Sandra Wirtanen

SOLAR CELLS INSIDE WOVEN TEXTILES

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Solar Cells Inside Woven Textiles

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Aalto University School of Arts, Design and Architecture
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Fashion, Clothing and Textile Design
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Master of Arts thesis abstract

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Abstract

Energy harvesting textiles are a relatively new field of research. In the future our clothes, accessories, and other fabrics could generate electricity from the sun and charge our devices on the go. While photovoltaic yarns, and solar cells printed directly on textiles are technologies of the future, there are already suitable solutions on the market for small scale energy harvesting. Some existing products such as energy harvesting backpacks and jackets already make use of these alternatives but mostly the level of integration of solar cells to the textile is low. The technology remains as a separate part instead of merging into the design and construction of textile.

The goal of this practice-based research is to create woven textiles that allow integrating existing solar cells to the functional and aesthetic design of the fabric. The background research aims to introduce the relevant terms and concepts about solar cells for textile design purposes, and paint an overall picture of the future of the photovoltaic textiles field.

During the practice-based research part, this knowledge is used for woven textile prototyping and testing. The thesis work establishes a design strategy which combines creative material experimentation with backing from applied scientific exploration. Traditional textile design practice is used to develop handwoven material drafts which allow inserting solar cells into the structure of multilayered cloth. To find out how the properties of textiles affect the efficiency of the solar cell, the textile prototypes were tested during several development cycles.

Solar Cells Inside Woven Textiles is a continuation of an interdisciplinary research project with the New Energy Technologies group from Aalto Engineering Physics department. The thesis builds on the knowledge generated during the previous process. Because of the collaborative nature of the project, the role of a textile designer in an interdisciplinary research project is addressed. The reflections are based on personal experiences during the process, and conversations with design and technology professionals about the subject.

This thesis work is positioned on the ground in-between design and science. The final outcome is a collection of woven textile prototypes showcasing the learnings and possibilities of designing for photovoltaics integration. Visualization of the collected data allows comparison of different materials, colors and weave structures and provides feedback of the design choices. Using textile design as a tool for scientific exploration may offer tangible proposals for future concepts and research questions. This work serves as one example of working as a designer in a hybrid environment.

Keywords woven textiles, photovoltaics, e-textiles, interdisciplinary design

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Tiivistelmä

Tekstiilit voivat tulevaisuudessa tuottaa sähköä ympäröivästä auringonvalosta. Vaatteisiin ja asusteisiin sisäänrakennetut aurinkokennot mahdollistavat kannettavien laitteiden latauksen, missä ikinä liikummekin. Taipuisia ja kevyitä aurinkokennoja hyödynnetään tänä päivänä mm. repuissa ja ulkovaatetuksessa, mutta teknologian upottaminen itse tekstiiliin on melko uusi tutkimusala. Vaikka aurinkosähköä tuottavia kuituja ja kankaita kehitetään, niiden ominaisuudet ja tuotantomäärät ovat vielä kaukana vaatetusteollisuuden tarpeista.

Tämä opinnäytetyö tutkii, miten olemassa olevaa aurinkokennoteknologiaa voidaan integroida osaksi tekstiilirakennetta ja mitkä kankaan ominaisuudet vaikuttavat kennon toimintaan. Opinnäytteen aihetta lähestytään sekä tutkimuksen että suunnittelun keinoin, ja työ jakautuu kirjalliseen sekä produktiiviseen osaan. Taustatutkimus avaa tekstiilisuunnittelun näkökulmasta keskeisiä aurinkokennotyyppejä, ja pyrkii esittelemään aurinkosähköä tuottavien kankaiden kenttää. Käytäntöön perustuvassa tutkimustyössä tätä tietoa käytetään kudotun kankaan suunnitteluun ja testaamiseen. Prosessissa hyödynnetään sekä tekstiilin- että tieteen strategioita uuden materiaalin kehittämiseksi.

Opinnäyte pohjautuu aikaisemmalle yhteistyölle Aalto-yliopiston Teknillisen fysiikan laitoksen kanssa, jossa etsittiin tapoja yhdistää aurinkokennoja vaatteeseen. Energy Harvesting-Sun Powered Textiles-projektia avataan omassa osuudessaan. Monialainen työ toimi tärkeänä alustana uuteen aihealueeseen ja idea sekä suuri osa aurinkokennotietämyksestä on lähtöisin kyseisestä projektista.

