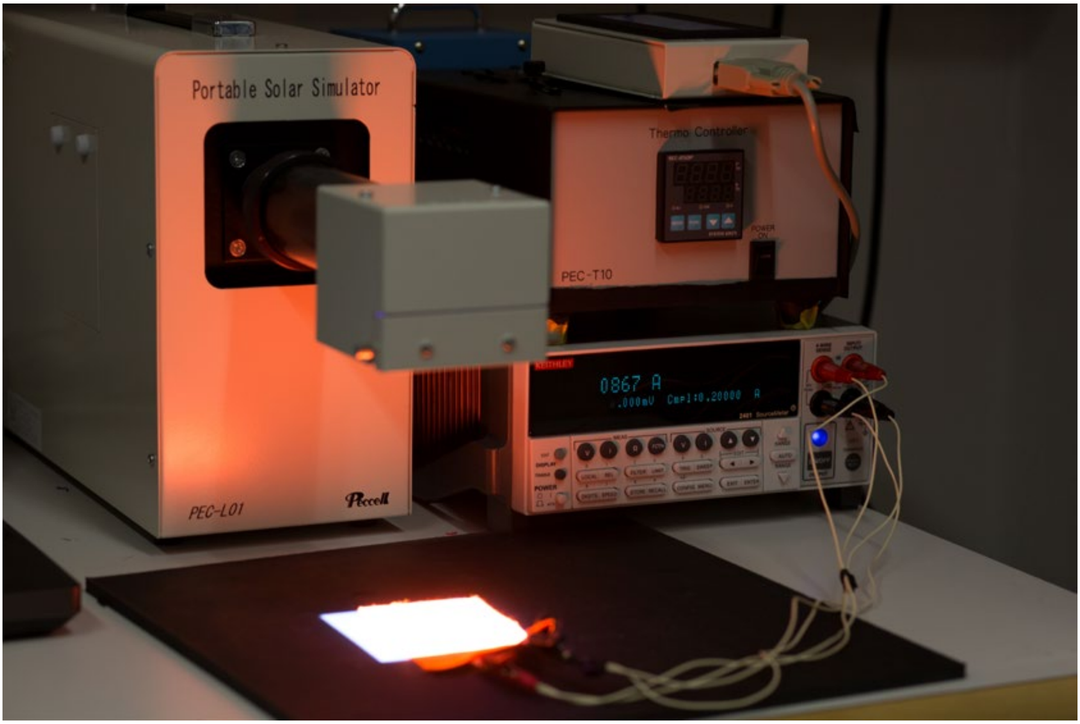
What complicates things, however, is that the solar cell efficiency depends on the intensity and spectral composition of light, the angle of incidence at which the light hits the solar cell surface, and on the temperature of the cell. For this reason, the efficiency is strictly speaking defined only at very specific conditions called standard test conditions (STC), or standard reporting conditions (SRC), which are:

- Standard solar spectrum AM1.5G with total power of 1000 W/m^2
- Solar cell temperature 25°C
- Light is incident perpendicular to the solar cell surface

These conditions can be arranged in a solar cell measurement lab using a calibrated light source called a solar simulator. The solar simulator uses a lamp and optical filters to produce light that mimics sunlight. Measuring the power output of a solar cell in a solar simulator, and knowing the cell area, reveals the efficiency of the solar cell.

However, solar cell manufacturers usually do not give the efficiency in their technical data sheets. Instead, they specify the rated power, or nominal power, called Watt-peak (W_p), which means the power the cell would produce at the standard test conditions. Nevertheless, it is easy to calculate the efficiency from the rated power and area of the cell. For example, if a solar cell has a rated power of 150 mW_p and 10 cm^2 area (using the earlier example), the cell efficiency is (150 mW / 10 cm^2) / 100 mW/cm^2 = 15%. In this way, the efficiency of different solar cell products may be compared.

↓ The solar cell efficiency is measured with a solar simulator. It is a lamp that produces light that mimics sunlight.

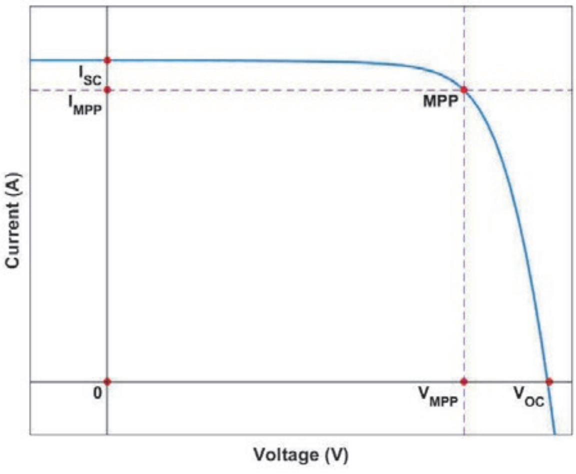


Current – voltage curve

The current – voltage curve is an important characteristic property of a solar cell: it tells all the possible current – voltage points where the cell can operate at that illumination and temperature. This is important because the electric power produced by the cell is the product of current I and voltage V: $P_{out} = IV$. Operating the cell at the point along the IV curve where the product is highest, maximises the power extracted from the solar cell, and allows determining the cell efficiency.

Knowing the current and voltage produced by the cell at the expected operating conditions is also important in deciding the size and number of solar cells needed to power the intended electronic application. The solar cell current and voltage also need to be suitable for the used power harvesting electronics. To help in the design process, the current – voltage performance of a solar cell is expressed in terms of its characteristic IV parameters. The table on the next page introduces these parameters and explains what they mean.

The most important IV parameter is the short-circuit current. It tells the maximum current that the solar cell can produce at certain illumination conditions. It is also the parameter that is most affected when the solar cell is covered with a textile. Covering the solar cell with a textile decreases the current generation in a way that depends on the light source, the solar cell type, and the properties of the textile. The other IV parameters, on the other hand, do not directly depend on these external properties, but instead, they follow from the amount of current generated in the cell. For the design of textile – solar cells integration it is therefore sufficient to understand how the textile cover affects the solar cell current – the effect on the other parameters can be determined by electrical measurements or predicted with a mathematical IV model of the solar cell.



← Current – voltage curve of solar cell. Figure from [Wederhorn 2020].

CURRENT – VOLTAGE CHARACTERISTICS OF SOLAR CELLS

I_{SC} or J_{SC}	**Short-circuit current (mA) or current density (mA/cm^2)** Current or current density produced when the solar cell is in short-circuit (SC) state. At SC, the voltage is zero and the solar cell produces the maximum current it spontaneously can at that illumination. The short-circuit current is directly proportional to the light intensity. This proportionality is the main reason why the power output of the solar cell also increases roughly linearly with light intensity.
V_{OC}	**Open-circuit voltage (V)** Voltage produced when the cell is at open-circuit (OC) state. At OC, the current is zero and the cell produces the maximum voltage it spontaneously can at that illumination. V_{OC} is proportional to the logarithm of light intensity, meaning that at low light it increases rapidly with light intensity but becomes almost constant at high intensities. This is a fundamental feature of all solar cells, but there are also differences in the solar cell materials that make some solar cell types, for example amorphous silicon, better at keeping high V_{OC} at dim light.
MPP	**Maximum power point** The point on the IV curve where the power output of the cell is highest, in other words the product of current and voltage $P = I\,V$ is maximal. It is the optimal point of operating the cell. Because the IV curve changes with light intensity, electronic power management circuits of solar cells often use an MPP tracking circuit to keep the operating point close to its temporal optimum (I_{MPP}, V_{MPP}) even when the light intensity varies.
FF	**Fill factor (%)** Fill factor indicates how close to a rectangular shape the IV curve is. It is defined as $FF = (I_{MPP}\,V_{MPP}) / (I_{SC}\,V_{OC})$. In other words, it represents the ratio of two areas drawn on the IV curve: one defined by the MPP, and the other by the SC and OC points (see figure).
PCE	**Power conversion efficiency (%)** The ratio of the power output of the solar cell and the incoming light power incident on the cell. Strictly defined only at the standard test conditions (STC) of 100 mWcm^2 light intensity, AM1.5G spectrum, 25 °C temperature and perpendicular illumination. The PCE is determined at the MPP, in which the cell produces its maximum power: $\mathrm{PCE} = \frac{P_{out}}{P_{in}} = \frac{P_{MPP}}{P_{in}} = \frac{I_{MPP}V_{MPP}}{P_{in}} = \frac{I_{SC}V_{OC}FF}{P_{in\,per\,area}\,A_{solar\,cell}}$ where $A_{solar\,cell}$ is the area of the solar cell, and the definition of fill factor has been used.

Current generation by textile-covered solar cells

A textile-covered solar cell produces current in direct proportion to how much light the textile transmits. In addition to the amount of light, the current output depends on the spectrum of light, the transmission spectrum of the textile and the spectral response of the solar cell:

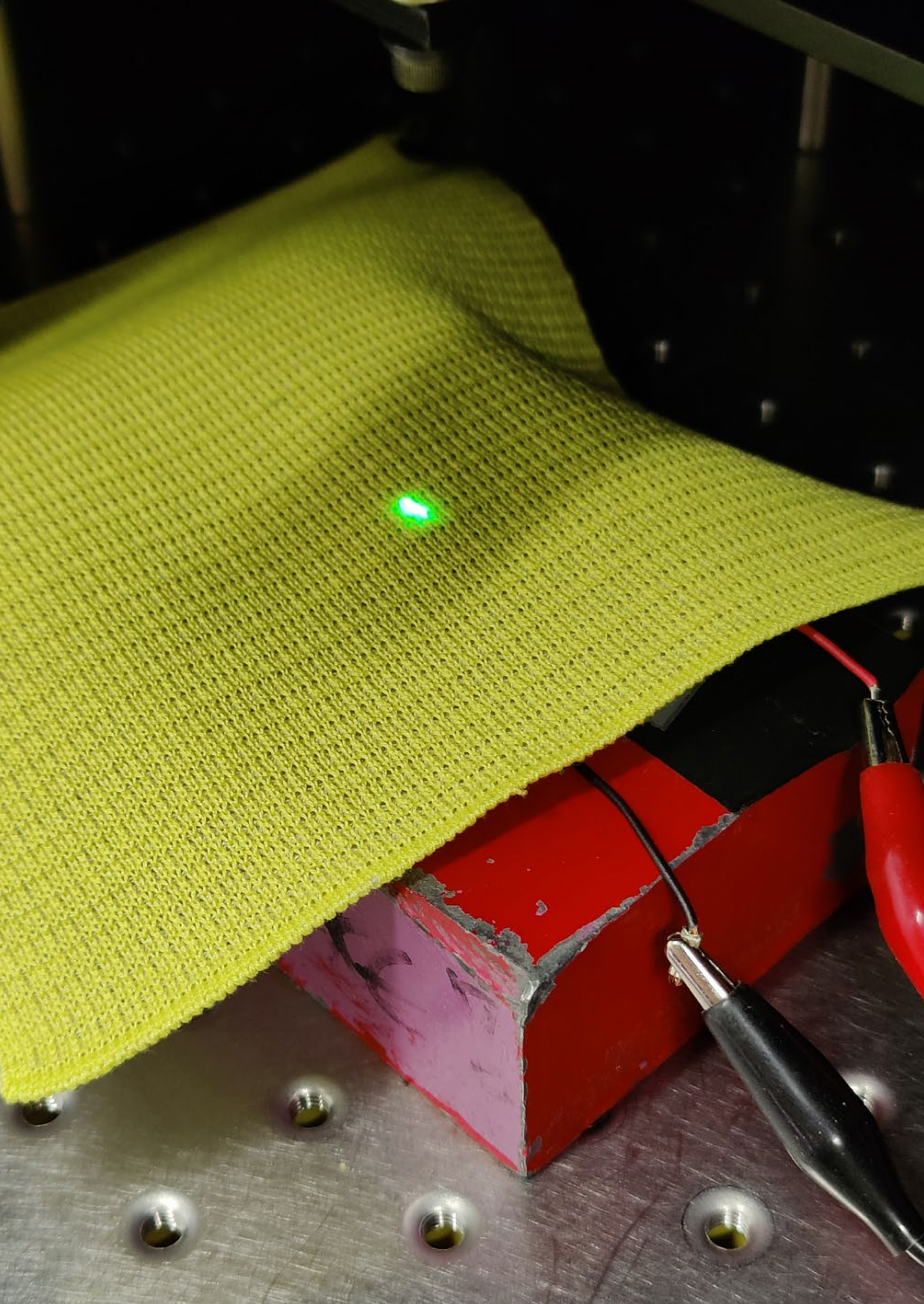
1. The light spectrum $\Phi(\lambda)$ determines the number of photons in the light at different wavelengths λ.
2. The transmission spectrum of the textile $T(\lambda)$, called transmittance, indicates how many of the photons at different wavelengths pass through the textile.
3. The solar cell's spectral response, also called external quantum efficiency EQE(λ), indicates how many of the photons of different wavelengths that hit the cell are absorbed and generate electrical current in it.

The short-circuit current density of the solar cell is obtained by multiplying the three spectral factors with each other and integrating the product over the wavelength range of light, i.e., adding together the contributions from different wavelengths, and multiplying the result by the elementary charge of one electron q:

$$J_{SC} = q \int \Phi(\lambda) T(\lambda) EQE(\lambda) d\lambda$$

The light spectrum can be measured with a spectroradiometer and the textile transmittance with a spectrophotometer. The spectral response of solar cells, in turn, can be measured with purpose-built equipment in which light is split to different spectral parts like in a prism, the resulting rays of different wavelengths are in turn directed at the cell, and the short-circuit current produced by the cell is measured.

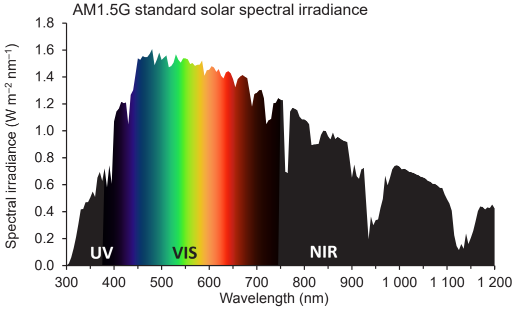
→ Spectral response measurement of textile-covered solar cell. Fabric from Bettina Blomstedt's collection.

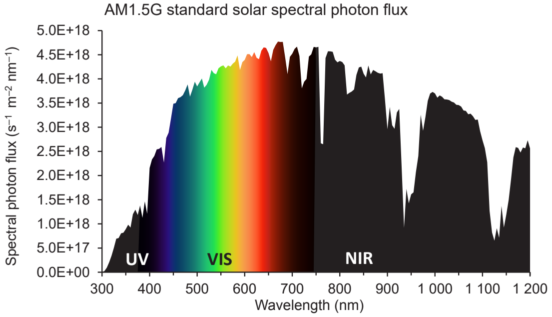


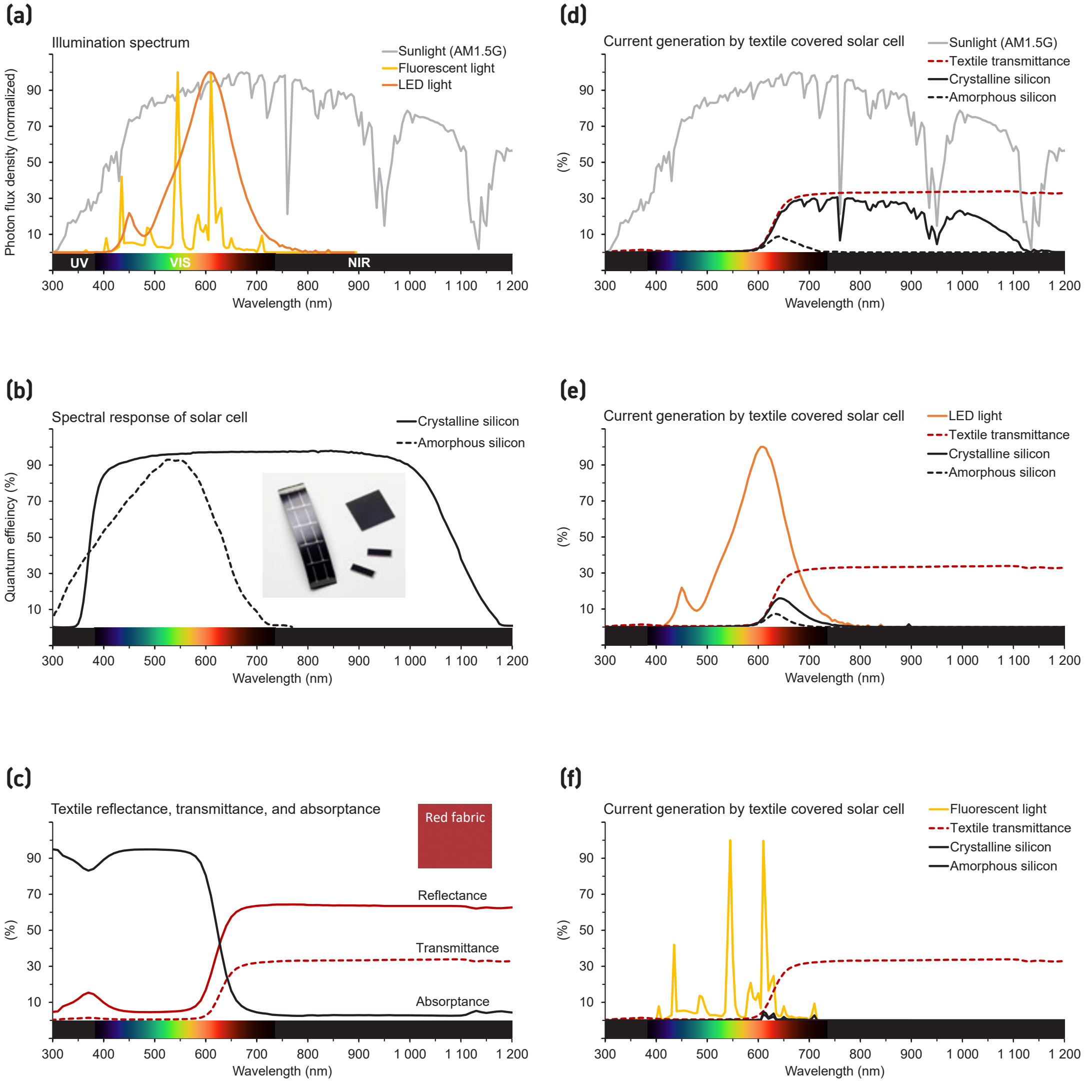
Although these measurements are not necessary in the design of textile solar cells, the design becomes easier if one understands how they together affect the performance of a textile-covered solar cell, according to the above equation. The equation shows that a solar cell produces the most current when its spectral response is high at those wavelengths where the light is abundant with photons. Textile, on the other hand, decreases the solar cell current the least when its transmittance is high at the wavelengths at which the spectral response of the solar cell is at its highest.

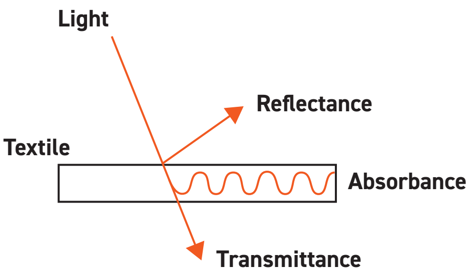
The graphs below illustrate these principles visually. Figure (a) on the following page shows the spectral distribution of natural and artificial light sources. Sunlight is rich in both visible (VIS) light in the 400–700 nm wavelength range and longer-wave near-infrared (NIR) light which is not detected by the human eye. On the other hand, artificial lighting such as LED and fluorescent light consists only of visible light. If we compare this to the spectral response of solar cells (b), we see that crystalline silicon cells (c-Si) are able to use both

The power intensity and the number of photons in sunlight depends on the light wavelength λ. The power distribution is called spectral irradiance and the number distribution is called spectral photon flux. They differ by the energy of one photon which is also dependent on light wavelength, being proportional to 1/λ. Of the sunlight photons attainable for photovoltaic conversion by crystalline silicon solar cells 3% is in the ultraviolet (below 400 nm), 41% in the visible (400–700 nm) and 56% in the near-infrared (700–1200 nm) region.

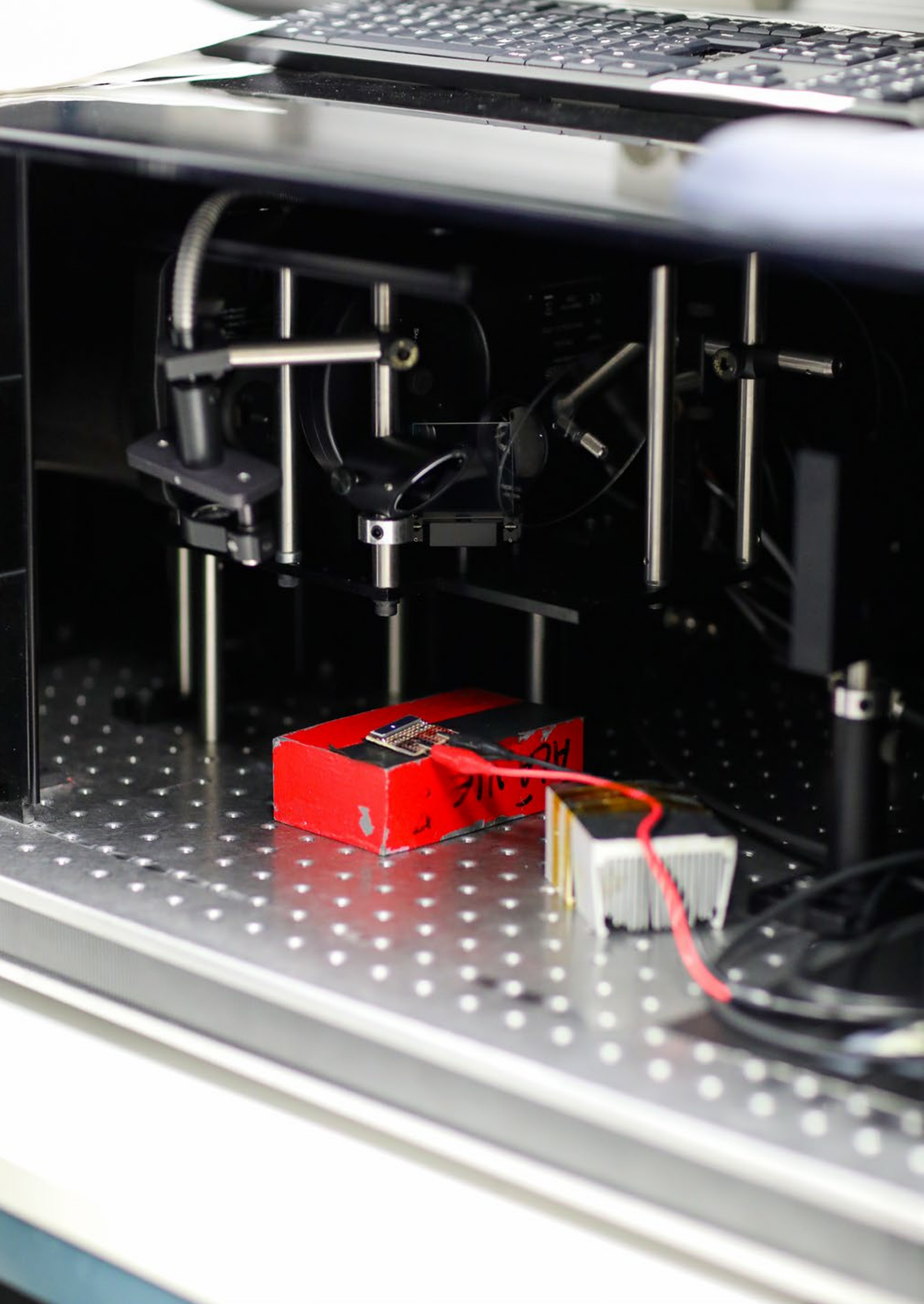








The spectral properties of light, solar cells, and textiles jointly determine the amount of electric current generated by textile-covered solar cells.



visible light and near-infrared light, up to 1200 nm, whereas amorphous silicon cells (a-Si) use only visible light, up to 700 nm. This means that they both may work well with artificial illumination, though the crystalline silicon cell utilises the outdoor sunlight more effectively. The effect of a coloured cover textile on both types of cells can be understood by keeping this in mind.

A typical coloured textile, for example a dark red workwear fabric shown in the figure (c) Foxa Action Jaguar 4156 Red*), transmits ca. 34% of the NIR light, but very little VIS light due its dark colour. Therefore, we can expect that under artificial lighting, an a-Si cell would generate only small amounts of current – originating from the small amounts of red light that can pass through the fabric unabsorbed – whereas a c-Si cell would generate current also from the NIR light.

We can see this more clearly in figure (d). The black curves show the product $\Phi(\lambda)T(\lambda)EQE(\lambda)$ for the two cells, in relative terms. The area under these curves represents the amount of current produced, and we can see that it is much larger for the c-Si than for the a-Si cell. We can also see how the transmittance of the cover fabric cuts the current production by determining how much light at different wavelengths can pass through the fabric to the cell. In this case, the amount is negligible below 600 nm because blue, green and yellow wavelengths are effectively absorbed by the red dye in the fabric. For the same reason, only red visible light (and NIR light) is effectively reflected by the fabric, which gives it the red colour.

Under LED lighting, figure (e), curves of the light and textile transmittance spectra only overlap to a small degree, which means that only a little red light becomes available for the underlying solar cells. Of this light, the c-Si cells produce more current than the s-Si cell, due to higher EQE in the 600–800 nm region. The situation is similar with the fluorescent lighting, figure (f), but the current production is even lower because in the fluorescent lighting there are hardly any photons in the 650–700 nm region where the textile transmittance would be high.

This example shows how important the spectral properties of light, solar cells, and textiles are for the design of solar cell integration into textiles. By correctly choosing a suitable textile – solar cell combination for the intended use conditions, sufficient energy harvesting capability can be ensured for an e-textile product.

* 74% PES, 26% PU, Oxford, 220 g/m^2, Soil and water repellent.

Janne Halme

Measuring energy harvesting capacity

Measuring the spectral properties of light, solar cells and textiles are important for understanding how a cover textile affects the solar cell performance, and necessary for the systematic design of optimised solar cell textiles. Nevertheless, simple electrical measurements are often sufficient to guide a practical design process, or to screen a large number of textiles for their suitability. The energy harvesting capacity of a solar cell, with or without a textile cover can be easily measured with a multimeter and a light meter.

Multimeter

Multimeters are handheld devices used for current, voltage, and resistance measurement. They are available in most hardware stores and can be used for testing all kinds of electrical and electronic devices and components. For testing textile solar cells, a model with high enough sensitivity for measuring the low currents produced by the solar cells, in the common use conditions, is needed. A good choice is a meter with 0.1 microampere, or lower current measurement resolution. To guide the choice, one can compare the multimeter resolution with the technical specifications for the solar cell's current at different lux levels. The lowest current resolution value should be ca. 100 times lower than the current of a bare solar cell, to ensure accurate readings even when the cell is covered by a textile. Voltage resolution is less of an issue; practically all multimeters have sufficient accuracy for measuring typical solar cell voltages that range from a few hundreds of millivolts to a few volts.

The multimeter measures the short-circuit current I_{SC} and the open circuit voltage V_{OC}. Multiplying the product with the fill factor FF gives an estimate of the maximum power output the solar cell would produce in that situation:

$$P_{out} = I_{SC} V_{OC} FF$$

For example, if I_{SC} = 50 µA, V_{OC} = 1.5 V, and FF = 0.60, the maximum power output is P_{out} = 45 µW (microwatts). Note that using the *FF* value from the manufacturer is an approximation. The real *FF* value can be somewhat smaller due to resistance losses in the electrical contacts and leads. Also, if a solar cell specified for indoor use is measured outdoors in bright sunlight, the *FF* value can be very low. To confirm the *FF* value, a current – voltage (IV) curve would need to be measured as described in the earlier section. In the field conditions, the IV curve may be measured with the help of a variable resistor connected in series with the cell. Collecting current and voltage readings for different resistance values generates an IV curve from which the *FF* can be calculated.

Light meter

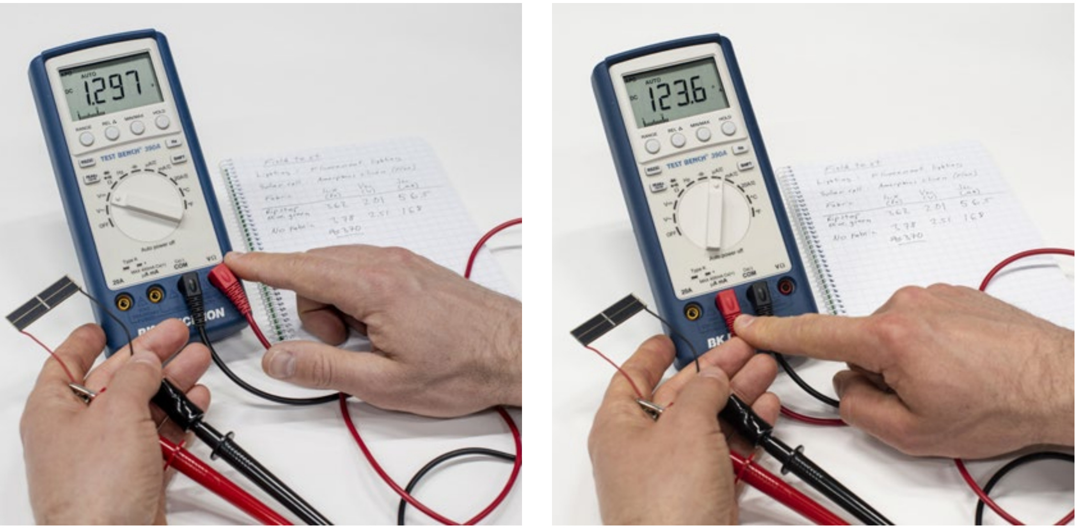
Because the solar cell current and voltage depend on the light intensity, a light meter is also needed to make the results comparable. A light meter, also called an illuminance meter or a lux meter, measures the visible light intensity which is called illuminance (units lux, lx). It describes how bright a light spread over a given area is to a human eye. Although lux meters are mainly used for measuring indoor lighting, they can also be used outdoors if the measurement range of the meter allows that. Indoor lighting ranges from 100 lx to 1000 lx, common values being 200–500 lx, whereas bright sunlight can be more than 120 000 lx. The main reason for the light measurements is to establish a point of reference. For indoor conditions, it is common to document the results at 200, 500 and 1000 lx. A room with dimmable lighting would be ideal, but the illuminance may also be adjusted by finding a suitable place in the room that gives the target lux value with reasonable accuracy. Smartphones may have built-in light meters and apps for them, which can be an adequate low-cost method.

Another way to establish an illuminance reference is to use one solar cell as a reference device. Adjusting the light intensity so that the reference cell produces the same current as it did in another measurement, tells us that the cell is receiving the same amount of light, and hence, the illumination conditions are similar. This works reliably only if the illumination source stays the same, for example if it is sunlight or fluorescent light. If the illumination source is different, the same solar cell can produce a different current even though the illuminance (lux) is the same. This is because the spectral response of solar cells, which determines the current, differs from the spectral sensitivity of the human eye, which determines the illuminance.

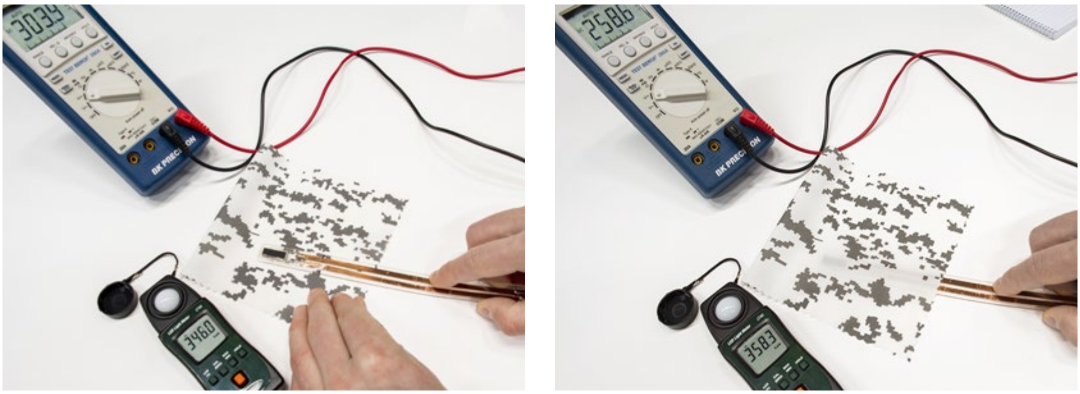
If the textile solar cells are designed for a specific indoor location, the designer may find it useful to purchase the same type of luminaries as used in that environment and set up a test bench where measurements can be taken in a controlled and reproducible way. Otherwise, field tests in different buildings and outdoors are recommended. Outdoor measurements are naturally subject to variation in light intensity, due to the time of day and weather. Shadows and reflections from the surroundings may complicate things further. It is for this very reason that photovoltaics research laboratories use a solar simulator for solar cell testing. Nevertheless, a clear sunny day works well if the illuminance or power intensity of the sunlight on the measurement platform is recorded every now and then. Small changes in the intensity may be corrected by tilting the measurement surface towards or away from the sun. Indeed, when taking measurements, remember that the amount of light falling on the solar cell surface, and hence the amount of current produced, depends on the solar cell's orientation with respect to the light source.

These simple measurements are an easy way to build a data library of the energy harvesting capabilities of textile-covered solar cells. Comparing the data with the power needs of an electronic application may be all that is needed to find a suitable textile – solar cell combination for an e-textile product.

↓ A multimeter can be used to measure the solar cell voltage (left) and current (right) at different illumination conditions.



↑ Testing the effect of cover textile on the solar cell current and voltage with a multimeter and a light meter. While measuring, care should be taken not to shadow the light meter or the solar cell when taking the readings. Errors are easily produced even by soft shadows cast by the measurer. Observe how moving around the test area affects the readings and try to arrange uniform and constant illuminance on the test area. (In the figure above, the multimeter and the person taking notes is too close to the measurement area – it is for illustrative purposes only). Note also that the studied textile must be placed in direct contact with the solar cell. Otherwise the fabric can act as a diffused light source that scatters light from a larger fabric area to the underlying small cell, increasing its current.



↑ If the studied textile is not uniformly coloured or has structural variations, it is good to take readings from different locations to have an idea of the variation in transmittance and its effect in the solar cell performance. Patterned textiles can be problematic for solar cells that have multiple individual cells in series, because the current is determined by the cell that receives least light.

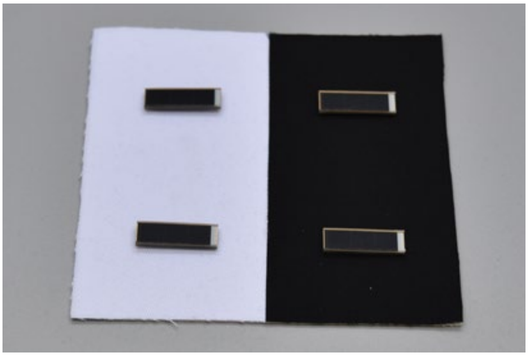
Janne Halme

Measuring visual concealment and colour

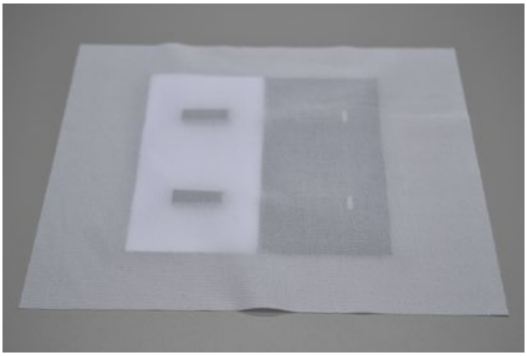
Integrating solar cells into textile requires considering both energetic and aesthetic qualities. The energetic performance can be determined by electrical and illumination measurements, as shown in the previous section, but there are no objective methods for measuring aesthetic qualities. Nevertheless, it is still possible to systematically evaluate the concealment capability of solar cell cover textiles, both qualitatively and quantitatively.

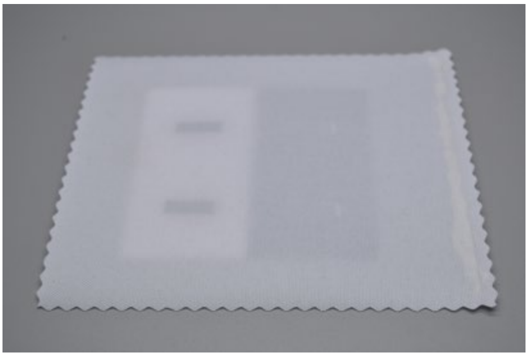
First of all, it is straightforward to simply cover a solar cell with various fabrics to see how the textile might conceal the solar cell. We soon see that the concealment is greatly affected not only by the opacity of the textile but also by the colour contrast between the solar cell and the background textile, which, for instance, may be a liner fabric in a garment. To put it on a more systematic basis, a handy tool for the visual evaluation can be made by glueing black and white fabric on a cardboard sheet, and then some solar cells on its black and white sides. At the same time, electrical wires may be attached to the solar cells for taking electrical measurements at the same time, as explained in the next section. It is easy and quick to screen and rank the concealment capability of a large number of candidate textiles with the black and white test card.

The concealment test card method can be used systematically by photographing the textile samples against the black and white test card at controlled illumination conditions. It is possible to compare different photos that have been taken in different photography sessions by calibrating the photos with a camera profile created with a colour target. The fabric colour can be extracted from the digital image with an image processing software, by averaging the colour pixels in the image over an area that is sufficiently large to be a representative sample of the textile structure. The colour coordinates extracted from the regions with black and white background can then be compared quantitatively by calculating a colour difference metric. The most used and recommended metric is the CIEDE2000 ΔE^* colour difference. Its value between two colours can be calculated with an online calculator, a suitable image processing software or with scientific software packages. Based on the ΔE^* value, different textiles can be ranked in terms of how capable they are of



The cover textile's capability to conceal a solar cell can be visually evaluated by covering the cells against a black and white background. The photo series shows increasing concealment by increasing thickness and coloration of the fabric.





decreasing the colour contrast between an object and its background and in that way concealing objects behind the fabric. The extracted colour coordinates themselves also tell how much the colour of a fabric shifts when a black solar cell, or a black liner fabric is placed behind it, compared to if the liner were white. This too can be an important factor in the solar cell textile design.

Colorimetric photography of the concealment capability of a textile. The textile sample is photographed over a black and white test card, next to a colour checker passport that provides the colour calibration of the digital images for reproducibility of the results.

Colorimetric measurement of fluorescent textiles

In addition to digital photography, the colour of a textile may be measured with a colour metre, or with a spectrophotometer. Both methods were tried in the Sun-powered Textiles project, however, they turned out to be unsuitable for the colorimetric analysis of fluorescent textiles, which were of importance in the project. Fluorescent orange and yellow fabrics are used in high-visibility workwear, and also optical brighteners used in many white fabrics are fluorescent dyes. Fluorescent dyes absorb short-wavelength radiation and emit it at longer wavelengths. For this reason, fluorescent colour can be very sensitive to the spectral composition of light under which it is measured or observed. For example, the UV light in sunlight amplifies fluorescent colours because the fluorescent dye absorbs invisible UV light and re-emits it as visible light. For this reason, it would be best to evaluate and measure the colour of fluorescent textiles under the illumination condition in which it is intended to be used. The light source used in a colour metre or a spectrophotometer is often unknown and may have a spectral composition that distorts the results. Colour-calibrated digital photography under realistic illumination conditions was found to be the most reliable method for colorimetric analysis of fluorescent textiles and their concealment capability.

Fluorescent colors are common in high-visibility workwear fabrics.

Janne Halme, Bettina Blomstedt and Farid Elsehrawy

Effect of textile property on the energy harvesting capability

One challenge for a designer of textile-covered solar cells is to find the balance between transparency and coverage of the textile. To harvest as much energy as possible, the textile needs to be transparent enough to allow the light to penetrate it, but to ensure the concealment of the technology, the textile needs to be opaque enough to cover the technology beneath it. The level of coverage needed depends on the preferences of the end-user and product use. It is important to remember that high levels of light transmittance come at the cost of visual appearance of the cell through the textile.

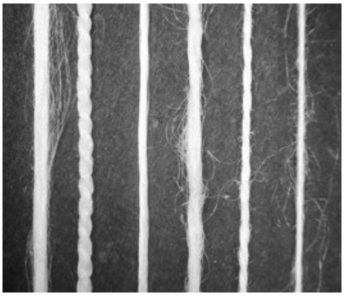
The reflectance, transmittance and absorbance of light by an object determines how the object is perceived. When it comes to textiles, the three actions of light are determined by a multitude of variables that constitute a textile. Textiles are complex materials consisting of fibres spun into yarns and further constructed into textiles. Light is affected by a number of aspects, including: the physical and chemical structure of a fibre, various finishing treatments and processes the fibre has gone through, and the three-dimensional design of the textile, i.e., the way in which the yarns create the textile. Each variable adds to the complexity of the analysis of the optical properties of textile fibres.

As light falls on a textile fibre, it may be transmitted into the fibre and reflected off the internal surfaces of the fibre, thus creating a stronger reflection. The cross section of a textile fibre determines how light is reflected from the fibre surface. A round cross section creates a smooth lateral fibre surface which reflects light seemingly in one direction, thus creating a lustrous yarn. On the contrary, a fibre with an uneven cross section and lateral fibre surface scatters the light and creates a dull appearance.

→ Fabrics from Zuzana Zmateková's collections.

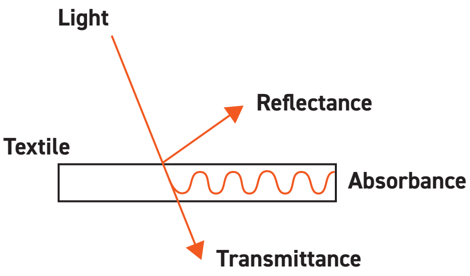
VARIABLES AFFECTING THE TRANSMITTANCE OF LIGHT

Fibre
Origin
Composition
Finishing treatments (chemical and mechanical



Yarn
Size
Colour
Composition
Finishing treatments (texturing, dyeing, bleaching, etc.)