Solar Cells Inside Woven Textiles sukeltaa vaatteen rakenteesta vielä asteen syvemmälle kankaan sisään. Opinnäytteen lopputulos on kokoelma tekstiiliprototyyppejä, jotka ilmentävät oppimisprosessia ja aurinkosähköä keräävien kankaiden suunnittelua. Erilaiset kudotut monikerrosrakenteet mahdollistavat aurinkokennon yhdistämisen osaksi kankaan funktiota, rakennetta ja estetiikkaa. Mittausdata antaa palautteen prototyyppien toimivuudessa ja mahdollistaa materiaalien, värien ja sidosten vertailun.

Monialaisuus on tärkeässä osassa opinnäyteprosessia ja tekstiilisuunnittelijan roolia tutkimusympäristössä pohditaan oman kokemuksen ja keskusteluiden pohjalta. Tekstiilisuunnittelun työkalujen käyttö jo tutkimuksen alkuvaiheessa tuottaa käsin kosketeltavia tuloksia, joiden pohjalta saattaa syntyä uusia tutkimuskysymyksiä tai tuotekonsepteja. Tämä opinnäyte toimii yhtenä esimerkkinä tekstiilisuunnittelijan mahdollisuuksista toimia teknologian, tieteen ja designin välimaastossa.

Avainsanat kudotut kankaat, aurinkokennot, älytekstiilit, monialainen suunnittelu

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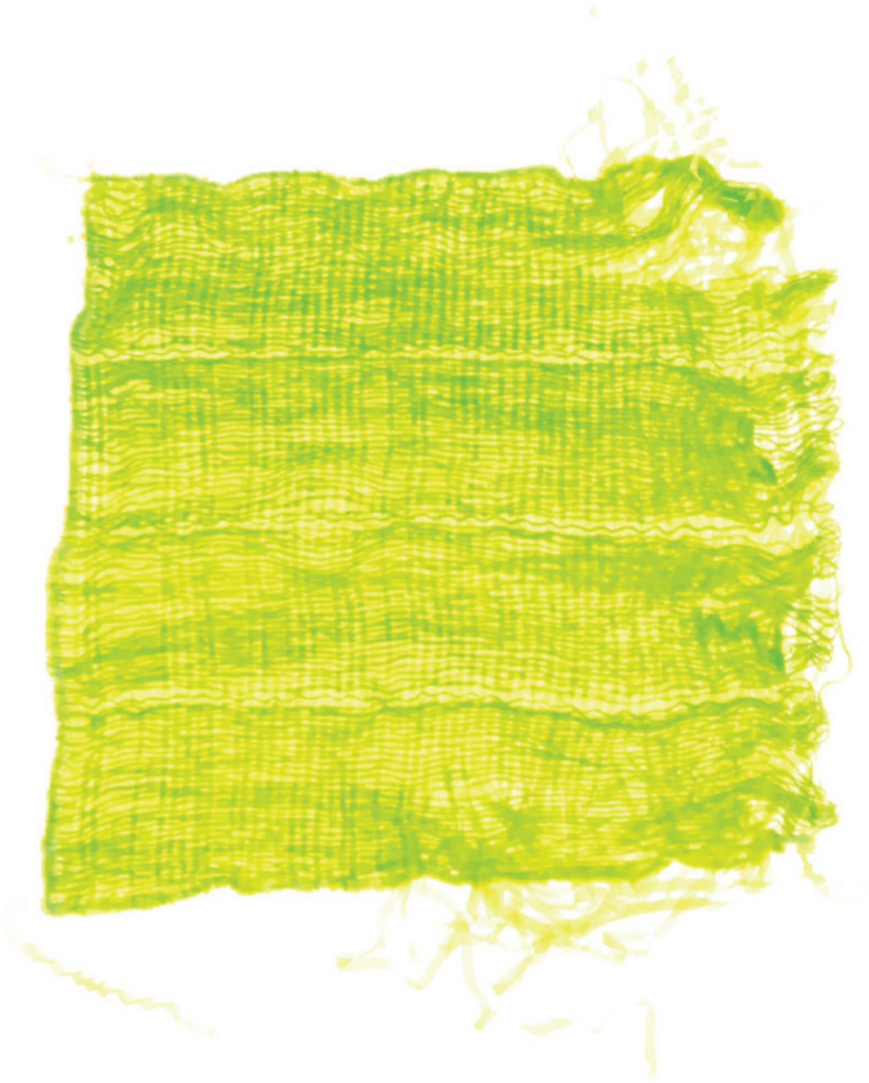
My dearest family, friends
and school mates



CONTENTS

1

INTRODUCTION

Sunlight is the origin of all life on Earth and we receive enormous amounts of it every single day. Photovoltaic cells, or solar cells, can convert this light into electricity. How would a world look like in which renewable energy from the sun could be harvested and used on our bodies to power our devices and smart textiles wherever we are?

Autonomous self-charging systems might one day adjust our clothes to a perfect temperature, guide us through a foreign city, or even help us move in a right way after surgery. In fields from healthcare to entertainment there is great potential in the technology, but the textiles needs to be re-designed to fit the purpose. The currently existing photovoltaic energy harvesting clothing, accessories and textiles haven’t yet explored the possibility of integrating the technology as part of the aesthetics of the fabric.

Combining solar cells, textile design and functional materials could lead to unprecedented future technologies that make our lives better. How to approach this emerging field as a textile designer?

The purpose of this thesis work is to find how solar cells could be integrated into woven textile materials and what factors need to be taken in account during the design process. How to incorporate the technology to become a part of the aesthetics and funtion of the fabric? In this thesis work my focus is on photovoltaics because by far they are the most efficient way to produce electricity with textiles on the go. Triboelectric and piezoelectric technologies are other interesting options for small scale energy harvesting. Especially research on energy harvesting from human movement has shown promising results, but these technologies are still in the beginning. (Bayramol et al, 2017) In solar cell technology there are already many usable small size, lightweight and flexible solutions available on the market. These solar cells could become an invisible part of personal energy harvesting if they were integrated into our textiles.

With no background in technology or science, my approach to photovoltaics and smart textiles is from a textile designers point of view. I attempt to understand the related fields on a level that is sufficient for the specific purpose rather than going very deep into technical details. My basic understanding about the technical aspects is largely based on our group discussions with the "Energy Harvesting-Sun Powered Textiles" team and the related prototyping process. The team consisted of professors, lecturers and students from Aalto University Department of Design and Department of Engineering Physics. Professors Peter Lund, Jaana Beidler, and Kirsi Niinimäki, University Lecturers Janne Halme, Ilona Hyötyläinen, Elina Ilen, Anna-Mari Leppisaari, Tiina Aarras, and students Sakari Lepikko, Alpi Rimppi, Eveliina Ronkainen and Anni Lehtosalo were all involved in the project and together we developed the concept of creating photovoltaic energy harvesting textiles. The following guidance from Janne Halme has had a major role in the direction of my thesis research process, especially the measuring methods used in the testing phase. And with the practical help from Alpi Rimppi, it was possible to build a prototype with interwoven, connected photovoltaics. Most of the photographs documenting the process are taken by Eeva Suorlahti.

Both familiar practices from textile design and unfamiliar scientific methods for data gathering have been used during this process. Because the subject and approach were new for me, this project is also a personal learning journey into the world of science, technology and interdisciplinary collaboration. The journey led to reach deeper into woven textiles, and expand the practice out of my comfort zone. To provide the thesis with personal reflective content about the learning experience, thoughts from different phases of the process are included along the way. Semi-structured interviews with Peter Lund (October 11, 2018), Janne Halme (October 8, 2018), and PhD Researcher Emmi Pouta (February 14, 2018) have been used as reference for reflection on interdisciplinary research, and role of designers in research. Lund is the leader of New Energy Technologies group at Aalto University Department of Applied Physics with a long experience of collaboration projects across different disciplines. Some of his views on the future of photovoltaics from our conversation, are also included in the related chapters. Halme is an expert in solar cells, and also a key figure in the New Energy Technologies group. Among other things he is involved in "ArtScience" projects combining solar cells and concepts from art. Pouta has a background in textile design and has worked in various teams including professionals from business, tech and design. She is studying how to create soft interfaces by integrating electronics into woven textiles.

Experimenting with textile materials, creative sustainability, and innovation are motivators for my work. Being one of the biggest global employers, the textile industry is facing some of the biggest environmental and social issues. Pollution, excessive use of natural resources and global warming present enormous challenges for the industry, and it is inevitable that massive changes have to be made. (Niinimäki 2011, 16) Many clothing and textile companies are turning towards science, technology and innovation as a way to thrive positive change. (Quinn 2010, 109-111) The challenges also present opportunities to create new, sustainable processes, and hopefully show a positive example for other fields. My path has led to focusing on textile design and ideas that propose creative solutions for a better future. Using values as a source of inspiration has encouraged experimentation with future materials and technologies such as 3D printing and solar cells, and pushed me to widen my perspectives on textile design through interdisciplinarity.