Knitted structure
Knit density
Thickness
Fabric weight

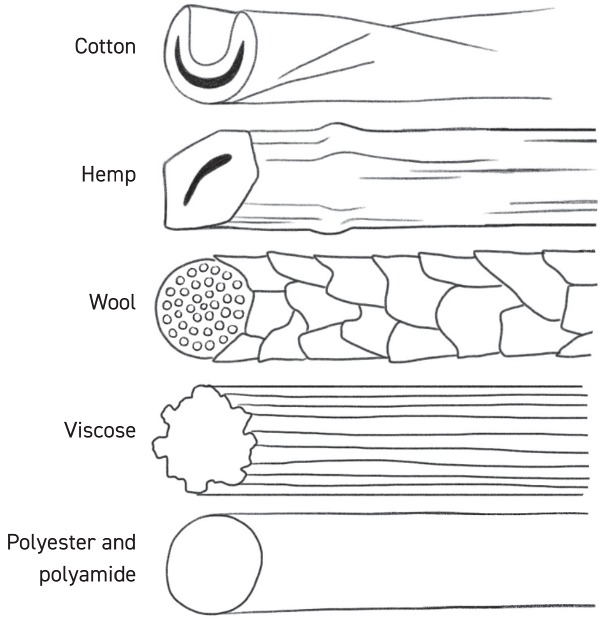


As fibres are processed into yarns, they go through various mechanical and chemical finishing treatments in order to improve the properties of the fibre, for instance, the lustre, friction, hand and durability, to mention just a few. The processes vary depending on fibre origin and end-use goals. The processes have a significant impact on the optical properties of textiles since they directly affect the surfaces of the fibres and therefore the yarn and the final textile. For instance, the smoothness of a yarn is affected by mechanical processes such as singeing and twisting, whereas chemical treatments, such as bleaching and optical brighteners, affect the reflection and scattering of light from the fibre and yarn surface.

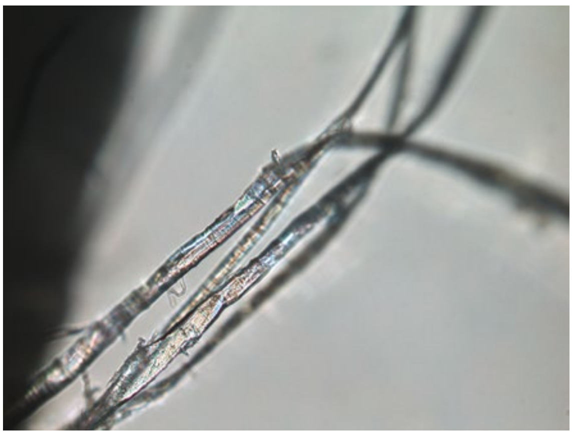
Fabrics from Zuzana Zmateková's collection.

←↓ Different textile fibre materials: a photograph of knit structures and drawings of the fibre cross-sections and shape.

← Interlock structure in all materials



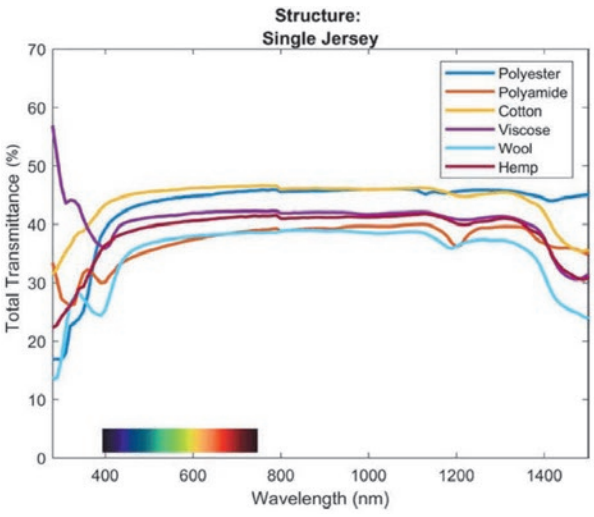
↓ A microscopy image of a hemp fibre.



Textile materials

A great variety can be found within textile materials. The numerous combinations of fibres, yarns and structures create a vast number of variables for a designer to play with. Textile fibres themselves also vary, even when they are made of the same raw material. For example, cotton fibres vary in length and can create many different kinds of yarns. Similarly, wool fibres vary in thickness and thus create numerous options in yarns.

There are two main groups of textile fibres in the garment industry: natural and man-made fibre. The origin of a textile fibre determines its physical and chemical structure, surface appearance and cross section. Natural fibres are limited to the way nature has designed them, whereas man-made fibres can be designed according to the desired properties and end-use requirements. The differences between textile fibres affect their transmittance of light, which informs their suitability for covering solar cells. In order to choose the best fibre and yarn for a design concept, it is important to know the raw material of the yarn and which processes it has been through.



Transmittance spectra of Single Jersey knits with different yarn materials. The material affects mainly the overall transmittance value and less its spectral shape. However, since the yarn material also affects the knitting process, the effect from the material and the textile structure are interrelated and cannot be easily distinguished.

Textile structure

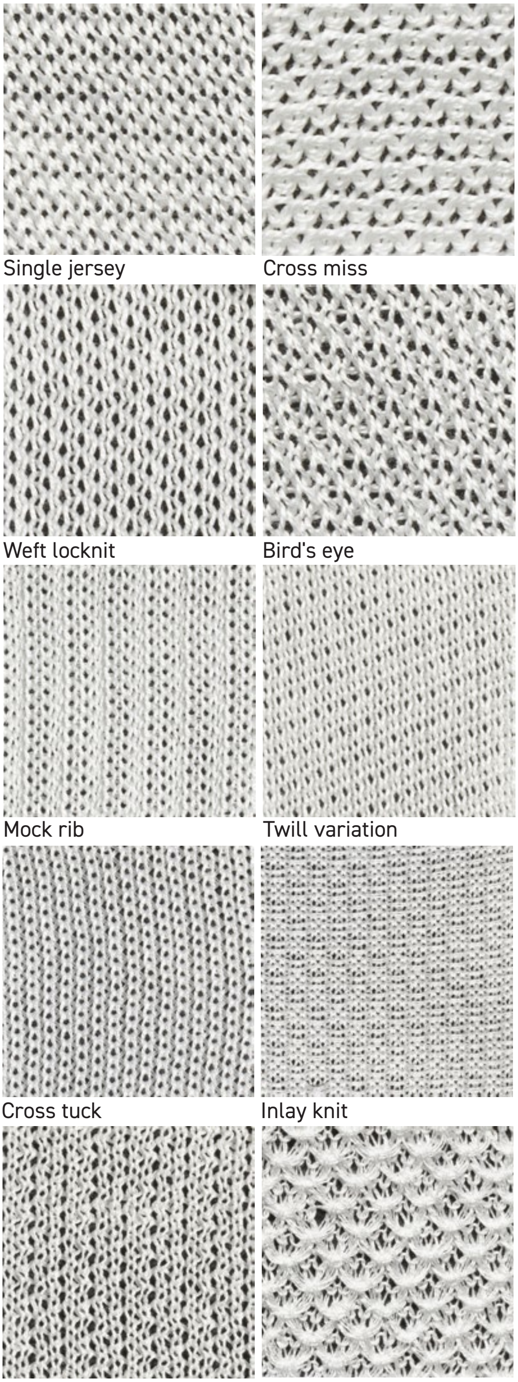
In addition to choosing a raw material and a yarn, the three-dimensional character of the textile structure must also be considered. As mentioned earlier in the handbook, the optimal textile structure should let the light through to the solar cell, while simultaneously covering the solar cell and concealing it from immediate sight. By concealing the solar cell visually, the product aesthetics can be determined not by the aesthetics of the technology, but rather by the designer.

The density and thickness of a textile structure affects its light transmittance. The denser the structure is, the harder it is for light to penetrate through the fabric onto the underlying solar cell. Hence, if the textile structure is dense and does not have gaps between the yarns, it can be hard for light to penetrate it even if the textile is thin.

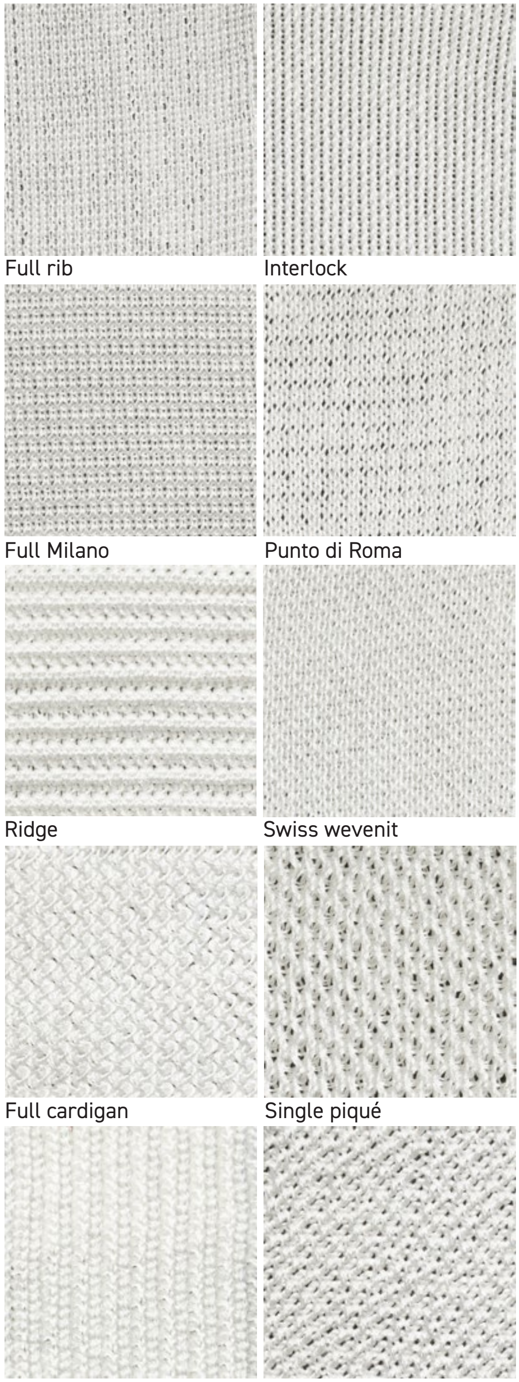
Integration of electronics to the clothes always adds weight to the system. The textile product must be able to carry the extra weight without changing the form in use. It can be affected by material technology, structure, and weight, but also by garment design. For example, too heavy knitted fabric with electronics tends to stretch and deform the textile product.

→ Different knit textile structures: ten single-bed and ten double-bed structures. Knit textile structures from Single jersey to Cellular blister are single-bed structures and from Full rib to Tech knit double-bed structures. The double-bed structures are thicker or denser with smaller openness factor, and hence, less transparent, which can be seen from the photographs taken against a black background.

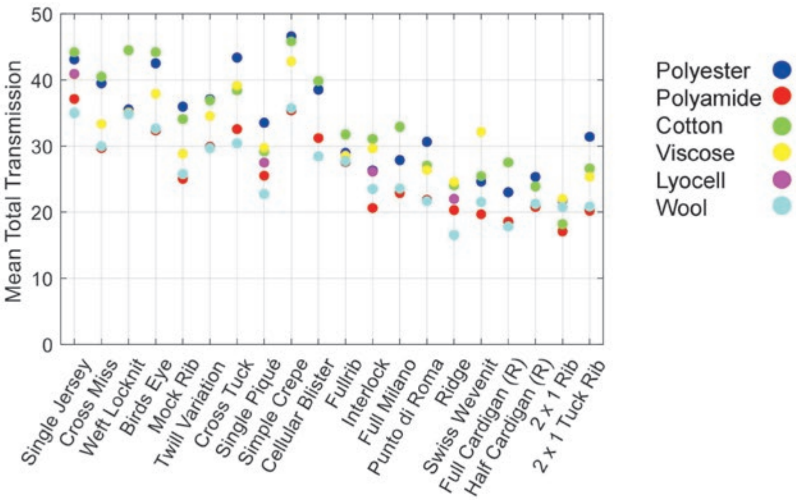
Single-bed structures



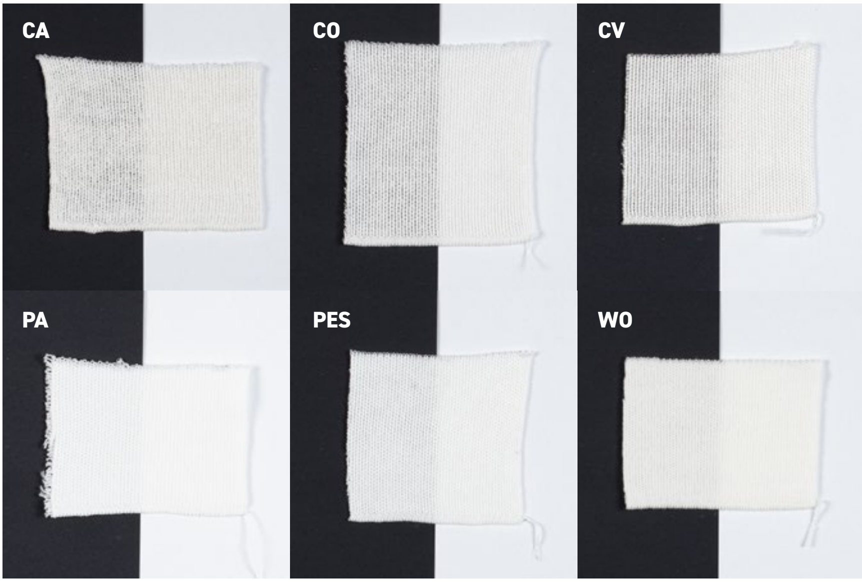
Double-bed structures

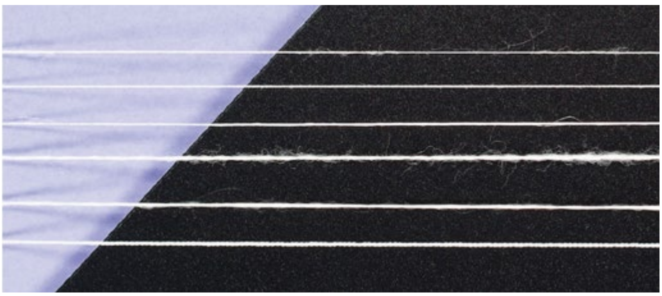


↑ The openness of the textile structure is the most important factor affecting textile transmittance. The openness factor, meaning the fraction of the surface area through which light can go straight through, can be determined from a microscope or a macro photography image by increasing the contrast to maximum and calculating the share of the white and black regions.

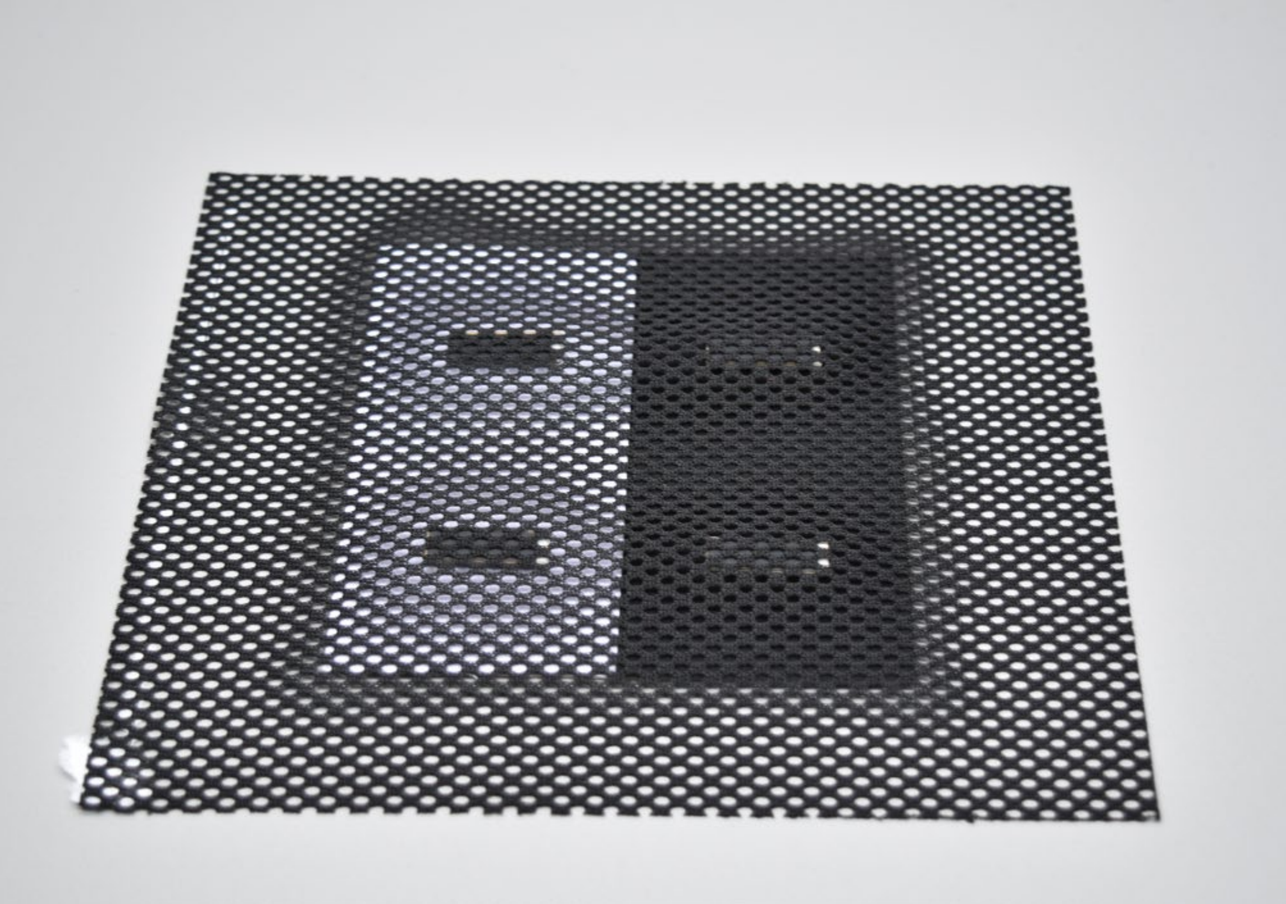


↑ For white fabrics, the mean (average) transmittance over the whole measured spectral range is a good indicator for both visual transparency and the amount of useful light reaching the solar cell, because the spectral transmittance of white fabrics is almost flat. The figure shows the result for 20 knit structures of different yarn materials. The single bed structures (leftmost 10) have higher transmittance than the denser or thicker double bed structures (rightmost 10).





Opacity of knits with the interlock structure. The concealment capability of a textile structure depends also on the yarn material. The yarns behave differently depending on their mechanical properties such as stretching and surface friction in the knitting process which can lead to different knit density. Also thickness and hairiness of the yarn affects opacity and openness of the fabric



Thickness and structure are more important than colour for the transmittance and concealing capability of the textile. Example of a black fabric with high transmittance and a white fabric with low transmittance.