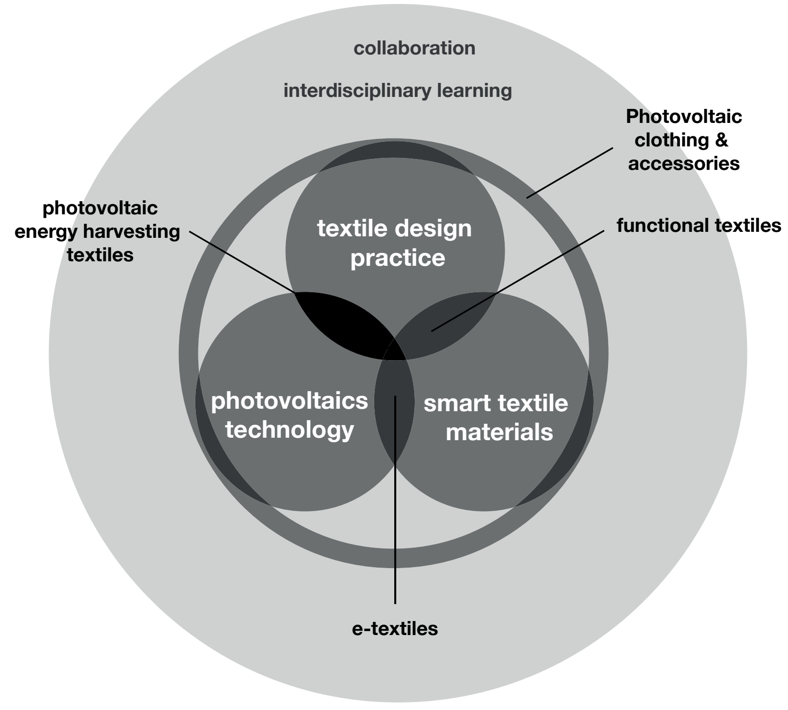


Fig. 1*: theoretical framework*

THEORETICAL FRAMEWORK & STRUCTURE OF WORK

Three central themes of this thesis are photovoltaics, textile design and smart textile materials. Together the different topics affect a wide range of industries ranging from fashion to architecture and nanotechnology.

The theoretical framework of this thesis is visualized with the figure above. (**Fig. 1**) Experimental textile design and prototyping by handweaving are in the center of this work, together with science and technology in the context of e-textiles, energy harvesting textiles, and functional textiles. The methods function as connectors between photovoltaics, smart textile materials and traditional textile design, creating multidisciplinary spaces in the interfaces of the fields. Clothing and accessories with integrated solar cells are also a closely related topic, situated outside of the main focus which is in woven textile materials itself.

Collaboration and interdisciplinary learning are also key elements of this thesis work. They are present during all the phases of the process in some form and affect the whole. The foundation of this thesis lies in combining different fields and therefore the work itself is a collage of connected concepts. Most of the learnings and realizations happened in the joints of these different subjects.

This thesis is divided into four main parts. The first part introduces the main topics and potential of energy harvesting textiles. The research questions, used methods and data description are also included in the section. In the Background & Research part, the thesis is positioned into the context of smart and functional textiles, and textile design. The research focuses on relevant photovoltaics technologies and concepts for woven textiles integration. The second part also opens up the previous project on photovoltaic clothing and accessories. The *Textile properties affecting the performance of integrated photovoltaics* chapter summarizes different factors that need to be taken in account when designing woven textiles for photovoltaic energy harvesting.

The third part of the thesis is dedicated to the process of explorative textile prototyping. This includes opening up the iterative cycles of the practice-based research, and findings in forms of textile prototypes and data. Documentation in form of photographs, data visualizations, and observations made during the process are also presented in this part. Finally, the fourth section sums up the research, reflects on the process and answers to the research questions.

TERMINOLOGY

Energy Harvesting is the process of deriving energy from external sources e.g. sunlight. **Solar cells**, or photovoltaic (PV) cells, convert solar radiation into electricity. Various photovoltaics include Silicon solar cells, Thin film CIGS (Copper Indium Gallium Selenide) solar cells and organic solar cells (also called polymer solar cells). To achieve a usable voltage and current, most times several solar cells are connected together and used as modules.

Efficiency of a solar cell is the power output of the solar cell divided by the incoming power (from sun radiation or other illumination source) The world records in efficiencies are over 40% but a very good efficiency is around 20%. **Energy payback time** means the time required to generate as much energy as is consumed during production and lifetime operation of the system.

The human eye senses wavelengths from 370 to 730 nanometers which means that all **visible light** and colors we sense are in this range. **Infra-red** range spans outside of the human vision in the electromagnetic spectrum (700 nm to 1 000 000 nm) but it composes almost half of all sun's irradiance. Ultra Violet wavelengths are shorter that visible light, from 10 to 400 nm. Most solar cell technology uses both visible spectrum and infra-red wavelengths in energy harvesting. (see **Figure 2**)

(Mertens & Roth 2014, 1-131; Livingstone 2002, 12)

Fig. 2*: solar irradiance spectrum*

TOPIC

In this chapter, I will be introducing the main topics. What are woven textiles and how can traditional methods be adapted for future technologies? Why should we become interested in photovoltaics and what are possible applications of photovoltaic energy harvesting textiles? Also, in new areas of material research, what is the role of a (textile) designer?

Woven textiles: functionality from the past and future

Weaving tradition is held to be one of world's earliest forms of technology and it evolved simultaneously in various communities. (Gale & Kaur 2002, 97) The jacquard loom invented in 19th century is often considered the first computer and the punching card method for programming woven patterns preceded modern coding. (Encyclopaedia Britannica 2018) Today, thousands of years later, weaving still remains an important part of the textile industry. While the foundation has remained the same through centuries, textiles have managed to always adapt to existing needs. (Gale & Kaur 2002, 173) Because of their unique properties like strength, drapability and lightness, textiles have potential to react, adapt, and communicate with the surroundings. Through times textiles have accompanied humans in adventures and "engaging with the forces of nature". (Quinn 2010, 245) Already for thousands of years various textiles have been used for sails, kites, and windmills to generate energy and speed from renewable sources. Their versatility makes textiles suitable for energy harvesting applications from integrated photovoltaics to converting kinetic energy from movement into electric power. (Gale & Kaur 2002, 97, 173; Quinn 2010, 245-246; Kirstein 2013, 1)

Functional features that can be controlled throughout the design and manufacturing process of woven textiles are texture, surface design, color, density, and transparency. Weave structures are the patterns that define in which order the longitudinal warp and transverse weft materials interlace. These systems together with materials and the weaving process form the aesthetic and haptic properties of textiles. Utilizing the interaction of material and texture with the surrounding light enhance creation of additional visual effects and even optical illusions. With weave structures, material combinations, and adjusting density of warp and weft, endless amounts of surfaces from soft to hard, and elastic to stiff can be produced. (Willmann & Forss 1996, 37-38; 112-119)

In multilayered weaves the warp is divided to segments that allow weaving two or more fabrics on top of each other. The warp density of each layer is naturally decreased, and the method can be utilized to generate transparency, thickness or opaqueness to certain areas. **Figure 3** shows how 'Pocket weave' structures may be joined together entirely or partially, and it is possible to alternate the order of the layers to create surface designs and decorative patterns. (Willmann & Forss 1996, 37-38) Pouta (2016) points out that multilayered weave construction may have surprising similarities with layer structures of other technologies. She visualizes this with an example of comparing a cross-section of a multilayered circuit board with a multilayered weave structure. Through design of warp and weft intersections and layer construction, electrical contacts can be built and conductive areas separated from each other. (see **Figure 4**, p. 7) These complex structures can be adapted for integrating various electronic components to textiles to become visible or hidden parts of the fabric. (p. 83-85)

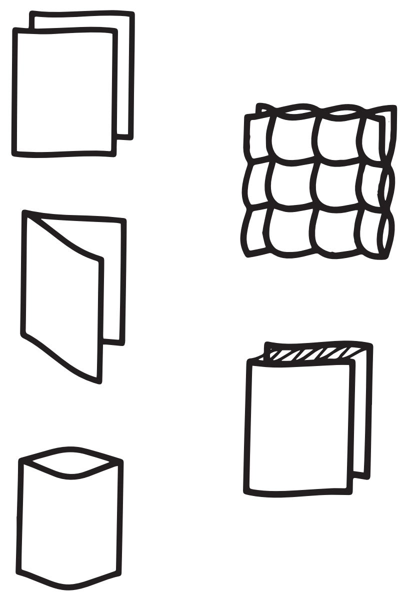


Fig. 3*: pocket weaves*

By adding electronics into textiles it will be possible to enhance the existing properties of the material and expand their functionality towards more complex and intelligent systems. Textiles are already protecting the human body, and serve our needs for beauty, expression and belonging. In the future, these materials can be transformed to provide us with superpowers and shift the way we communicate with our surroundings, our bodies and other beings. From nano-level engineered fibers to advanced weave structures for embedding electronics, textiles provide a platform for endless exploration in the space between art and science. Electronic textiles have potential to improve our lives and have a massive impact on how we use technology on our bodies. (Stoppa & Chiolerio 2014; Ilen 2015, 3)

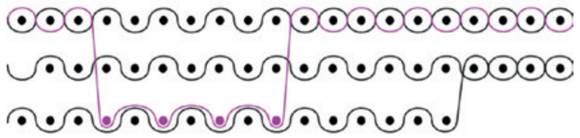


Fig. 4*: multilayered weave structure*

Why photovoltaic energy harvesting textiles?