Colour

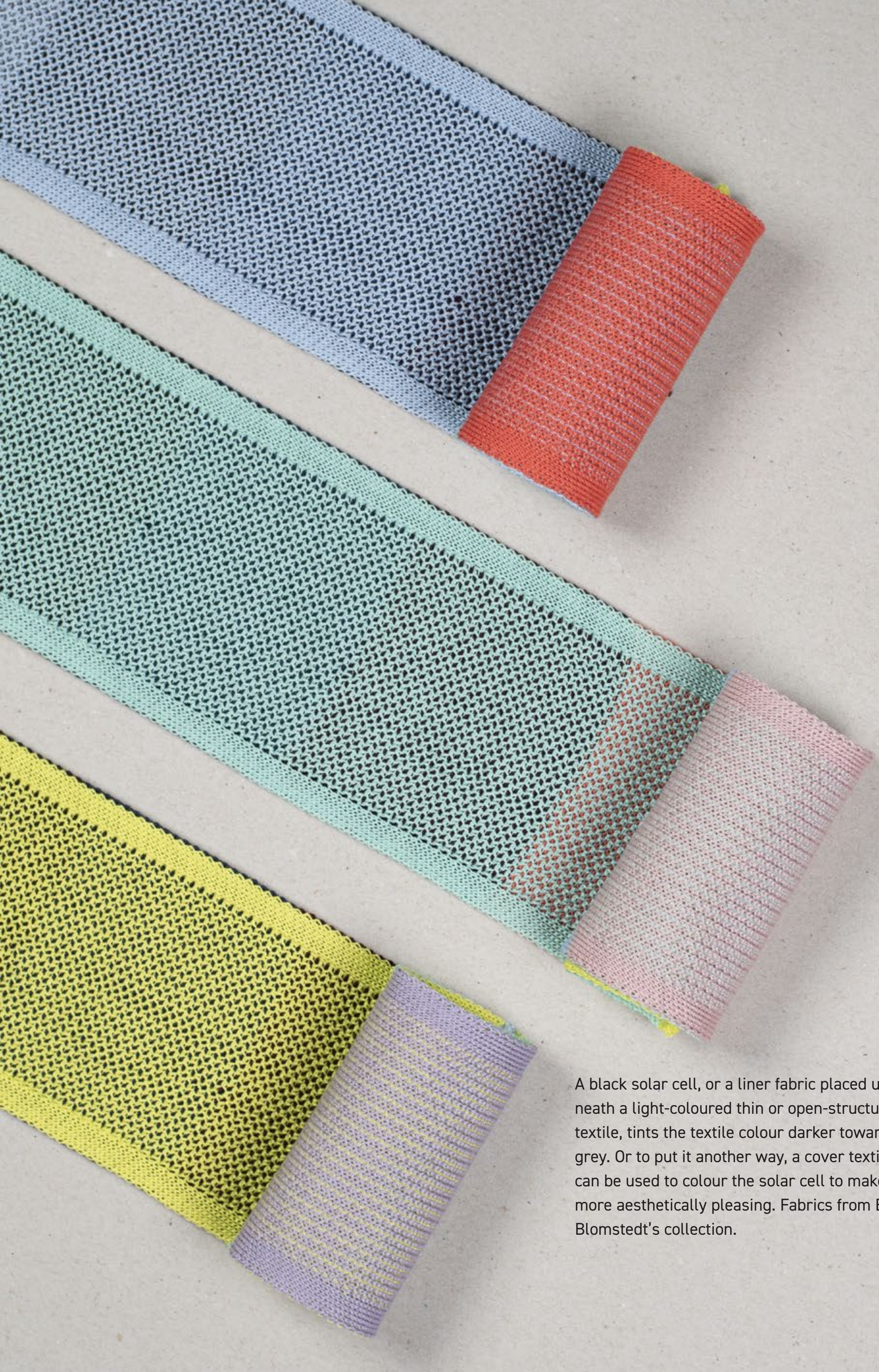
Colour has obviously a big impact on the transmittance of light through a textile. The darker the colour, the less light is transmitted. However, the matter is more complex than this. The thickness and openness of a textile are directly linked to the transmittance of light and have a bigger impact than the colour alone. This means that a black fabric that is thin or has an open structure, may have higher transmittance than a thick or dense, light-coloured fabric.

Two different types of black dyes or pigments are used in textiles: synthetic organic dyes which absorb in the whole visible wavelength range but not in the near-infrared (NIR) region, and carbon black dyes which absorb both in the visible and in the near-infrared region. The synthetic dyes are better for the solar cell application because they allow the NIR sunlight to pass through to the solar cell, where they can generate current if the cell is of the NIR sensitive type like crystalline silicon. Checking which type of black dye a textile has, requires measuring its transmittance spectrum. However, one can get an idea by also testing different black fabrics in sunlight, with the crystalline silicon cells: if two fabrics are equally opaque as seen by the eye, but the other solar cell works much better, it probably has the synthetic black dyes and the other carbon black dyes. Also, other colour dyes that have a sharp onset of absorption at the edge, between visible and near-infrared wavelengths, are preferable for the same reason.

The relative importance of textile colour and thickness depends on the desired outcome and end-product. For example, if the colour is the most important factor and it should be for example a dark navy blue, then the textile structure should be as thin or as open or loose as possible to provide maximum transmittance. On the other hand, if the durability of the textile is the most important factor, using a sleek polyester yarn may allow choosing a denser and heavier fabric, especially if the yarn colour is light. And if the energy harvesting capacity is the priority, a thin and light-coloured fabric or a fabric with an open structure works best. Such a fabric has low opacity and concealment capability, however, prioritising the power generation and high concealment, the designer may consciously consider using colours that are mixtures of light colours and black - because this is in effect what happens when a highly transparent textile is placed over a black solar cell. The concealment can then be reached by using a black liner fabric which camouflages the solar cell against the dark background, whereas the textile structure blurs its shape.

Here are other observations about the effect of the textile properties on the energy harvesting capacity of a solar cell, that were also made in the Sun-powered Textiles project:

- A transparent thermoplastic polyurethane (TPU) coating on the reverse side of a fabric does not significantly affect the textile transmittance; The TPU coatings are thin transparent films that transmit both visible and NIR radiation.
- High visibility yellow and orange fabrics that are used in workwear and safety vests seem to produce a relatively high solar cell power, while concealing the cells well. The fluorescent textile absorbs short-wavelength light, but unlike normal dyes, they re-emit part of it at longer wavelengths. Depending on the thickness of the fabric, up to half of it may be emitted towards the solar cell, augmenting its current. A bright fluorescence may also directly help with visual concealment.
- The concealment capability is not solely a result of the textile's transparency – the textile structure, patterns and prints can also help in concealment: they can break the image of the underlying rectangular cell or draw the attention of the eye away from it.
- Light scattering by the textile has yet another effect. A textile that scatters light effectively, blurs the image of the solar cell placed behind it, like a shower curtain blurs the image of a person standing behind it. The thickness of the textile and the distance between the textile and the solar cell has a big influence on the blurring effect.

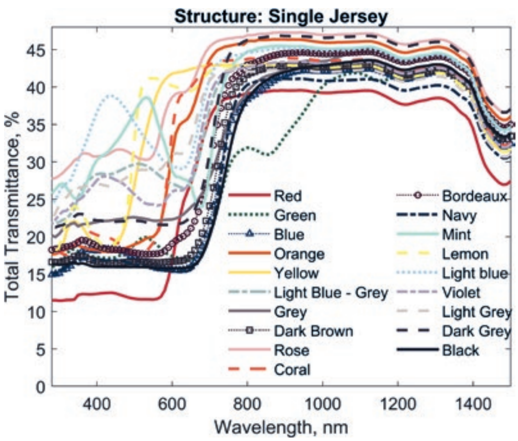


A black solar cell, or a liner fabric placed underneath a light-coloured thin or open-structured textile, tints the textile colour darker towards grey. Or to put it another way, a cover textile can be used to colour the solar cell to make it more aesthetically pleasing. Fabrics from Bettina Blomstedt's collection.

Plastic foils that produce colour due to the light interference on their thin coating layers. Materials from Zuzana Zmateková's Master of Arts thesis prepared in the Sun-powered Textiles project.

STRUCTURAL COLOURS

Ideally, the colour of the optical cover of a solar cell would be generated by the light interference phenomenon instead of light-absorbing pigments. Such colour formation is called structural colour. Examples of naturally occurring structural colours are the blue colour of butterfly wings and the colours that appear on a thin film of oil on the surface of water. Structural colours can also be manufactured artificially by various coating methods, and due to their low absorption loss, they are the most energy-efficient way to produce colour on solar cells. Theoretically, it has been shown that ideal structural colours would decrease the solar cell power by no more than 10% while producing a broad range of bright colours. However, dyeing of fabrics with structural colours is difficult because the structural colour coating would need to be done on the surface of yarns or fibres. However, it is an interesting research topic, because, unlike organic dyes, structural colours do not fade when exposed to light for a long time.



Spectral transmittance of different coloured single jersey knits. The effect of colour can be seen in the visible range between 400 and 700 nm: the transmittance is low because the dye in the yarns absorbs part of the light. Lighter colours have higher visible transmittance, as would be expected. In the near-infrared region above 700 nm, almost all dyes show negligible light absorption: the transmittance is high and at about the same values as for the undyed knits (shown in the earlier figure). A crystalline silicon solar cell placed underneath these coloured knits would be able to effectively use the NIR light whereas an amorphous silicon solar cell would be affected more by the colour because it uses mainly visible light.

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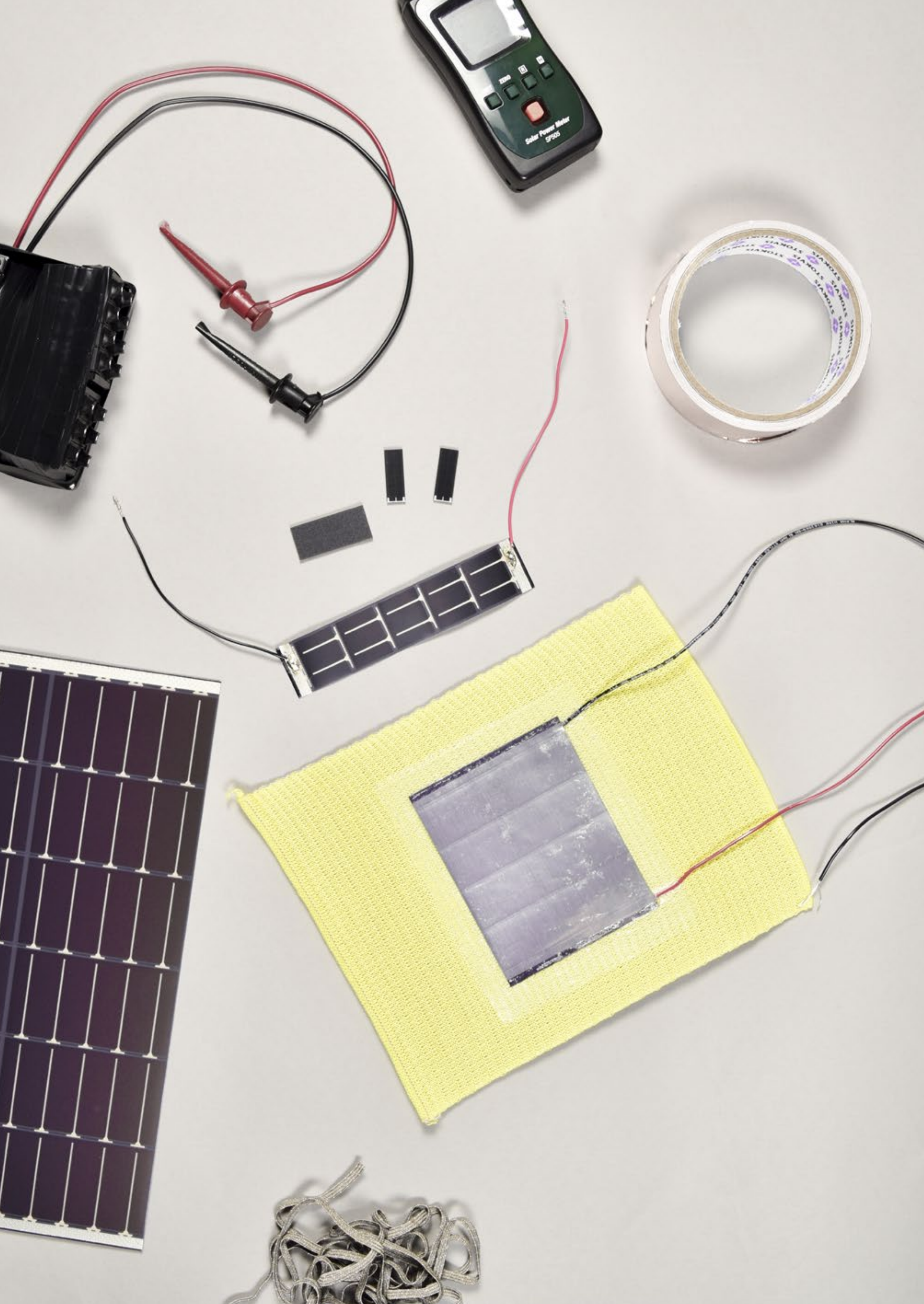

Solar Power Meter
SP505

5

FEASIBILITY FOR ENERGY AUTONOMOUS OPERATION

Solar cells hidden underneath textile layers work well but what can they be used for? This chapter discusses the feasibility of powering wearable electronics with textile-integrated solar cells and describes how the feasibility can be evaluated in practice.

Janne Halme

Evaluating the feasibility of textile-covered solar cells

Textile-covered solar cells need to be larger than uncovered cells to produce the same amount of power. However, electronic devices and sensors used in wearable electronics consume so little energy that a relatively small solar cell can produce all the energy they need. Therefore, a somewhat larger textile-covered cell may still be small enough to make it feasible for practical use, especially when it is hidden behind the fabric and is not visually noticeable.

The key questions concerning the feasibility of the textile-covered solar cells are the following:

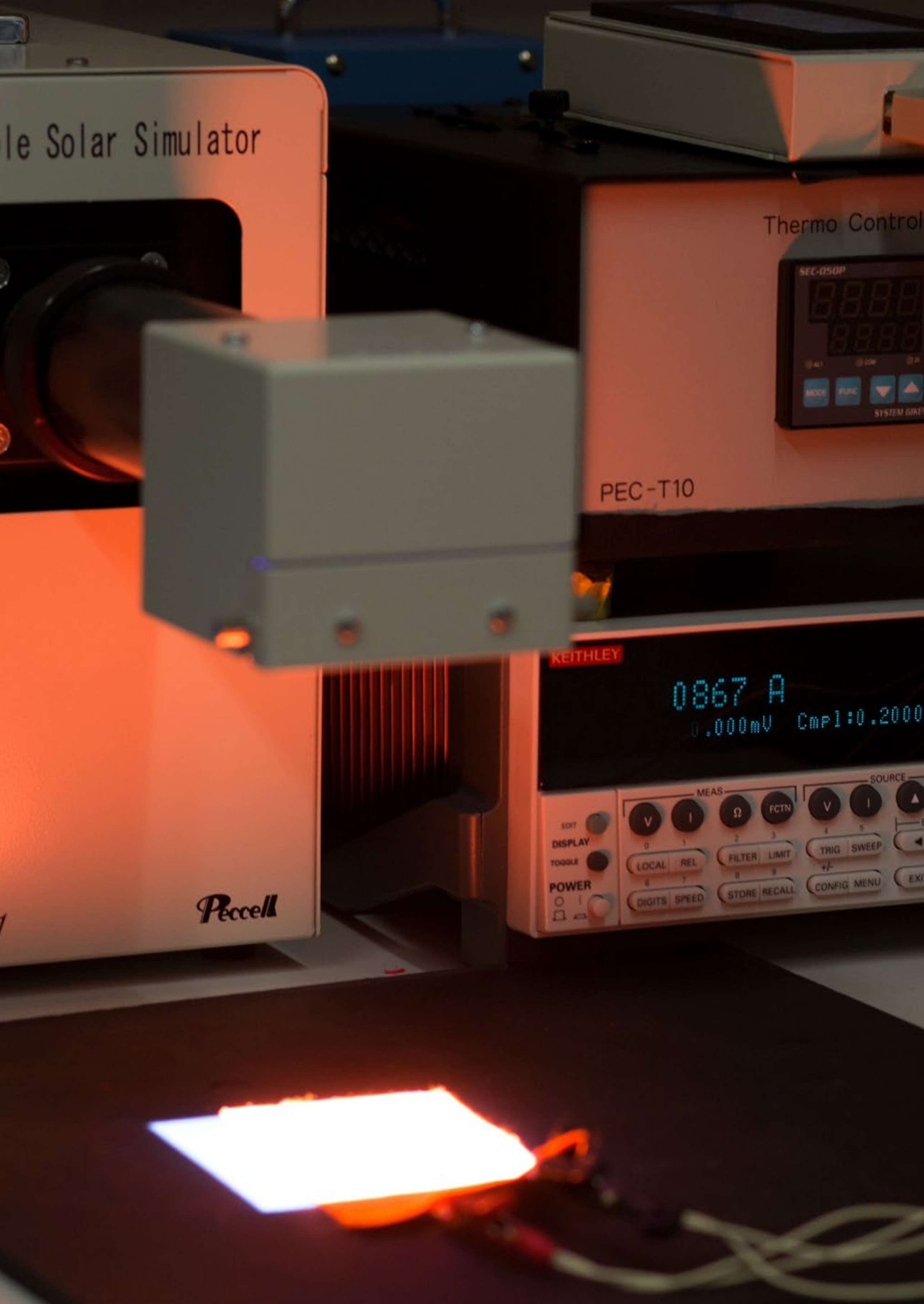
- How large does a solar cell area have to be to power a wearable electronics product?
- And, how much larger does it need to be to compensate for the textile cover eating away some of its power capacity?

If the area required for powering at least some wearable electronic devices, under typical use conditions, is small enough to be feasible for comfortable integration into a garment, textile solar cells could be useful for practical wearable applications. For other applications, comfort of wear may not be the question, but cost might be – a larger solar cell is more expensive than a smaller one.

This section tells us how to perform a technical feasibility analysis for estimating the solar cell area required for making a wearable electronics system energy-self-sufficient.

IN BRIEF, THE FEASIBILITY DEPENDS ON:

1. how high the daily average energy consumption of the electronic application is;
2. how much sunlight or artificial lighting is available at the place where it is used;
3. how much area is available on the garment for installing the solar cells;
4. what other factors may limit the maximum solar cell area (e.g., flexibility, weight, cost);
5. how visually concealed the textile solar cells should be.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How much energy is needed?

A feasibility analysis of textile-integrated solar cells begins by estimating how much energy the solar cells would need to produce. Using existing electronic products as a guideline can be helpful for this. Concrete applications help understand the scale of energy that can be harvested with solar cells and which applications it is sufficient for. The feasibility of the applications can be evaluated by calculating the solar cell area required for the application's energy autonomous operation at different illumination levels and times spent in the light.

Manufacturers do not usually specify the energy consumption of electronic products directly, but it can be calculated if the following information is given about its battery:

- Battery type. This can be used to deduce the nominal battery voltage V_{bat} (V, volts).
- Battery lifetime t_{life} (hours or days). In other words, how long the battery lasts in normal use.
- Charge capacity C_{bat} (Ah, ampere hours).

The energy storage capacity of the battery in Watt-hours (Wh) can be calculated by multiplying the battery capacity with the nominal battery voltage: $E_{\mathrm{bat}} = C_{\mathrm{bat}} \cdot V_{\mathrm{bat}}$. The average power consumption (W) can then be estimated by dividing the storage capacity with the battery lifetime: $P_{\mathrm{ave}} = E_{\mathrm{bat}}/t_{\mathrm{life}}$. If the battery lifetime is more than 24 hours, the daily average energy consumption (Wh) is simply $E_{\mathrm{daily\ ave}} = P_{\mathrm{ave}} \cdot 24$ hours. If on the other hand the battery lifetime is less than 24 hours, the mean active use time per day (t_{ave} in use) must be estimated, after which the daily average energy consumption can be calculated as $E_{\mathrm{daily\ ave}} = P_{\mathrm{ave}} \cdot t_{\mathrm{ave}}$. This is the amount of energy the solar cell needs to produce on an average day to power the electronic application without needing to recharge or replace its batteries.

How large a solar cell area is needed?

The solar cell area required to fulfil the daily average energy demand of an electronic device depends on the

- daily average energy consumption of the application ($E_{\text{daily ave}}$)
- average time the application is under illumination per day (t_{light})
- output power density of the solar cell at that illumination ($P_{\text{out per area}}$).

The output power density of a textile-covered solar cell depends further on the textile transmittance, spectral response of the solar cell, and the solar cell current – voltage characteristics, and it can be determined in different ways:

- Field tests with a multimeter and a light meter are good because they directly tell the power generated at realistic use conditions.
- Laboratory measurements with a solar simulator or an indoor lamp setup can be used for more reproducible results.
- Approximate values can be estimated from the solar cell manufacturers technical specifications.

When the solar cell power density is known by measurement or estimate, the area needed to fulfil the energy needs of the application can be calculated by equating the daily energy production and consumption
$E_{\text{daily ave}} = E_{\text{solar cell}} = P_{\text{out per area}} \cdot A_{\text{solar cell}} \cdot t_{\text{light}}$ and solving for $A_{\text{solar cell}}$:

$$A_{\text{solar cell}} = \frac{E_{\text{daily ave}}}{P_{\text{max per A}} \cdot t_{\text{light}}}$$

Note that this is a rough estimate that assumes constant illumination on the solar cell surface for a known amount of time, but it gives a good basis for an initial feasibility analysis.

The solar cell power and the product usage determine how large the solar cell area needs to be. A separate solar panel with a cable connection might end up being used rarely and for just brief moments, whereas the flexible amorphous silicon solar cells integrated under the hi-visibility orange workwear jacket might be exposed to sunlight throughout the day.

Solar cells embedded into a garment are exposed to different and widely varying illumination levels during a typical day. For example, a factory worker wearing a solar cell jacket might spend most of the day indoors at about 500 lx, but also visit briefly outdoors at 10 000–100 000 lx during breaks. An outdoor worker, on the other hand, might do the opposite, spending most of the time outdoors. To gain a meaningful understanding about the possible power generation and the required solar cell area for energy autonomy, it is helpful to break down the illumination conditions and the average daily exposure time to them to three different categories, and then calculate the required solar cell area for their different combinations. If the required solar cell area calculated in this way is significantly smaller than what can be comfortably fitted on a garment, the use case can be considered feasible.

The adjacent tables show the results from feasibility calculations for four different electronic applications and two use scenarios for each of them: one for indoor use, and one for outdoor use. The four applications are listed in the following table.

ELECTRONIC APPLICATION	DAILY AVERAGE ENERGY CONSUMPTION (mWh)
Therm-IC – Heated vest with Bluetooth remote control	62 000
Coats & Osram – Signal Active illumination of garments	19 000
Omron HeartGuide – Smartwatch with blood pressure measurement	310
Bluetooth Low Energy beacon for indoor positioning and people identification.	0.13

The Therm-IC heated vest is designed to provide warmth for the user for 3–10 hours, depending on how large an external power bank is used with it. The heating can be controlled with a smartphone via Bluetooth connection. The Coats & Osram Signal Active Illumination is a wearable safety light system aimed for providing safety for workers at dim light conditions. Omron HeartGuide is a clinically accurate wearable blood pressure meter in the form of a wristwatch. In addition to blood pressure, it measures steps, activity and sleep quality. Bluetooth Low Energy beacons are used for personnel tracking and identification. The beacons communicate and transfer data, for example to smartphones or gateways. The daily average energy consumption of the evaluated applications is widely different, ranging from 62 000 mWh for a heated vest, down to 0.13 mWh for a Bluetooth Low Energy beacon. This greatly affects the solar cell area needed in each case.

For each use case, one indoors and one outdoors, a suitable solar cell and a representative fabric was chosen as an example. For indoor use, an amorphous silicon solar cell was paired with a white indoor workwear fabric. The white fabric is a good choice for indoor use because it allows a fair amount of visible light to pass through to the cell, and indoor lighting is mainly visible light. For outdoor use, a single crystal silicon cell was paired with a sturdy high visibility orange workwear fabric to represent, for example, use in outdoor building construction work.

ILLUMINATION CONDITION	INDOORS	OUTDOORS
Fabric	96% PA 6.6, 4% PU, Plain Structure, 240g/m², White, Soil and Water repellent finishing	100% Polyester Oxford structure, 165g/m², High Visible Orange (EN ISO 20471). Soil and water repellent finishing
Solar cell	Amorphous silicon cell (Panasonic AM-1819CA)	Single crystal silicon cell (IXYS KXOB25-14X1F)
Power density without fabric	5.5 μW/cm² (200 lx)	19 mW/cm² (100% Sun)
Power density with fabric (estimated based on fabric transmittance)	2.4 μW/cm² (200 lx)	3.6 mW/cm² (100% Sun)
Illumination levels	200 / 500 / 1000 lx	1 / 10 / 100% Sun
Illuminated time	1 / 6 / 12 hours	1 / 6 / 12 hours

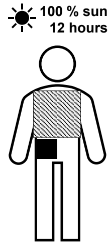
For these calculations, the power density produced by the textile-covered solar cell was estimated based on manufacturer's specifications for power output of the uncovered solar cells at 100% Sun (1000 W/m²) outdoors and 200 lx indoors. The power output at the other illumination levels was calculated

THERM-IC – HEATED VEST WITH BLUETOOTH REMOTE CONTROL

$E_{daily\ ave}$ = 62 000 mWh.

AREA (cm²) WITHOUT TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	3 400 [2]	1 400 [2]	970 [2]
	500	2 100 [2]	870 [2]	610 [2]
	1 000	1 500 [2]	610 [2]	430 [2]
OUT-DOORS (% sun)	1	570 [2]	230 [2]	160 [2]
	10	180 [2]	74 [2]	52 [2]
	100	57 [2]	23 [2]	16 [2]

AREA (cm²) WITH TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	9 700 [2]	4 000 [2]	2 800 [2]
	500	6 100 [2]	2 500 [2]	1 800 [2]
	1 000	4 300 [2]	1 800 [2]	1 300 [2]
OUT-DOORS (% sun)	1	1 300 [2]	540 [2]	380 [2]
	10	410 [2]	170 [2]	120 [2]
	100	130 [2]	54 [2]	38 [2]

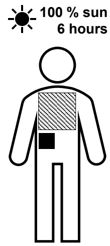


COATS & OSRAM – SIGNAL ACTIVE ILLUMINATION OF GARMENTS

$E_{daily\ ave}$ = 19 000 mWh.

AREA (cm²) WITHOUT TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	1 900 [2]	760 [2]	540 [2]
	500	1 200 [2]	480 [2]	340 [2]
	1 000	830 [2]	340 [2]	240 [2]
OUT-DOORS (% sun)	1	320 [2]	130 [2]	91 [2]
	10	100 [2]	41 [2]	29 [2]
	100	32 [2]	13 [2]	9.1 [2]

AREA (cm²) WITH TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	5 400 [2]	2 200 [2]	1 500 [2]
	500	3 400 [2]	1 400 [2]	980 [2]
	1 000	2 400 [2]	980 [2]	690 [2]
OUT-DOORS (% sun)	1	730 [2]	300 [2]	210 [2]
	10	230 [2]	94 [2]	66 [2]
	100	73 [2]	30 [2]	21 [2]

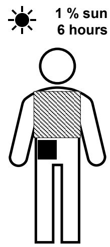


OMRON HEARTGUIDE – SMARTWATCH WITH BLOOD PRESSURE MEASUREMENT

$E_{daily\ ave}$ = 310 mWh.

AREA (cm²) WITHOUT TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	240 [2]	97 [2]	69 [2]
	500	150 [2]	61 [2]	43 [2]
	1 000	110 [2]	43 [2]	31 [2]
OUT-DOORS (% sun)	1	40 [2]	16 [2]	12 [2]
	10	13 [2]	5.2 [2]	3.7 [2]
	100	4 [2]	1.6 [2]	1.2 [2]

AREA (cm²) WITH TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	690 [2]	280 [2]	200 [2]
	500	430 [2]	180 [2]	130 [2]
	1 000	310 [2]	130 [2]	88 [2]
OUT-DOORS (% sun)	1	93 [2]	38 [2]	27 [2]
	10	29 [2]	12 [2]	8.5 [2]
	100	9.3 [2]	3.8 [2]	2.7 [2]

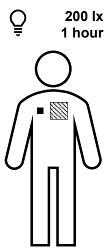


BLUETOOTH LOW ENERGY BEACON FOR INDOOR POSITIONING AND PEOPLE IDENTIFICATION

$E_{daily\ ave}$ = 0.13 mWh.

AREA (cm²) WITHOUT TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	4.9 [2]	2.0 [2]	1.4 [2]
	500	3.1 [2]	1.3 [2]	0.89 [2]
	1 000	2.2 [2]	0.89 [2]	0.63 [2]
OUT-DOORS (% sun)	1	0.83 [2]	0.34 [2]	0.24 [2]
	10	0.26 [2]	0.11 [2]	0.076 [2]
	100	0.083 [2]	0.034 [2]	0.024 [2]

AREA (cm²) WITH TEXTILE		TIME (h) 1	6	12
IN-DOORS (lx)	200	14 [2]	5.7 [2]	4.1 [2]
	500	8.9 [2]	3.6 [2]	2.6 [2]
	1 000	6.3 [2]	2.6 [2]	1.8 [2]
OUT-DOORS (% sun)	1	1.9 [2]	0.77 [2]	0.55 [2]
	10	0.60 [2]	0.24 [2]	0.17 [2]
	100	0.19 [2]	0.077 [2]	0.055 [2]



based on this, assuming that it scales linearly with light intensity, i.e., power at 10% Sun was 1/10 of the power at 100% Sun, and power at 1000 lx was five times the power at 200 lx. This may either over- or underestimate the true values depending on the solar cell type. For more accurate calculations the power densities could be measured with a multimeter at real use conditions as explained in the earlier section. Note also that the specified illumination is assumed to fall on the solar cell surface, in other words, the calculations do not consider the effect of solar cell orientation on the area need. Illuminance and irradiance levels are usually reported on a horizontal surface, whereas the solar cells on a garment are mostly in vertical orientation.

The feasibility varies greatly between the example applications. The two most power-hungry applications, the heated vest and the heart guide, could be powered with textile-covered solar cells only if they were used for up to 6 to 12 hours in bright sunlight every day, which would be unlikely. However, powering small electronics like Internet-of-things (IoT) sensors that have daily average energy consumption of only a few mWh would be feasible. For example, in the case of the BLE beacon 14 × 14 cm^2 area would be enough for energy autonomous operation with just 1 h cumulative exposure to 200 lx indoor light. For 6 hours at 200 lux the required area would be only 3.6 × 3.6 cm^2. Indeed, IoT sensors are often powered by a small solar cell integrated on their

← Feasibility calculations for four different electronic applications, for an indoor and outdoor use scenario and nine different combinations of illumination level and time of exposure to it. The results in the tables show the total solar cell area required to make the electronic application energy autonomous in each case. To get a good idea of the solar cell size, the area values are expressed as the length of the edge of a square shaped solar cell, squared. For example, 100 cm^2 means a 10 cm × 10 cm cell, or a cell with 100 cm^2 area. A square side of ca. 50 cm may be considered an extreme upper limit for a reasonable solar cell area on a garment. The dark background colour in the table marks those cases that stay below this limit: the light grey background means that the case would be feasible with uncovered solar cells, whereas the cases with dark grey background would be feasible even with a textile-covered cell. The drawings compare the solar cell area with the garment area in an exemplar case: the black square representing uncovered cells and the striped square textile-covered cells.

case. The same would be possible with wearable sensors powered by solar cells; the solar cells would only have to be somewhat larger due to being covered by the textile.

It is good to keep in mind that the calculated solar cell areas do not need to represent one large solar cell, but the area can be divided into smaller parts by placing cells on multiple positions: on the sleeves and on the front and back of the garment. However, integrating all electronics in one package would have the advantage that it would simplify manufacturing and improve the recycling at the end of use life, and provide better mechanical protection for laundry.

Although these results were calculated in an approximate way, they give a good insight about the scale of energy consumption of devices that are feasible to be powered with textile-covered solar cells. Comparing the solar cell size requirements with the available textile area on a garment, visualises the numerical results in a tangible way. This was important for the project partners because it helped them communicate the opportunities and limitations of the Sun-Powered Textiles technology to their customers. The analysis also helped in selecting the application and the solar cell sizes for the demonstration jackets.

→ This section was written based on the results reported in Linda Wederhorn's master's thesis prepared in the Sun-powered Textiles project.

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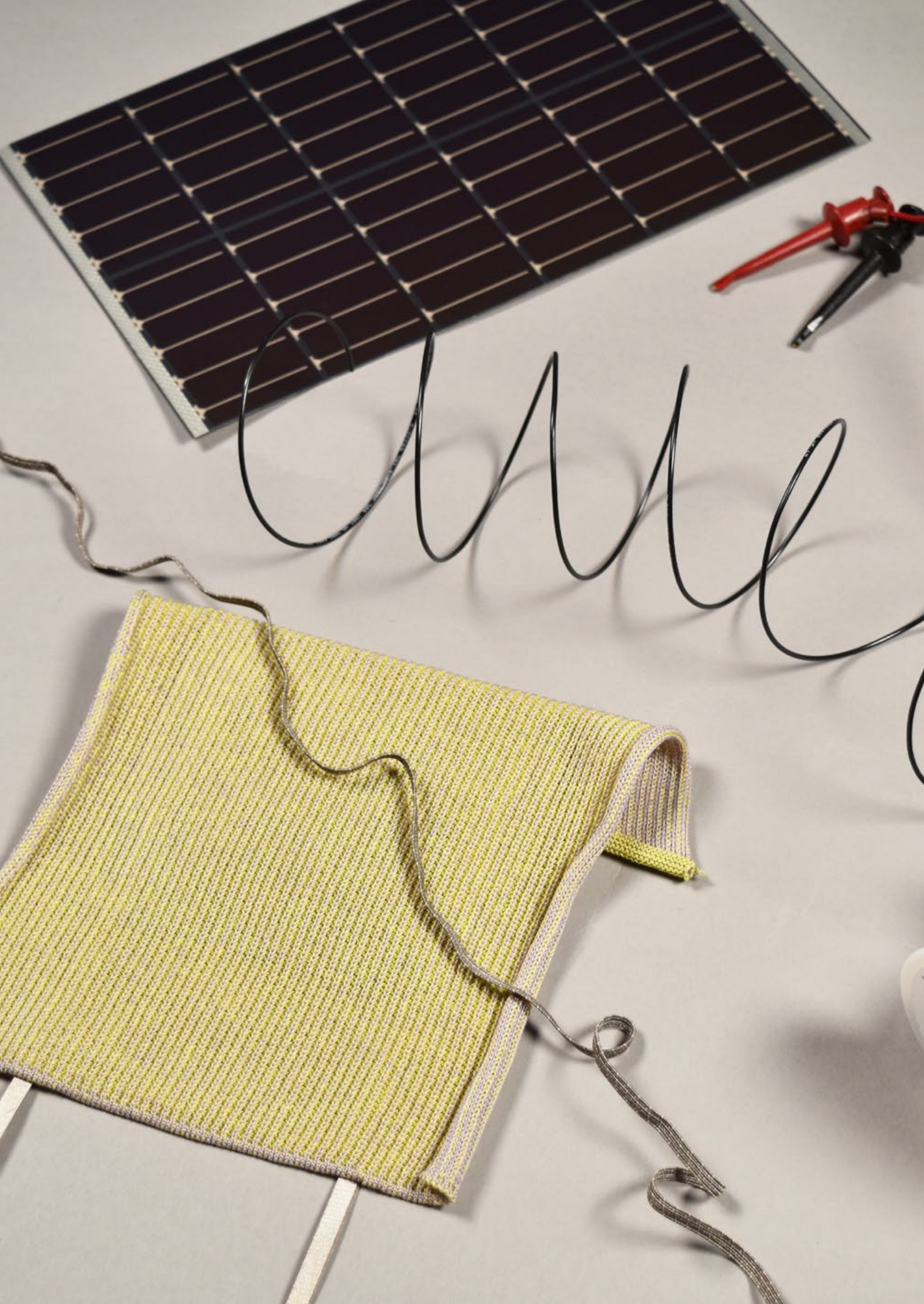
Wederhorn, L. (2020). Feasibility of powering wearable devices with textile-integrated solar cells. Master's thesis, Aalto University, 2020.



6

MANUFACTURE OF A TEXTILE SOLAR CELL COMPONENT

This chapter presents alternative methods that can be used to incorporate electronics with textiles and describe their main features, their washability and recyclability. Encapsulation is a reliable embedding method for different solar panels, and this method will be discussed in detail. The benefits of those methods for variable cells and applications will also be described. The reliability of the encapsulation technology is proven via the washing treatment testing procedure.

Elina Ilén

Attaching electronics to textiles

The methods of how to attach electronics to textiles can be divided into four main categories depending on their integration level. The levels are: add on intelligence, coated intelligence, embedded intelligence and seamless intelligence. In the final solution, the incorporation can be combinations of different levels. For example, electronics, which are attached with snap buttons (add on intelligence), can be embedded in the textile by creating a protective pocket for it (embedded intelligence). Alternatively, electronics that are incorporated into a yarn (seamless intelligence) can be made waterproof by lamination, or by coating the textile (coated intelligence), or with waterproof adhesive, as well as covering them with layers of textiles (embedded intelligence). Furthermore, embroidery techniques can be applied to produce embedded and seamless intelligence for e-textiles. Choosing the correct attachment method depends strongly on the application and its requirements. Therefore, it is important to consider the following aspects:

- What are the users' needs and expectations for the product?
- Is it a machine-washable product?
- How often must it be cleaned and how?
- What kind of physical stress (stretching, abrasion) is the product exposed to?
- How is the product recycled?
- What is the most effective and reliable way to mass produce the product?

In conclusion, it can be stated that all conventional yarn and textile modification and finishing technologies are applicable and beneficial in e-textile manufacturing too; only the materials vary, and in most cases the conductive element is required.

As an example, the fibre-like solar cells that can be woven into textile structures, have remained a scientific curiosity. Producing a waterproof encapsulation which endures repetitive washing is challenging at fibre level: it can be too thick for conventional large-scale textile manufacturing processes. More importantly, weaved structures give low surface coverage, which drastically lowers the power output per unit surface area of the textile, unless the solar cells are used as cm-wide strips, which, however, would again make them easily distinguishable from the textile.

The methods of attaching electronics to textiles can be divided into four categories based on their incorporation levels. The levels are presented with the main features of waterproofness and recyclability.

Add on intelligence – fasteners:

The electronic component is visible and removable, and attached with snap buttons or textile stickers (Velcro®), etc. It can be removed for washing and covered with fabric (a pocket). The electronics have a casing which can be made waterproof. Recycling is relatively simple: Both parts, electronics and textiles, are processed differently after use.

Coated intelligence – adhesives:

The electronic component is an incorporated, slim, flexible, and even stretchable film. It is laminated with adhesive on the textile substrate. Also, conventional printing techniques can be applied to form electrical components, and they can form a slim and smooth, plastic-coated, waterproof surface. Recycling may be challenging: Even though hot melt can be reheated for delamination, it might be difficult to tear the electronic component off the film.

Embedded intelligence – through encapsulation:

The electronic component is encapsulated between textile layers. Encapsulation protects electronics, and it might be unnecessary to use a casing. Various adhesives can be applied, but waterproof film adhesive produces a washable encapsulation. Hot melt encapsulation enables recycling: The area is reheated after use, and layers are separated. Electronics and textiles are processed differently after use.

Seamless intelligence – yarn integration:

Microscale, or even nanoscale electronics are integrated at yarn or fibre level. The structure is not waterproof, and therefore, the integrated component itself has to be waterproof, or water resistant. Alternatively, textile waterproof technologies have to be used. Recycling is very complicated, and in some cases even impossible with current technology.

Connecting solar cells with electronics

Conductive yarns as wires. Solar cells have to be connected with other electronic components such as sensors, energy storage, and circuit board. Each solar cell has two contact points where separate wires are connected. The contact points are most commonly made of silver. The properties of wires include flexibility, even stretchability, washability, adhesion to TPU (used in textile-cell encapsulation), and electrical conductivity. The wire must endure similar handling and care processes, like garments or other textile-based products. Hence, the best options for a wire are conductive fibre-based yarn or yarn-based textile structures such as braid or narrow woven band. The conductive fibre element in the yarn or textile structure can vary from silver and steel to carbon and conductive polymers. However, silver has the highest conductivity and has no corrosive feature with water. Most importantly, a commercially available silver-coated polyamide fibre produces a strong and flexible textile fibre, which is then applicable with most textile technologies such as braiding, lacing, fabric and band weaving or knitting, non-woven and embroidery. The conductivity of the yarn wire is dependent on the amount of silver in the structure, the structure itself, and how the interconnections with conductive fibres are ensured.

The sufficient conductivity of yarns depends on the electrical output of the solar cells and on the yarn length: keeping the conductors short reduces the resistive losses. The electrical output information and the yarn resistance can either be measured with a multimeter or the information can be found in the technical specifications of the products. The solar cell output is compared with the resistance of the yarns. The electrical resistance (Ohms) of the yarns should be lower than ca. one-tenth of the ratio of open circuit voltage (Volts) and short-circuit (Amperes): $R_{\text{yarn}} < 0.1\ V_{OC} / I_{SC}$ to avoid significant power losses in the electrical conduction. The contact resistance between the solar cell and the conductive yarn can be measured by connecting two yarns on one of the cell's electrical terminals, measuring the yarn-to-yarn resistance and comparing the result with another measurement of equally long continuous yarn without the contacts.

Conductive tape as a wire contact holder. The wires need a reliable connection to the cell. The common way in electronics is to solder via tin alloy, the wire to the contact points. However, this method is not optimal for e-textiles, as it

Conductive adhesive tapes for attaching textile cables to solar cells. Silver-coated polyamide fibre-based textile structures, either as a yarn, or as a braid, or a narrow-woven band, are the best wire options for textile-based electronics. Good conductivity is important, as the high resistance of the system can be comparable to higher power consumption. Accordingly, the high conductivity and flexibility of materials are desired for use in textile-integrated energy harvesting applications.

produces thick 'metal droplets' on the solar cell surface, which is fragile. When the solar cell or other electronic component is embedded in the textile, it can be seen through it and the connection can easily break when bending if standard copper wire is used. Moreover, conductive yarns and textile-based wires are not suitable for soldering because the process temperature is too high for the organic fibre in the structure. The best option to connect the conductive yarn to the solar cell is by using conductive one-sided adhesive tape. It is a simple method which does not need any special equipment or skills like soldering. The aim of this connection is to ensure the connection and hold the wire in place until the textile encapsulation takes place. After encapsulation the wires cannot move. Applicable conductive tapes vary in terms of width, conductive material, and manufacturing technology. The conductive tape ensures the connection, but it is not a prerequisite, and nonconductive tapes can also be used. The tape is placed on top of wire and the wire is attached to the contact point of the cell. Moreover, there are commercially available conductive double-sided adhesive tapes, and they conduct through the tape. In this case the tape can be placed between the cell and the wire, but the conductivity of the tape must be considered.