The sun is the origin of all life on Earth. During the atomic fusion, it releases enormous amounts of radiation. Part of it is lost on its way to the Earth's atmosphere but still the continuous power density reaching the globe is approximately 1000 W/m2. Every year the sun provides us with multiple times the energy than we currently consume. In theory a "800 km x 800 km area in Sahara" covered with photovoltaics with a 10% efficiency could provide the whole world with sufficient energy, without pollution or emissions. (Mertens & Roth 2014, 41) The reality of course is more complicated because of both geographical and temporal variation of sunlight intensity on the Earth's surface. However, the potential of solar power is undeniable in replacing fossil fuels and slowing down global warming. (ibid. 21, 40- 42)

According to Professor Peter Lund from the New Energy Technologies group in Aalto University, the future looks bright for photovoltaics and the field is growing. There is a shift in thinking around solar cells, and in many places around the world photovoltaics are seen as an obvious technology for the future. In addition to industrial solar power plants, individuals are actively engaging with new technologies and decentralizing electricity production. The end users of electricity are also becoming producers, often called "prosumers". Photovoltaics are already included in the urban planning of many cities, and solutions for building integration have been developed for over two decades. (P. Lund, personal communication, October 11, 2018)

The next steps for photovoltaics could be in applications even closer to the human body. Integrated to textiles, solar cells could provide us with portable energy when we need it most like navigating through a foreign city or reminding us to move in a right way after surgery. (Krebs & Hösel 2015) These technologies could power our devices and smart textiles on the go during free time, work, commuting, or in places where energy isn't otherwise available. (Quinn 2010, 247) Photovoltaic energy harvesting could also help to overcome one of the urgent challenges in e-textiles: providing the electronics with safe and renewable power sources. (Zhang et *al.* 2016) Current batteries require charging or changing regularly and take up a large space. Instead of using conventional batteries, the power could be supplied with energy from our surroundings that would otherwise be wasted. (Stoppa & Chiolerio 2014) Advances in nanotechnology have resulted in electronics becoming smaller and more efficient in energy use, which makes charging them with photovoltaics possible. (Schubert & Werner 2006) Instead of a large energy-consuming display, information is projected straight into the eyes, and computers smaller than sand grains can be embedded to everyday objects. (IBM 2018) By including energy harvesting technology into the smart textile platforms, it would be possible to make the materials wireless. These textiles could be harnessed for the use of healthcare, thermoregulation, entertainment, lighting and safety, or highly sophisticated applications from military to professional sports. With independent power systems, electronic textiles could create true value to the user.

Role of textile designer in material research

Developing complex textile materials of the future requires "hybrid" knowledge ranging from chemistry to electrical engineering and design. If we want photovoltaics and smart textiles to become an integral

testing textile with a solar simulator

part of our everyday, form, texture and color should be seen as "part of the function". (O'Mahony 2011, 19) Especially with technologies that are a part of our living environment or very close to the human body, the role of visual and tangible characteristics cannot be disregarded. Comfort, ergonomics and the desirability of design become important features when technology enters our everyday material life. (ibid.) This is an area where designers could have a major impact.

In the article The cross-section of a multi-disciplinary project in view of textile design, Townsend, Karttunen et al. (2017) discuss the role of a textile designer in smart textiles development. According to their research, textile designers skills are a rarely used resource in projects aiming for wearable smart textiles systems. Textiles might be in the center of the material development but designers are not included in the process. This creates a "distinct gap between the technologists and the designers." (ibid.) Using textile skills like weaving, dyeing and surface design, the level of integration of electronics into the cloth could be improved technically and especially design-wise. Including a designer to the process may result in electronic textiles that are easier to approach and accept while generating new research questions. On the other hand, designers have a lot to learn from scientist about technical details, testing, etc. that would make the designs more functional, and maybe open new possibilities in aesthetics. (Gale & Kaur 2002, 167-177)