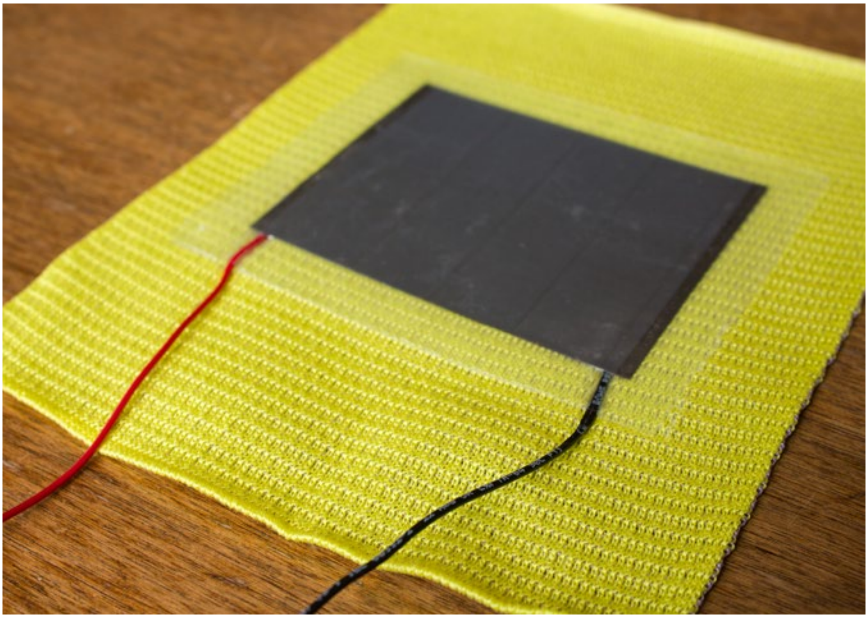
Encapsulation as a reliable integration method

Merging rigid solar cells with soft and flexible textiles is challenging both aesthetically and physically. The sharp edges of the solar cell may damage the textile if the integration is not well designed. Furthermore, the placement of wires and other electronic components needs to be designed in an unobtrusive way for the user. The electronics and the energy source need to be encapsulated into one unit and sealed in order to make the unit waterproof, thus improving the washability of the garment.

Commercial solar cells are compact, effective, lightweight, and low-cost products. Thanks to their current properties, they are an attractive alternative to be used also in wearables. Commercially available silicon solar cells are durable in various external conditions because of their advanced processing and encapsulation technologies. Both rigid and flexible solar modules are available in a wide range of sizes, so they can be used in diverse applications. The printing technique is developed for producing thin, lightweight, and even bendable photovoltaics. However, they have not been developed specifically for embedding into textile or to tolerate the requirements of textile products. The actual problem that prohibits the manufacturing process of such solar modules in industrial scale for wearable textile applications, is that in addition to solar cells, the integration of other electronic components requires an effective and reliable process, and all this must be conducted durably enough to tolerate ordinary textile use and care. Machine laundry is a stressful treatment for a solar cell. Previous research has focused on the integration technologies and developing textile-like solar cells too, but the durability in the real conditions during use, such as machine wash, has not been studied before.

A washable e-textile system is possible with textile encapsulation. It can be done with TPU or latex-based barriers. The former has been proven to improve the washing durability of screen-printed textile antennae, and it has also been demonstrated that encapsulation improves washing durability of electrically conductive coating on textile. Encapsulation improves the system usability, manufacturability, and product acceptance. However, in most of the current e-textile or textile wearable solutions, textile encapsulation has not been used, but the products include a removable electronics case, consisting of a replaceable battery and a circuit board (CB). A permanent encapsulation is not possible since the batteries need to be replaced, but it would be possible

Fabric encapsulated solar cells.
Fabrics from Foxa Oy collection.

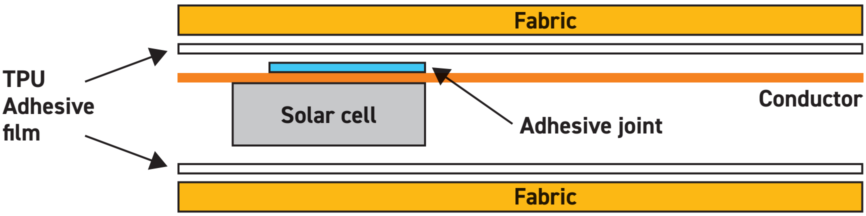


↑ Demonstration of an encapsulated solar cell from reverse side without the fabric liner.

to permanently encapsulate a complete electronics system (see figure below), including the circuit board, cables, sensors, and energy storage, by including solar cells and the energy source in the same encapsulated system.

The knit fabrics and other flexible and stretchable fabrics provide a soft feeling, good fit, and a smooth and neat appearance to garment-embedded electronics. In addition, the textile encapsulation protects the solar cell modules from mechanical stresses during use, and during washing, and provides aesthetic visual concealing. Moreover, the lamination of the cell between two fabric layers guarantees a stabilised position and location in the final product, which impacts product reliability in use.

↓ The layer structure of the encapsulated textile-solar cell module. The hot melt encapsulation with a waterproof adhesive film prohibits the unnecessary water and chemicals penetrating into the solar cell. The textile in the module structure protects the solar cell from mechanical stresses (abrasion, impacts etc.) during laundry, but also in all other wearing conditions. The encapsulation ensures the location, placement, and angle of the module in the clothing. It is also an effective, industrialised method for covering the solar cell in the clothing manufacturing process.



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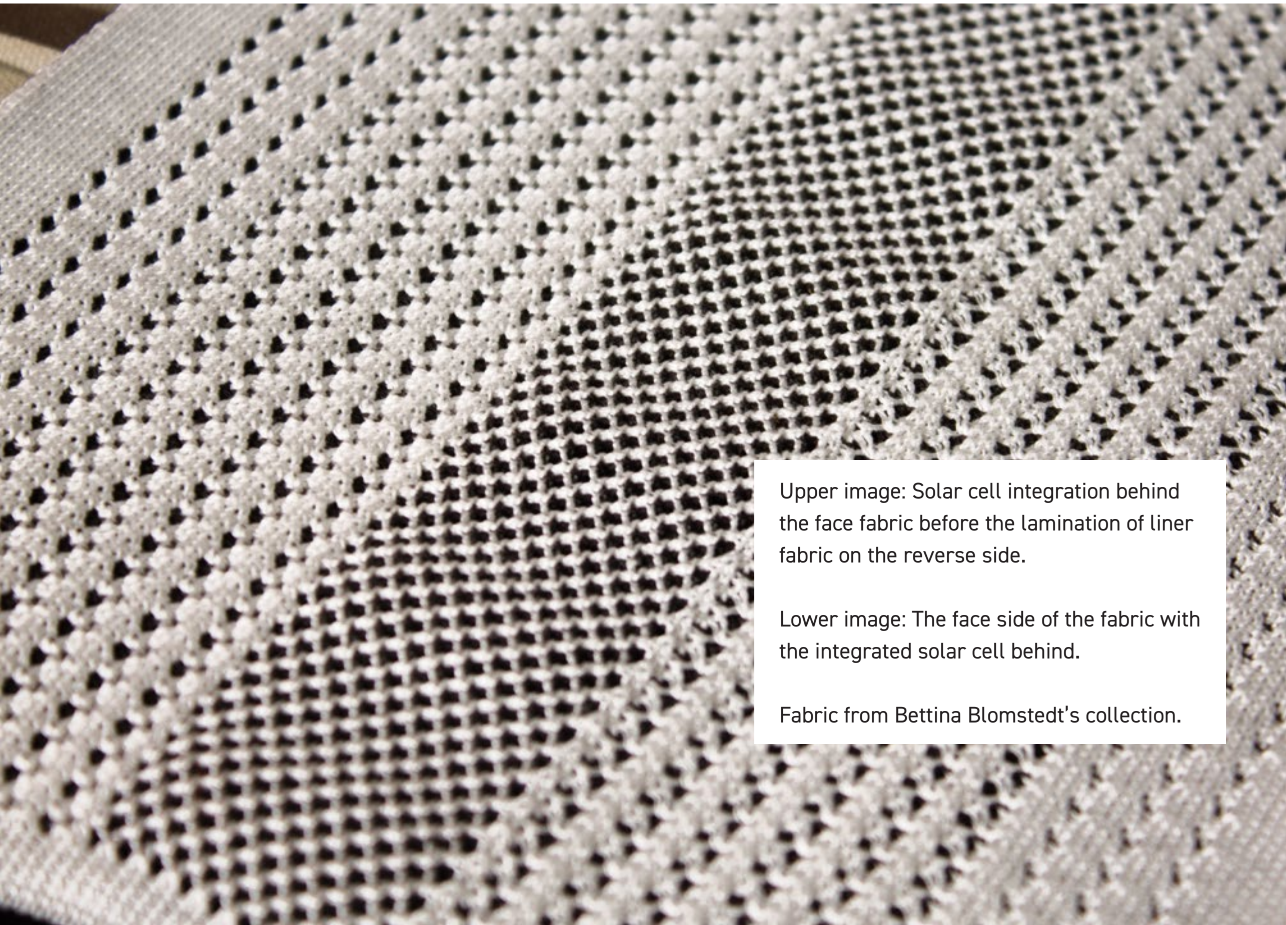
Practical advice for manufacturing

The encapsulation should be made as late as possible in the garment manufacturing process. If the electronic components pass the seams, the encapsulation has to be made for ready-made garments or textile products. However, encapsulation can only be made to a flat and two-dimensional surface, not on an uneven surface like a pouch. Thus, depending on the application, it has to be made before sewing or other assembly methods used in the end product manufacturing.

The optimization of process parameters is always required. The temperature (120–130°C), pressure (2,3–2,7 bar) and time (20–25 sec.) are adjusted according to the construction dimensions and the materials of the components. The recommended process parameters for adhesive film dictates the range of final process parameters, where the fabric's melting points must be considered as well.

The appearance of the textile material might change in the encapsulation process, when air gaps between yarns are removed by adhesive film, and the fabric flattens in the process. Typically, the biggest variation takes place in three-dimensional and fluffy structures. Encapsulation by lamination with adhesive film always stabilises the textile structure to the form it is before the lamination. Hence, if the knit is stretched before the lamination, it stays stretched after the encapsulation. Encapsulation may also affect the transmittance of the textile.

When electronic products are tested, it is important to apply the appropriate testing standards of textile products. Notably, the durability standards designed for testing textiles are more stressful for electronic components than for the textiles. It would therefore be insufficient to follow only electronics testing standards. According to the International Organization for Standardization ISO, the basic principle is that smart textile products and textile systems are expected to meet the same requirements as similar 'non-smart' materials and systems, and also the specific requirements of their particular properties. Nowadays, therefore, many of the existing specifications for chemical safety and durability of textile materials and structures are applicable to textile electronics as well. However, the variety of smart functionalities in the form of electronic devices, sensors, actuators, antennas, power supplies etc. are not directly applicable to textile testing standards with defined acceptance levels.



Upper image: Solar cell integration behind the face fabric before the lamination of liner fabric on the reverse side.

Lower image: The face side of the fabric with the integrated solar cell behind.

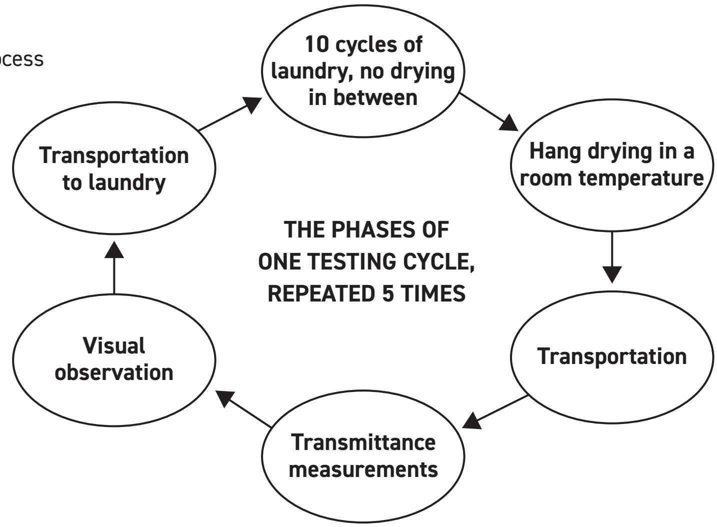
Fabric from Bettina Blomstedt's collection.

Washing durability of textile solar cells

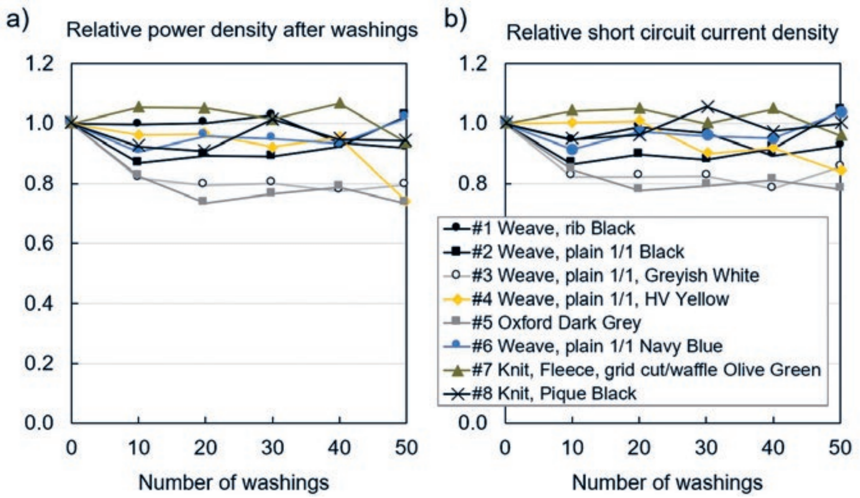
In the Sun-powered Textiles project, the washability of components was proven by conducting a systematic washing test. It consisted of 5 cycles where one cycle included 10 consecutive laundry cycles followed by flat drying at room temperature. After the 10 laundry cycles and drying the samples were transported to a laboratory for light transmittance measurements and visual observation of possible changes in them. In other words, the sample drying process and the measurements and observations were conducted 5 times, i.e., after 10, 20, 30, 40, and 50 cycles. The 50 laundry cycles correspond to washing of a solar cell embedded smart textile product once a week over the use period of one year, or once a month over about four years. Hence, it corresponds to the life cycle of professional wear textiles, which are designed to be very durable and long-lasting.

The rigid textile-encapsulated crystalline silicon solar cells were put into a washing bag and washed in the following programme: temperature 40 °C, spin 1000 rpm and 55 min, in a type A washing machine (Wascator FOM71 CLS). The laundry temperature (40 °C) followed the fabric manufacturer's instructions. The washing bag protects the washing machine from damage that could occur if the wires or solar cells broke and got loose during the laundry cycles. The washing machine was filled with cotton ballast to reach 2 kg standard load. The detergent Bio Luvil Professional Sensitive (by Unilever) did not contain phosphates, optical brighteners, or fabric softeners. Existence of these chemicals accelerate removal of conductive particles, which destroys the system.

The washing and measurement process of a textile solar cell module



After 50 laundry cycles the visual daylight observations were conducted by comparing the washed samples to unwashed fabric samples. The possible delamination of textile encapsulation, breakages of yarns, or pilling caused by abrasion on the fabric surface were examined. No significant changes could be observed.



↑ Small rigid single-crystal silicon solar cells endured 50 cycles of washing without significant changes in their energy harvesting capacity.

End of use aspect of encapsulation

One of the main challenges in solar cell technology integration in textiles is the issue of **recycling**. The designer should consider the full life cycle of the product and acknowledge the estimated lifetime and separation of the various components included in the product. The designer should also recognize the need for adjustments and make sure it is possible to repair a broken component without damaging the product. Furthermore, the integration of the electrical components should be carried out in a way that ensures the possibility of material separation and recycling at the end-of-life of the product.

The textile encapsulation used in the Sun-powered Textiles project can be disassembled by reheating the component. The TPU film becomes soft and the textile concealment can be stripped off. Hence, both the fabric and electronics can be recycled within their own processes.

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7

CREATING AN OPTIMAL TEXTILE-SOLAR CELL MODULE

This chapter discusses the matters and issues which need to be considered when creating concepts and designing and developing textile products around solar cells. It summarises knowledge discussed by providing a checklist to support the reader's ideation and development phase.

← Fabric from Zuzana Zmateková's collection.

Elina Ilén and Elina Palovuori

Concept development starts from product requirements

The textile solar cells might have various end uses, not only in garments, but also in other textile-based products, such as bags, or products used in building construction (See chapter 1). In many cases textile-based products provide rather wide areas where solar cells can be embedded unobtrusively. However, the creation of the optimal textile solar cell depends on the product application (See chapters 3 to 5). The product requirements must be considered holistically throughout the entire product lifetime, from meaningful product design (See chapter 2), to effective, valuable, and reliable production and use phase (See chapter 6), not forgetting the end-of-use aspects either (See chapter 8). It is essential to gather a competitive and knowledgeable team of experts from necessary fields, to ensure that the comprehensive list of product requirements is met (See chapters 7 and 10).

Sometimes, compromises or trade-offs between the properties must be made. Furthermore, the most important thing in decision-making is to consider the user.

- How much does that change affect the user?
- Does compromising worsen the user experience?

For example, if the visual appearance and design variability are the most crucial characteristics of your solar-e-textile application, it is important to hide the solar cells in the product. In that case you may need to choose a dense, thick, or intensely coloured fabric to cover the solar cells. That may restrict the ambient light passing through the fabric to the solar cell, and thus decrease the amount of electrical current produced. This means that the use of bigger solar cells is needed in the product, which may then be more costly and less comfortable for the user. Sometimes it might be important to protect the solar cells against environmental factors to make them more durable and long-lasting, which could be another reason for using thicker cover materials. Other factors may also affect the user. Since all the product properties are tightly interdependent, you need to think not only about the end product, but also how it can be made. Making the product industrially scalable may also compromise the user experience and/or the technical functionality.

Defining the product requirements of a textile product

It is important to always define the product requirements. In case of textile-embedded electronics, both textile products and electronic components, including solar cells, must meet those requirements. Otherwise, trade-offs must be made. When the product idea or use case, that would benefit from autonomous solar energy, is created, one needs to start defining the product requirements. To begin with, one needs to ask very basic questions regarding various user scenarios:

- Where and in what kind of conditions is the application used and why?
- Which problem does it solve?
- In which use cases or conditions is the application necessary, or offering the best solution?

The next phase of the definition process focuses even more on user needs. The typical questions at this level are:

- Does the technology need to be hidden?
- Do they need to differentiate visually?
- Is the product comfortable in use, i.e., is it lightweight and is unobtrusive technology applied?

These questions culminate in a holistic understanding of user experience and product acceptance. If the user needs are not fully considered in the concept development phase, it is more difficult, or even impossible, to correct them at a later stage.

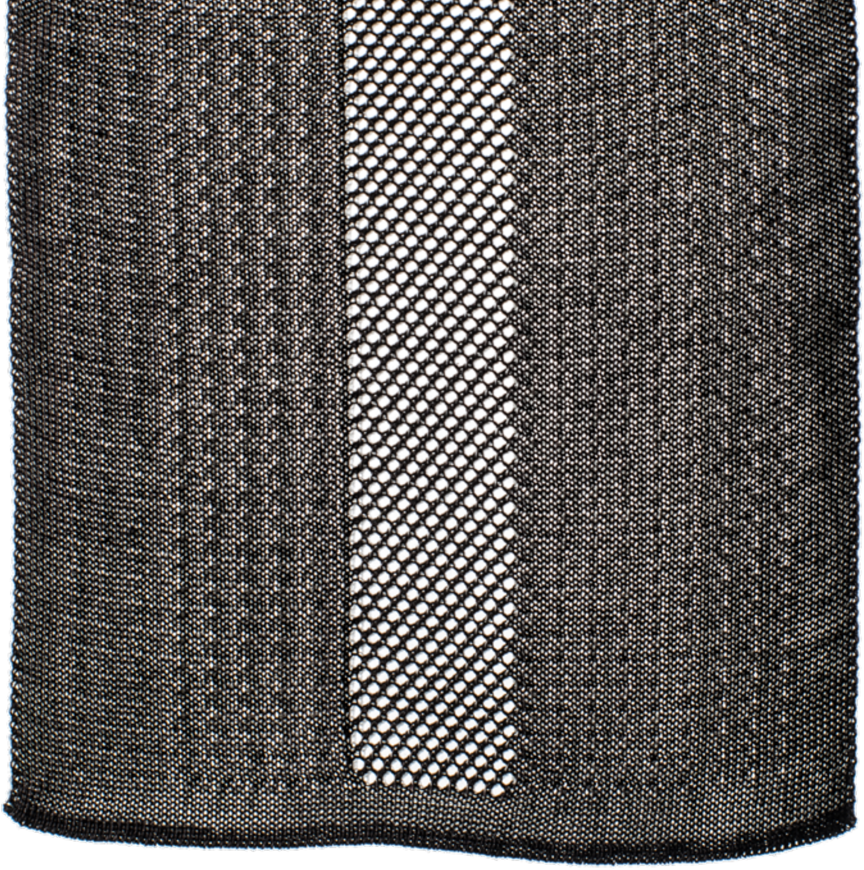
After the above-mentioned issues are defined, it is time to focus on concrete product requirements. It is important to answer questions regarding the product lifetime, washing or cleaning frequency and method, mechanical and chemical durability. The answers to these issues prompt one to think of the technologies, materials and components used in the product, as well as manufacturing technologies. It is beneficial to understand the already existing product value chain and the networks in supply chain when defining design briefs for materials, components, and the product itself. In case the aim is to make a mass-produced product, this knowledge must be involved in the product design and development phase, and built into the product from the beginning.