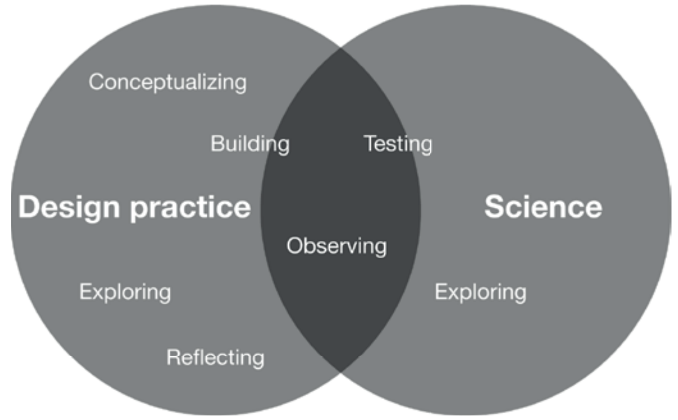
At Aalto University, a design driven approach to materials innovation has been studied in the field of cellulose-based biomaterials. Lost in the Woods by Pirjo Kääriäinen & Liisa Tervinen (2017) showcases various examples of multidisciplinary projects that combine science, design, engineering, and business. For example Ioncell-F is a sustainable textile process developed at Aalto University and University of Helsinki which allows making woven fabrics from cellulose pulp. Their "Recipe for Successful Collaboration" lists "ingredients" and "methods" from learnings and experiences gained from different stages of the interdisciplinary processes. Kääriäinen and Tervinen stress the importance of an open mindset, patience, willingness to understand and learn from each other, and hands-on work together. "A large spoon of courage" to accept failure and trust jumping into unknown is also on the ingredients list. From design to technology, all choices need to be done in the context of a common goal. After all, a successful collaboration can produce innovation that has great impacts on many fields. (Kääriäinen & Tervinen 2017)

RESEARCH QUESTIONS

Textile-based photovoltaics for renewable energy harvesting is a relatively new area of research. (Bayramol et al. 2017) The development of new materials and nanotechnology can be slow and therefore it is justifiable to look into what has been made already and how the knowledge could be used now. By using technology that is already available on the market, it is possible to create proposals for novel solutions which don't necessarily demand years of development or laboratory work. Prototyping and testing future ideas even though all of the components aren't completely perfect or ready yet is the biggest advantage of this approach. This is especially interesting for testing possible concepts and designs for materials.

This thesis seeks for methods to combine textiles and photovoltaics by using handweaving and experimental textile design as prototyping methods. The main research question is: How to design woven textiles that enable integration of existing solar cell technology? When doing so, how does inserting the solar cell into a woven textile structure affect the performance of the solar cell? This leads to the third question: What are ideal textiles for hiding solar cells?

Along the technical aspect, the thesis also explores hybrid knowledge in textile design. Is it possible to design aesthetically interesting textiles while focusing on a specific function of photovoltaic energy harvesting? And what skills and knowledge does a textile designer need to work in an interdisciplinary project such as energy harvesting textiles?



DATA & METHODS

***Fig 5**: methods*

"The difference between design and research seems to be a question of new versus good. Design doesn't have to be new, but it has to be good. Research doesn't have to be good, but it has to be new. I think these two paths converge at the top: the best design surpasses its predecessors by using new ideas, and the best research solves problems that are not only new, but actually worth solving. So ultimately we're aiming for the same destination, just approaching it from different directions."

- Paul Graham, Computer Scientists
(Paul Graham 2018)

In *The Encyclopedia of Human-Computer Interaction*, Stappers and Giaccardi (2018) address some of the similarities and differences between research and design. Whether it is knowledge or a creative solution, both research and design aim to "create something new" building on previous knowledge. Even though the purpose and results can be very different, 'analysis' and 'evaluation' are "research activities" that are used both in design and academia. (ibid.) As a method "explorative prototyping" can be a powerful tool to bridge design practice and research. (Stappers 2007, 81-89)

Through the creation of a physical artefact, in this case a 'textile prototype', new knowledge is gained in the "practice-based" research. (Candy 2006, 1-3) Generating concepts, building prototypes and observing and evaluating them form an iterative process of five steps: "exploring, conceptualizing, building, testing, observing and reflecting." (Uğur 2013, 3) This 'cycle model' is used in Uğur's (2013) practice-based research studying emotional and sensorial connections between the user and wearable technology. The example was chosen because it is using design-driven prototyping as a way to connect textiles and electronics. The study also acknowledges aesthetics and human needs as central concepts.

The confluence of design practice and scientific methods create a space for applied data collection, observation, and explorative prototyping as seen in **Figure 5**. The five step 'methodology loop' starting with exploration and ending with more questions after each round, has been adapted from the Human-to-Computer Interaction Design process to the thesis process. (ibid. 2- 4) The steps are used as a backbone rather than followed strictly, and the emphasis on design and technology varies depending on the step. For example, applied scientific testing methods play an important part in the 'testing' and 'observing' steps. (Uğur 2013, 2-4; Stappers & Giaccardi 2018) In the following chapter the five steps of the cycle model, and how they are applied to this practice-based research, are explained. The Textile Prototyping Process part gives a more detailed description of the included practical steps.