The requirements are the basis for the framework for textile material and product design. The final textile material properties are affected by the raw material, structure and chemical treatments conducted in the manufacturing process from fibre to yarn and textile, such as fabric. All these parameters also have a significant influence on solar cell energy harvesting capability. The density of the fibre, yarn or the textile structure is the main factor in optimising the harvesting capability. The denser the material is, the less light passes through it. In addition, colour affects harvesting capability. Dark colours absorb light, which prohibits part of the light from going through to the solar cell. However, it does not mean that the colour black cannot be used. The loss can be compensated with the material density. A less dense material improves the feature. For example, the thick, even 3-dimensional textile structures, can be considered inappropriate for effective energy harvesting; but, by optimising the reflection of light in the fibres, by fibre material, fibre shape in cross section, colour, and the density of textiles, the required harvesting capability can be achieved. The effect of hiding the solar cell can be achieved by dense and dark fabric, which can decrease the harvesting capability. However, well-hazing material can also be created by a more 3-dimensional net type structure, which provides full visual coverage of the solar cell. The printing technology also affects the optical properties of the textile. For instance, if the printing paste or dye stuff forms a light solid repellent layer on top of the textile, it blocks the sunlight to the solar cell.

Selecting the solar cell for the purpose

When selecting the right type of solar cell for the application, the main stem comes from the product requirements, and all the above-mentioned aspects must be covered. When thinking of the technical capability of solar cells, the important questions are:

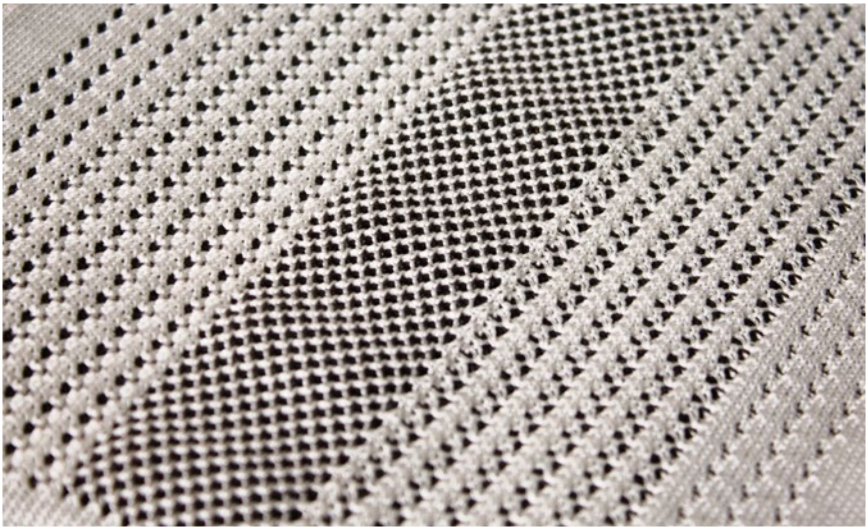
- How much data is transferred and how often?
- How much energy is required?
- Is the application used outdoors, indoors, or both?



↑ Net structure in the fabric, reverse side.

↓ Visually well-hidden solar cells behind the same fabric, but having high harvesting capability due to the holes in textile.

Fabric from Bettina Blomstedt's collection.



After defining these conditions, the number and size of different solar cells can be calculated. The harvesting of different combinations of solar cells and textiles is best made by experimenting and building the standardised testing set up (See chapter 4).

Garment design limitations

If the solar-e-textile application is a piece of clothing, proper pattern making is crucial. Sometimes, at the prototyping phase, one may simply glue the solar cells onto a ready-made garment, and it will function just fine for proofing the concept. Sometimes, it is possible to integrate the solar cells into existing textiles or pieces of clothing. Usually, when it comes to ready-made commercial products, there are special needs for pattern making in solar cell textiles, compared to "ordinary" garments.

The size, shape and quantity of the solar cells, and the other electrical parts, wiring and sensors needed, may affect the quantity, location, and the shape of the seams in the garment. When the size and the number of solar cells is known, one must think about how to fit them on the garment. For example, the electrodes and sensors cannot go over the seams, as the seam would create "a bump" which would decrease the harvesting capability of the garment. During the design process it is also necessary to consider the level of integration and if the solar cell needs to be removable, for instance for washing. Thus, one must decide whether the solar cell is in a pocket inside the garment, or on the surface of the garment, or whether it is integrated separably. Once integration level is chosen, it is essential to consider different integration methods, such as lamination. It is also important to ensure that the solar cells do not restrict the stretching of the fabric or the movements of the wearer. The electrical parts may be heavy and cannot be integrated into very lightweight fabric. It might be necessary to add some buckram to keep the garment in the intended form.

← Color affects the hiding capacity of the fabric. Similar solar cells encapsulated to similar fabrics but in different colours.

Technical functionality and safety

In solar cell powered textiles, new technical functionality, durability, and safety aspects in addition to the normal textile-related ones must be considered, tested, and validated. The demands depend on the product application.

For example, medical applications need a certificate for medical devices to endure the operational reliability. Applications meant for recreation, amusement, or showing the wearer's sense of fashion and lifestyle, have a freedom to emphasise other properties rather than just technical functions.

What happens if it does not work? If the application does not work, will it just be a bit uncomfortable? Will it be a big waste of money? Might the wearer potentially die if it stops functioning? It is a basic expectation that all textiles used for garments do not include toxic materials or chemicals. Applications to be used directly on the skin need to be non-allergenic. That also applies to solar cells and other electronic parts used in e-textiles. When solar cells are used, usually a battery is still needed in the system, if the application needs to function without ambient light, for energy storage.

Textile maintenance and care need to be taken into account in all design of e-textiles. If the product needs to be machine washed, that needs to already be considered at the beginning of the design process. In addition to washing, textiles are routinely tested and validated for safety durability with certified test procedures. For example, abrasion resistance and colour fastness, and depending on the application, several other test procedures are committed to textile materials by their manufacturers. The paradigm of designing e-textiles and textile wearables should be moved from maximum electronic performance to a holistic approach, in order to understand the unique combination of electronics and textiles. According to the holistic approach, the suppliers of solar cells, or other electronics that are used in textile integration, should be sure to undertake durability tests.

The demands for the fabrics depend on the application. The fabrics or fibre structures covering the solar cells need special attention. The fibre content, yarn properties, textile structure, dyes and finishes need to support the solar cell sandwich structure, letting the ambient light through, still being easy to process in garment assembly, looking good, and serving the chosen application's manufacture, use, care, and end-of life solution.

Fabric from Zuzana Zmateková's collection.

A checklist tool for the creation process

The table presents the first questions to be considered before starting to develop solar cell powered textiles or any e-textiles.

STARTING POINT QUESTIONS IN DEVELOPMENT PROCESS ABOUT USER NEEDS AND PRODUCT REQUIREMENTS	TICK THE BOX
Which existing problem does the application solve? Which real needs will it satisfy?	
Is there a competitive solution for that? What is the value of textile-integrated electronics / sun-powered textiles?	
What is the goal, or the outcome of the project? For example, a concept, a feasibility study, a functioning prototype, an industrially scalable product which is ready for market?	
What are the user scenarios? Who is the user? What kind of conditions and occasions?	
What are the main functions and technologies to be used?	
What is the estimated market size for this product?	
What could be an acceptable price range for the solution/product?	
Is there a knowledgeable R & D team available for all required areas, such as design and usability, textiles, electronics, including the solar cells, and scalable production?	

When solar energy is a valuable and relevant property for the user in the textile-based solution, the next table functions as a tool for the development process. The table tool uses the professional wear jacket showcase of the Sun-powered Textiles project as an example of a product to be developed. The first column places the question which has to be solved and proofed. The second column presents how that can be done.

The questions are not in order of relevance, but the evaluation must be done separately for each application. Also, the risk management for each property has to be conducted according to application.

The first "Quick and Dirty" prototype for proofing the concept: How much energy can be harvested in use? How does it feel when it is worn? How could the encapsulation be made?

Proof of product requirements

The following table presents how workwear product requirements were proven in the Sun-powered Textiles project.

USER NEED / PRODUCT REQUIREMENT	HOW TO PROOF THE NEED OR THE PRODUCT REQUIREMENT
Textile materials	
The light permeability of the textile	Transmittance measurements for choosing the optimal optical properties for the fabric (Chapter 4). The measurement presents how much light the fabric passes at the wavelengths used by the solar cell.
Solar cell concealing capability of the fabric	Visual inspection (Chapter 4)
The properties of fabric for the application (the durability, safety, functionality, colour)	Choose reliable, commercial, properly tested for purpose fabrics and electrically conductive textile wires
Solar cells	
The required harvesting capability	The needed energy has to be calculated for each application using information about its battery capacity and battery lifetime in typical use (Chapter 5)
Harvesting capability indoors and outdoors	Transmittance measurements and field tests (Chapter 3)
Wearability and comfort	Choose flexible or lightweight and small enough solar cells. (Chapters 3 and 5)
Suitable for the textile application (meets the usability in textile integration durability, safety, functional needs etc.)	Conduct wash and other durability tests according to the textile/garment prototype. (Chapter 6)
Compatibility with other electronics components	Supplier product specifications, prototyping (Chapters 9 and 11)
Compatibility for encapsulation process, tolerance for heat, pressure, time, and adhesives	Product specifications and testing the cell encapsulation tolerance via prototyping (Chapters 9 and 11)

USER NEED / PRODUCT REQUIREMENT	HOW TO PROOF THE NEED OR THE PRODUCT REQUIREMENT
Production	
The integration level of the solar cells and other electronics into textiles (fibre/yarn/fabric/a separate module in a pocket)	Consider the technologies used in the entire application, proof by prototyping (Chapters 2, 6 and 9)
The location of solar cells on the textile	Define the most effective locations on a garment application for gathering energy and in terms of production, no seams allowed in the cell area and design optimal pathways of wires
The production process phases and scalability	Solar cells should be attached at the latest possible phase to the garment and by using the commercial components and manufacturing technologies (Chapter 6)
End-product properties	
Product maintenance and care	Washing test for the textile integrated solar cells
User satisfaction and product acceptance by customization of the appearance	Hiding the solar cells under a cover layer textile adds possibilities to vary the appearance of the product
Product end-of-use aspects (repairability, replaceability, recycling...)	Product design includes end of use aspects (Chapter 8)
Product safety	Reliable material suppliers should be ensured by providing the information needed

8
SUSTAINABLE ASPECTS

Sustainability, including environmental, ethical, and social aspects, must always be considered in product development and production. The scope of the Sun-powered Textiles project was to integrate commercially available solar cells into garments to provide energy autonomy to the smart textiles. Therefore, the sustainability aspects were considered at the point when the solar power module was integrated into the garment, and the way the garment would be used was also factored in. Hence, the sustainable aspects of producing the textile-solar cell component are discussed in this chapter.

← Fabrics from Zuzana Zmateková's collection.

Elina Ilén, Janne Halme and Elina Palovuori

Sustainability of the textile-solar cell component

Co-defining the sustainable guidelines. It is important to define the sustainability goals and preferences for products collaboratively in the early stage of the process. It is crucial to synchronise the code of conduct and values of every partner of the project and create common goals for sustainability. In the Sun-powered Textiles project, the sustainable design guidelines for the solar cell components integrated into textiles were defined in close co-operation with company partners. The most important factors were durability, i.e., long life cycle of an e-textile component, and that it was easy to care, repair or replace the e–textile component before the garment wears out, or reuse the component in a new garment, if it happens to last longer than the garment. Even though the electronic component stops working, it should still be possible to use the garment as normal clothing.

Lifetime longevity and durability. The life cycle of a technical textile product or professional wear is supposed to be comparably long. The extreme properties such as high abrasion resistance, waterproofness, washing resistance and vapour permeability are required. It is worth making long-lasting and washable textile products because technical textiles are considered more sustainable, the longer they are in use. The durability aspects have an impact on all stages of the supply chain: cultivation of raw materials; producing the components such as textile, electronics, and solar panel products; manufacturing the end products; circumstances of the manufacturing sites, such as logistics, handling and storage. The recycled and recyclable textile materials are also applicable for embedding solar cells.

Repairability, replaceability, reuse and recyclability. One option to fulfil the demand of repairability and replaceability is to make a modular component that can be taken off the garment and replaced by a new or a fixed component. This supports the scalability of industrial manufacturing as well. The most cost-effective way is to embed the electronic component in a ready-made

From Zuzana Zmateková's Master of Arts thesis prepared in the Sun-powered Textiles project.

garment. This is because the wires can go over the seams, and, in this way, it is possible to avoid using extra connections of wires that could be needed due to the seams. Encapsulation as an integration method for solar cells enables repairability, replaceability, reusability, and recyclability of e-textile components, not only textile solar cell components but also other e-components of the system. Once the encapsulated area is heated, the adhesive softens, and the components can be stripped off.

Solar cell sustainability

The focus of the Sun-powered Textiles project was not to develop solar cells, so commercial solar cells were applied. The supply chain and the lifecycle analysis of solar cells are not transparent, which makes it impossible to consider the lifetime sustainability of textile-solar cell components.

Solar cells integrated on textiles are not necessarily the most sustainable way of charging textile electronics. It would be much better to charge wearable electronics with mains power produced with renewable energy, such as solar power. A solar cell which is integrated into a garment always causes more environmental damage than if the same solar cell was to collect energy continuously outdoors. When a solar cell is integrated into a garment, it produces significantly less energy during its life cycle than the one installed outdoors, which increases its environmental impact per amount of energy produced. This is because most of the environmental effect of solar cells comes from their manufacture, not from their use. In other words, the environmental impact of solar cells is directly related to how much light they are exposed to and convert to electricity during their life cycle, which in turn depends greatly on where and when they are used.

Solar cells do not reduce the environmental effect of textiles either. Adding material, such as solar cells, to textiles increases their environmental impact. However, textile electronics bring along new useful features to the textile product. It is therefore essential to compare the environmental impacts of solar cells to the environmental effects of an alternative way of producing the same feature or function. Also, the designer of a textile electronics product should consider whether the added feature is useful enough to justify accepting the environmental damage it causes. This consideration must always be carried out on a case-by-case basis. Energy needed for wearable electronics could be produced for example by piezoelectric, electromagnetic, or triboelectric generators, or by a thermoelectric generator from the heat produced by the user. Even sweat salts can be used to charge a battery. Nevertheless, the weakness of all these alternative technologies is that they produce significantly less energy than solar cells in the conditions and ways in which textile products are normally used. This means that a significantly larger device is needed to produce the same amount of energy, which would increase the environmental impact because a larger device consumes more materials and energy. On the other hand, solar cells do not produce energy in the dark. Not many textile products are used in the dark, but there still may be some specific cases where one of the abovementioned technologies would be a more environmentally friendly alternative to solar cells to implement energy-self-sufficient textile electronics. Again, this would need to be studied on a case-by-case basis.

Finally, the sun-powered textiles concept assumes that there is a need for energy-autonomous electro-textile systems and proposes that a good solution to fulfil that need is to laminate solar cells between textile layers. In the design process, it is nevertheless important to carefully consider how significant a feature energy autonomy is for user experience, reliability, durability, functionality, and cost of the product and its use. If energy autonomy is a nice-to-have but not a necessary feature, using a rechargeable battery with wireless charging from the grid, could, for example, be a more sustainable design. A systematic analysis of the environmental sustainability of wearable solar cells, in comparison to small replaceable or rechargeable batteries, would be an important topic for further research.

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9

CASE: SUN-POWERED TEXTILES IN JACKETS

This chapter describes the concept of sun-powered jackets and their development process from proven idea to final working prototype. The principle of iterative design and development process is discussed. Each process phase has a clear output, the argumentation of the phase is discussed.

← Jacket fabrics from Bettina Blomstedt and Zuzana Zmateková's collections.

Elina Ilén

Concept creation and development

The Sun-powered Textiles development project concentrated on the construction of a textile-solar cell component that can be used in many product applications, but it was still crucial to show the component in its context as a tangible working prototype which was a jacket in this case. Creating the concept and building the full prototype makes the component development work more approachable to a wider audience. At its best, the working prototype inspires the recipients to apply the solar cells in future applications. It also proves that the developed component works in its context or even in several contexts.

In the Sun-powered Textiles project a case concept of a worker who does physical work both indoors and outdoors was created. The thermal balance of the body helps to keep efficiency throughout the work shift. In this solution solar cells were integrated into six different jackets, each made of different fabric. The sun-powered textiles were used for powering temperature and humidity sensors located in the neck which is the area that produces the most sweat. The information is transferred via BLE (Bluetooth Low Energy) technology to the mobile phone where the worker can follow the thermal comfort during the shift.

→ Fabrics from Zuzana Zmateková's collection.

Iterative Design Process

It is advisable to use the iterative design approach in many kinds of development processes. The first step of the process is to define the goals. Then, the goals need to be divided into subgoals and their critical order needs to be defined, i.e., which goal needs to be solved first before moving on to the next goal. This order is also called the *critical path* of the project. These targeted subgoals are proven with testing and evaluation of prototypes. Depending on the character of the challenge that needs to be solved, it is important to consider if a partial prototype is sufficient instead of a full prototype. When a target such as a measurement or a phenomenon can be proved with a partial prototype, it obviously saves time and decreases costs.

Typically, one iteration cycle, and one type of prototype should answer 1 to 3 questions only. Parallel sampling is usually recommended. Either the questions should have no relation to each other, or they should be in such an order that if the first question fails other questions cannot be studied. Only if the first question is solved, it is possible to move on to the following question. When the time and costs are only spent for relevant challenges in a row, the process is effective. If one of the questions fails, the project goals must be revised, or the project must be stopped.

The main phases of the cycle are: defining the requirements, designing the product, development via prototyping and testing, and evaluation of results. The amount of required iteration cycles is obviously related to the product complexity which is equal to the amount of research questions, unknown issues, or risky parts.

If one tries to solve too many interlinked issues with one prototype, the root cause for an improvement gets lost. It may be possible to reach the goal by combining all the challenges to the same prototype, and fewer cycles would be needed, but in case the experiment fails, the root cause cannot be indicated. Changing one parameter at a time guarantees a systematic development process where the effect of each improvement can be clearly detected.

Sun-powered Textiles design process

design brief for solar cell embedding method

1. Analysing the optical properties of fabrics

- Measuring the transmittance of about 300 commercial workwear fabrics
- Mapping the fabric properties: weight, material, structure, density, colour, finishings
- Analysing the effect of each property on harvesting and concealing capability

design brief for fabric development

DEFINING

EVALUATION OF RESULTS

DESIGNING THE PRODUCT

DEVELOPMENT VIA PROTOTYPING AND TESTING

4. Developing the embedding method for a jacket (commercial jacket)

WORKSHOP 1

- Encapsulating the solar cells with an optimal commercial fabric
- Developing the test set up and devices
- Validating the testing set up indoors and outdoors

effects of colour, materials and structure on the harvesting and concealing capabilities

cell types for the fabric development

DEFINING THE REQUIREMENTS

DESIGNING THE PRODUCT

DEVELOPMENT V

EVALUATION OF RESULTS

3. Fabric design development process

- Designing the fabrics
- Manufacturing samples
- Measuring the harvesting and concealing capability

2. Selecting the solar cells

- Searching the commercial solar cells
- Analysing their properties
- Selecting the solar cells for the study

The main phases of the/one iteration cycle are: defining the requirements, designing the product, development via prototyping and testing, and evaluation of results.

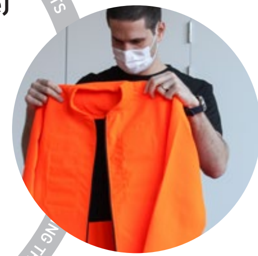
validated transmittance testing set up and encapsulation method for field studies

5.

Field tests with a jacket (orange)

WORKSHOP 2

- Making the jacket from an optimal commercial fabric
- Embedding solar cells behind the surface fabric
- Conducting the field tests



solar cells of optimal sizes in optimal locations in the jacket

6.

Optimal fabrics for showcase jackets (black)

WORKSHOP 3

- Embedding solar cells behind the most potential fabric samples on top of a black jacket
- Validating the integration method with fabrics
- Evaluating the concealing capability and appearance of fabrics

fabrics for showcase jackets and electronics integration method

7.

Producing a fully working prototype

WORKSHOP 4

- Producing the jacket from optimal fabric
- Validating the integration of full electronics system: solar cells, humidity and temperature sensor, and their connections
- Field measurements and analysis

validated working prototype for reproducing

8.

Production of fabrics and manufacture of jackets

WORKSHOP 5

- Producing 3 different developed fabrics
- Producing the final jackets from developed fabrics
- Integrating cells and electronic components into the jacket

working prototypes for exhibition and dissemination


Work

10 TRANS-DISCIPLINARY COLLABORATION

Transdisciplinary work has great potential to produce innovative product concept ideas. The entire value chain must be involved already in the development phase so that ideas can turn into commercial products or services. This chapter describes the challenges and provides success factors for transdisciplinary projects. Also, the Sun-powered Textiles project team members tell about their experiences of collaboration.

Elina Ilén and Elina Palovuori

Transdisciplinary work as a driving force for innovation

There are many definitions for transdisciplinary research and development, but in this book it is defined as a process where researchers and non-academic stakeholders from different disciplines collaborate to create new knowledge and innovations. The transdisciplinary context provides a fruitful ground for innovative concepts, research and development ideas, and this has been proven in the field of e-textiles. The knowledge of material, textile and product industrial design and engineering as well as electrical and software engineering is a prerequisite for the team. The ultimate target of innovation is always commercialization. Then, the required skill set includes an experience of mass production technologies and commercialization of each field. In addition, in every product development project, the end-user's perspective should be taken into account in the entire process, from planning to implementation. As an example, when e-textile products are developed for medical or health care use, medical personnel and patients must be involved in the process. Innovative project concepts require continuous communication between experts from multiple fields. Seeking innovative project ideas requires knowledge, intelligence, and creativity. One must know who to contact, and then create and maintain relations between experts in different fields. It is important to have constant dialogue. In the concept creation phase, sharing ideas in different forums increases potential for new project openings.

As a positive curiosity, a transdisciplinary team might create unexpected inventions during the process when learning from other disciplines. Some technology or knowledge can be commonplace in one field but another is struggling in a similar situation. Interdisciplinary projects can provide unexpected new ideas or solutions almost by accident. The project timeline, budget and funding should allow new openings and spin-offs, or even allow to re-target the research during the process.

→ Hands-on prototype making with transdisciplinary team


Connect to a VIA
Enter Room Name
Join

Success keys for the creative transdisciplinary collaboration

→ **The entire product value chain must be presented.** In application-based research and development projects, the starting point is to describe the whole value chain, and position each partner's profile, requirements, and role in the value chain. The benefits from collaboration between companies and university researchers are unquestionable, but finding the balance in workload and responsibilities between academic partners and private sectors is essential. Typically, company partners provide customer insight, materials or components, testing devices or prototyping services for the project, whereas academic partners conduct research and lead the project management operations. In the Sun-powered Textiles project, the entire value chain was covered by merging physics and electronics expertise with insights from textile design, product development, and production technologies. Industrial partners complemented the expertise of academia. **Foxa Oy** and **Lindström Oy** brought perspectives of textile end-users, and electronics company **Haltian Oy** provided hardware and software solutions for the project. Close collaboration with the companies enabled academia to focus on key research challenges.

→ **Build a competitive operative team and avoid knowledge gaps.** The project planning phase is crucial, and ideally, the people in project initiation should also be involved in execution. This way information is not lost, but most importantly the consortium partners are likely to believe in the project due to the competitive nature of the team. The importance of confidence in team dynamics between the initiator and other partners should never be underestimated. Finding a competitive team is essential, but not always that simple. The extensive knowledge of different disciplines, and capability to apply the gathered knowledge boldly and critically are essential for success in concept creation and product development. Additionally, the knowledge should always partly overlap at least in the basics of each discipline. This will ease communication and decrease the time the team needs to get familiar with the topic. In the Sun-powered Textiles project, the knowledge about textile materials, design, and production with technical and physical basics for the photovoltaic phenomena, resulted in the development of a strong academic team.

A competitive team needs an experienced mediator, who can communicate effectively with all team members, motivate them into developing alternative solutions and guide them through the challenges towards their goals. The person with this profile is capable of combining and applying the information and shared knowledge, as obviously, the experts tend to seek innovations primarily from their own discipline. Ideally, the person also has a wide range of knowledge, with a proven track record of operating in business and academia and is skilled in team management. Hence, the rest of the team can focus on their expertise in the project, and misunderstandings can be avoided or solved effectively.

The expected qualities of each team member are:

- A problem solving mentality
- Professionalism, with a good command of their individual subject
- Communication skills, flexibility, and a positive attitude
- Capable of working in a team, i.e., willing to share information and lend a helping hand

→ **Every R&D project needs a proper project management resource.** The time needed for project management should be allocated carefully and should not be underestimated. Every team member's role must be clearly defined in the early phase, and the resources should be allocated so that everyone can work in their area of core competence and motivation. Despite the size of the project, dual roles should always be avoided. For instance, if an academic researcher has a role as a manager and a product developer in the same project, they have too many roles. It inevitably leads to a situation where project management and product development are the primary roles for the researcher, and they cannot jeopardise the achievements and success of the whole project by focusing only on their own research. Therefore, the core competence is probably not fully utilised. Each member should have only one main responsibility: academic research, product design and development, or project management. In addition to their main responsibility, the team members support and assist each other in many ways, which is a fundamental principle for successful and collaborative R&D projects. In the Sun-powered Textiles project, the roles were divided into the following categories: project management, research and development in engineering and design. Project management was divided into the operational management, including scheduling and communication between the partners, and the research management, including leading and conducting of research activities.

It is important to meet the project goals and keep to the schedule; and in a longer project and with several team members, the goal might get lost along the way. The role of project manager is essential, and they must communicate regularly with all stakeholders. However, there must be room for bubbling minds to expand the topics creatively without diluting the project goals. Readiness to adjust the set goals agilely is also an important characteristic of the management team. Despite careful planning, unexpected requirements are bound to arise during the project, and resources might not be allocated to cover these requirements. It is in fact important to be prepared for surprises and allocate money for unexpected situations, as it is impossible to foresee all the possible scenarios. Money does not solve everything though. Even if there is money allocated, e.g., for hiring a new project manager, it may still not be ideal to hire one in every situation, as it takes time to find a suitable candidate and then show them the ropes – in some cases this may even take a few months.

→ **A clear common goal for succeeding in interdisciplinary research and development.** Project management ensures that the team is motivated, and shares the same goals, and maintains the required expertise throughout the project. It is understandable that the project will have certain goals, and that each team member might have their own personal goals and motivations, depending on the role of the value chain. The project manager must have the skills to keep to the project goals and simultaneously keep the team members motivated. In addition, operational team members' goals might be different from other stakeholders'. Their different expectations might put pressure on the development team as well. A manager has to be aware of all the motivations and solve how to apply them into the process.

The project benefits from collaborative and participatory methods by allowing each individual member to express their perceptions and needs, independent of group dynamics. Project management needs to be capable of gathering knowledge from experts in a complex interdisciplinary and collaborative innovation project. The most beneficial collaboration takes place when all the team members' expertise is utilised. In the Sun-powered Textiles project, most of the collaborative work was carried out in face-to-face workshops which had different themes from potential product concepts for developed textile-solar cell components to making prototypes for research and exhibiting.

→ **Allocate enough time for knowledge sharing and interactive learning.** Project orientation might take a long time, as members have different professional and cultural backgrounds. It takes time to get to know each other, build trust, and achieve mutual respect, but it is important to allocate time for the team to fully understand the development targets of the project. It is challenging just to grasp the basics of a discipline, never mind the terminology and vocabulary, and so it is essential to use the process of repetition to ensure that all the team members have achieved a sufficient level of understanding before it is possible to proceed. Providing room for everyone to practise their skills and learn from each other to gain their full potential is important. The drawback is that this *practising period* might cause frustration and decrease the motivation of others when progress cannot be seen. Good team dynamics have long-term benefits, which expand beyond one specific development project. Wide networks and close communication enable learning from each other. Collaboration creates new questions, new solutions, and widens perspectives even unconsciously.

Even though a project will have clear and common goals, conversations as working practice are vital for knowledge sharing. An interactive learning process moves the project towards common goals. For example, in the Sun-powered Textiles project, the designer described the creation methods and technologies of textiles, which helped the group understand how light behaves in a textile. Usually, a development project exposes what you did not know. In the interdisciplinary environment, unknown questions arise and are also answered quickly. Knowledge sharing and learning is more effective than individual learning.

DESIGNER'S PERSPECTIVE

How do you feel about interdisciplinary collaboration?

One of the most rewarding aspects was the chance to widen my perspective. It was valuable to discuss and notice how the background (e.g., field of study) of each individual team member brought out various perspectives on a topic. The interdisciplinary collaboration also reminded me to stand back and listen without prejudice or judgement. With an open mind, it was possible to learn from my colleagues who are experts in their field. It was also satisfying to be able to teach something from my own field to my colleagues.

What did you learn during the project, and from the others, e.g., designers, engineers, company members or project managers?

The Sun-Powered Textiles project involved many different stakeholders with different goals, so one had to learn how to listen and fulfil the expectations of others while keeping personal goals in mind.
It was sometimes challenging to find a balance. The project taught me ways of systematic and more analytic research and helped me recognise my personal strengths in an interdisciplinary team, where as a designer I could help open new areas of research.
I learned that I might use the same word as an engineer, but we would mean completely different things. I noticed that I had become so used to communicating with other designers that I did not realise that I needed to explain words or phrases because they seemed self-explanatory to me. But eventually, through the necessary explaining I also found strength in my own expertise and realised that I sometimes take my knowledge for granted.

What was different in the process, methods, or communication, compared to what you are used to?

The main difference for me as a textile designer was at the beginning of the project, where the designing was preceded by a long iterative process of measuring and evaluating results, so the conclusion could be drawn for the consequent phase of prototyping and design research. Even though in design you always start with some sort of research, it is usually more open-ended, and it can freely move to the testing or prototyping phase.

Due to the collaboration between the companies, it was crucial to take all the parties involved into consideration throughout the project. This collaborative way of working also meant that sometimes it felt frustrating to wait for responses, and it seemed that the project was moving along rather slowly.

Any positive surprises, challenges, or frustrating moments?

Any frustration during the project was almost always due to communication. It took a long time to build up the team dynamics and to realise my role within the team. I guess that part is so time-consuming that were we to embark on a new project together again as the same team, it would take significantly less time to get going with the actual work.

On a positive note, I do feel that the interdisciplinary way of working is extremely valuable and generates immense potential, if you are able to keep an open mind.

ENGINEER'S PERSPECTIVE

How do you feel about interdisciplinary collaboration?

I found interdisciplinary collaboration very fruitful – it was challenging, but then again collaborating with people from entirely different social bubbles forces one to be more open-minded, creative, and adjustable, which is great.

What did you learn during the project and from the others, e.g., designers, engineers, company members or project managers?

As a practical engineer, I learned to appreciate design-related things and the creative process behind every piece of art, and even behind small yet very carefully thought-out details in daily life.

Any positive surprises, challenges, or frustrating moments?

Sometimes it felt like engineers and designers were from different planets. It was hard to try to explain some very basic things to someone not familiar with them – and it was the same the other way around – it was hard trying to get to grips with the essentials of textiles, workwear, and design.

MANAGEMENT PERSPECTIVE

How do you feel about interdisciplinary collaboration?

Meeting people and having inspirational discussions is always uplifting. Seeing and experiencing a variety of new ideas, different ways of thinking, working, and communicating is interesting. Getting to know each other, and trust each other, is so valuable in teamwork. The feeling of working towards the same goal together is always inspirational.

One of the most meaningful experiences in our interdisciplinary collaboration was to be able to support others in their various personal needs and motivations, to reach our common goals. Of course, the collaboration also demanded some tolerance and patience from us all.

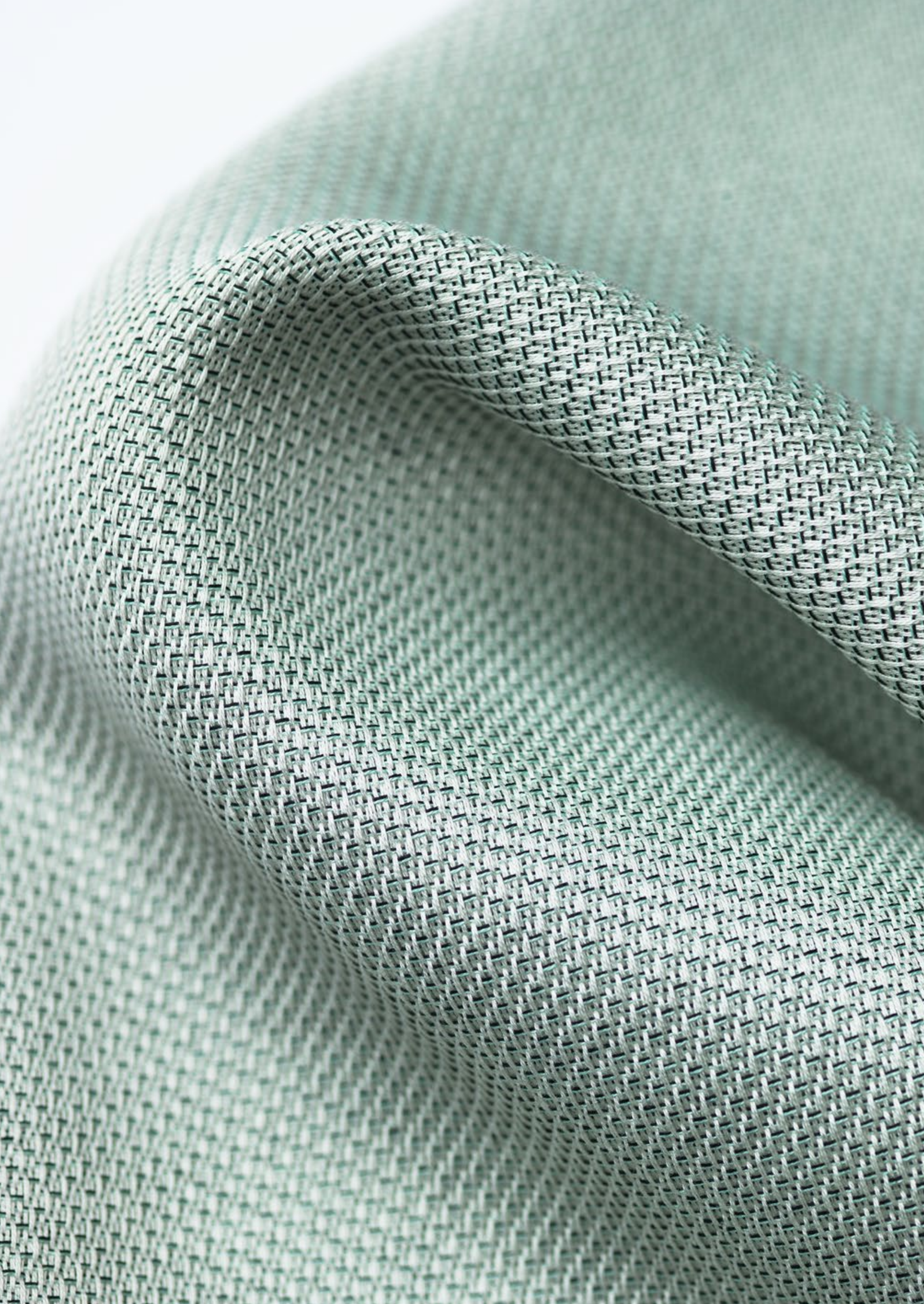
What did you learn during the project, and from the others, e.g., designers, engineers, company members or project managers?

Projects with many stakeholders, different interests, and persons from many backgrounds with different levels of engagement, need extremely precise communication. Repeating the message, about the goals, the schedule, etc., to the team and to the customers, is essential. Keeping the project goals clear in our mind during all the mundane work is not easy.

Any positive surprises, challenges, or frustrating moments?

We had a proper project plan with well-defined goals guiding the way. Still, our good results surprised me.

The Covid-19 lock-down definitely affected our work and the results. I'm experienced in working remotely. However, working on textile related tasks and decisions, I feel it would have been much more effective, inspirational, and innovative, to touch the textiles and other materials and talk about them together, around the same table with my team members and the project partners. Without haptics something is lost.



11 CONSIDERATIONS FOR E-TEXTILE PRODUCT DEVELOPMENT

This book presents a selection of aspects and topics required for the design, development, and manufacturing of textile-integrated solar cells. It also provides practical advice in the journey from a great innovative idea to a real scalable product. Furthermore, the Solar-powered Textiles project presented in this book focused on the development of a single component, a textile-integrated solar cell, rather than the entire e-textile system or application. Smart textiles have unquestionably a high potential to become a game changer in many industry sectors in the future. This chapter concludes some of the improvements which could change the development and market of smart textiles significantly.

← Fabric from Bettina Blomstedt's collection.

Elina Ilén and Elina Palovuori

Challenges to be tackled in product development

Comprehensive product acceptance. The readiness of technologies no longer limits the development work, so the transformation from a technology-driven approach to a design and user-driven approach, is essential. The focus is to find the valuable use cases which satisfy the user from all perspectives; pleasant appearance, proven benefit, easy-to-use and care, but most importantly, product safety and data security play a key role already in the concept development phase. Already at an early stage of the project, one should focus on understanding the user's feelings for the product. Even though technologists "know" that the product is safe to use and data management is secured, the most important part is to convince the user, otherwise the user does not believe in the product and does not buy it. In case of e-textiles, this concern is always present and should not be underestimated. Creating a competitive transdisciplinary team where all required knowledge is involved, and including real end users in the process of concept development, decreases the risk to develop a solution which fails in product acceptance.

Tailored e-textile solutions for each application: The design of every e-textile and smart garment starts with identifying the user needs to define the design problem. *Who is the user, why and where is it used? What is the value for the user?* Because there are various textile products, and they are usually intended to fulfil very specialised needs of the user, the smart textiles behave accordingly. There are garments and accessories for various occasions, environments, weathers, professions, and manufactured in many materials, styles, fits, price slots, sizes, etc. When thinking of integrating electronics into textiles the above-mentioned needs of the textile and the needs of the "smart" components must meet. In addition to these obvious user needs, the needs of the business and the industrial manufacturing have also to be taken into account at the design stage. Because of the variety of needs, there is no "standard solution" or commercial components for each part of the system – energy supply, sensors, data processors, wires and other components, or manufacturing technology – that would fit with every textile-based solution. In this development, the range of solar cell full capacity varies between 1 and 44% after the textile encapsulation. It therefore loses some of its capacity, or even all of it. The textile properties, such as material, thickness, density, and colour impact the optical properties of the material significantly and thus also the harvesting module capability. The textile properties must be optimised according to the application.

Component testing in development process: The commercially available solar panels were not initially developed to be integrated into textile. That caused a lot of durability testing for solar cells, and there was no guarantee that they would pass the test. Various standardised tests for durability and safety are normally performed to all trimmings, “the hard components” in textiles, such as buttons, zippers, velcros, hooks, etc. This is done to ensure that the textile products are flexible, durable, and soft, and that they tolerate textile manufacturing processes, use and care. It is a prerequisite for the manufacturers of these components to test the durability before the components are offered to garment manufacturers. It would be a significant breakthrough for wearable technology and the smart textile market if the manufacturers of solar cells, sensors, and electronics were to design their products for textile integration and test them accordingly. Nowadays, the testing of electronics components in the application development for smart textiles consumes time and money, and, most importantly, increases the risk of complete failure, because most of the components are not yet proven to fit textile products.

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→ **TIP:** search the literature for later publications from the project by the authors

Author presentations

ELINA ILÉN, CORRESPONDING AUTHOR

Prof. D.Sc. (Tech.) Elina Ilén has years of experience in leading, researching, developing, educating and commercialising functional and smart textile products and textile-based wearable technology, both in business and academia. In addition to her academic career, she provides product design and development services globally. She is keen on researching and developing products which improve the well-being of the user or environment, and which have a high social impact.

JANNE HALME

D.Sc. (Tech) Janne Halme is a researcher and educator on new energy technologies and solar energy. He is interested in interdisciplinary research, entrepreneurship education, sustainability, and innovation. His scientific research field is solar energy physics and engineering, and especially coloured and printed photovoltaics. His speciality is optical and electrical characterization and modelling of solar cells, and their durability testing and degradation analysis. Experienced in innovation and entrepreneurship education, he explores the liminal space between art, science, and technology.

ELINA PALOVUORI

M.Sc. (Tech) Elina Palovuori is a textile generalist with long experience in developing and producing textile-based wearables, smart textiles, and innovations. Her professional background is in textile material development, textile production technology, and quality assurance with standardised testing procedures for textiles. She has a holistic and analytical approach to her work and research, towards a sustainable textile future.

FARID ELSEHRAWY

Ph.D. Farid Elsehrawy, is an expert in optical design, modelling, and characterization of solar cell devices. His experience spans years of numerical and experimental research in the fields of optics and photovoltaics including photonic management of quantum dot solar cells. In the field of textile-integrated solar cells, his research interests include coloured photovoltaics, light trapping, and colour calibration.

BETTINA BLOMSTEDT

M.A. Bettina Blomstedt is a textile designer specialised in knitted structures, fibre technology, and sustainable innovation within the field of advanced textile design. Her work focuses on concepts and solutions for a better future. Due to her expertise in knitted structures, including the ability to program and operate industrial knitting machines, she is able to solve problems relating to both the technical and the aesthetic side of design. Her passion for purposeful design drives her to question various aspects of a project until the very end.

Sources of images

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various project team members.
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Sun-powered Textiles presents a new approach integrating solar cells into textiles in an efficient, durable, and washable way. Textile is capable of passing light through it when it is designed for that purpose. The solar cells are embedded underneath the textile which visually conceals them, and together they form a textile cell module that can harvest energy from indoor or outdoor light. The textile solar cell energy harvesting module can be widely applied in electronic textiles (e-textiles) and wearable technology, such as occupational and professional wear, sportswear, well-being, and fashion.

This book summarises the findings, learnings, and best practices from the Sun-powered Textiles project (Aalto University, 2019–2021) in concept creation, product design prototyping, and industrialisation of textile-integrated solar cells. It provides concrete advice for solar cell selection, integration methods with textiles, and instructions to measure and calculate the required solar cell areas for different applications.

Beyond solar cells in textiles, the book also gives general ideas and guidelines for developing smart textiles and textile wearables. This book is a must-read for everyone interested in learning more about designing and manufacturing energy-autonomous e-textiles.

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