The Five Steps

The first step, 'exploring' usually includes learning and collecting background information through literature research, questionnaires or surveys. In this case, the previous interdisciplinary project and findings from it served as a basis, together with other related research. Learning the needed weaving skills also required some hands-on experimenting.

In the ‘conceptualizing’ step, ideas for applications and executions for physical products are generated and collected. The need and possible users may be addressed. Some of the big questions like “what” and “for who” had already been discussed during the Energy Harvesting-Sun Powered Textiles project which made this step focus on the practical process. In the textile context, this means gathering ideas for potential materials, structures and designs.

In the ‘building’ step, virtual or physical prototypes that concretize the research questions, concepts and ideas are made for further processing. Properties like feel of the surface, movement, weight, flexibility, and response to the surrounding light cannot be imagined without a physical artefact. Therefore textile skills like weaving, dyeing and surface design were used to create tangible materials for testing. In the final round, the prototyping step also included some electronics fabrication.

The ‘testing and observing’ step is for qualitative and/or quantitative data collection using the created prototype as medium. In “controlled settings” behavior of possible participants is observed, and the process is documented for further analyze. Instead of evaluating user experience, the step was adapted to this thesis for collection of scientific measurement data about the textile prototypes. The changes in short circuit current when covering the test solar cell with a textile were measured. The Department of Applied Physics solar cell measurement laboratory facilities were used to ensure stabile conditions during the process. The final round of textile prototypes went through a more detailed process and the gathered data included quantum efficiency, spectral transmittance, and current-voltage curves of the prototypes.

Finally, in the ‘reflecting’ step, ideas and further questions are collected to prime the next cycle. The generated measurement data was compared, and the materials ranked according to their performance. Also, design and suitability for the purpose of photovoltaics integration were evaluated. Showing the prototypes of the final round at Tekstiili18 exhibition presented an opportunity to discuss and receive feedback from outside the project.

Prototyping textiles

Prototyping is a widely used practice in product and service design. It is a quick way to visualize ideas and transform them into tangible experiences that can be discussed and evaluated. Simple or more sophisticated three-dimensional sketches allow gathering valuable data about the project without large investments. The process is open for trial and error, and invites people to discuss the potential, and find alternative approaches to the case or problem on hand. (Hallgrimsson 2012, 15-18) In the MA thesis How Design Can Contribute to Materials Research (2014), Itälä studies how ‘explorative prototyping’ could also be used to benefit more abstract interdisciplinary research. Through case studies he states that including ‘nonlinear’ design-thinking in material science could help to envision futures and “contextualize” the theoretical knowledge. (p. 136)

The terms ‘prototyping’ or ‘explorative prototyping’ are not commonly used in connection with traditional textile design or handweaving even though the processes have similarities. In functional textiles however, prototyping is used as a method for technical development. Designing woven textiles for the industrial or handlooms is a unique process which involves planning, sketching, choosing materials, designing patterns, drawing the weave structures, testing, and the physical act of weaving. Weaving practice is interplay of technical knowledge and aesthetics. Limitations of the technique and materials provide clear boundaries for expression, and creativity feeds on learning technical skills. (Willmann & Forss 1996, 11-20) The outcome is a combination of interlaced fibers that behave in different ways depending on the structure. In this thesis work I use the term ‘textile prototype’ because it highlights the selection of textile strategies as a framework for explorative prototyping.

solar simulator at the Department of Applied Physics solar cell measurement laboratory

Applied data collection

Generating systematic data creates opportunities to invent novel design solutions and understanding the material and functionality more deeply. A designer on the other hand, can bring additional tools and a different perspective to the scientific method as discovered in the interdisciplinary research by Townsend et al. (2017). During the science-led process, the textiles designers role started shifting from “passive” to taking part in the data collection process. The scientific methodology was adapted so that it could be used by the designer for independent examination of materials and using the data for textile development. This shift in direction resulted in contributions that would have been missed if everyone stuck to the original plan and only stayed in their area of expertise. Adjusting scientific methods so that they can be used by designers during the creative process enables overlapping of fields. This could help to “bridge the gap” between science, technology and design in interdisciplinary projects. (ibid.)

2

BACKGROUND & RESEARCH

The following part explains the positioning of the work in the fields of e-textiles, functional textiles and textile design. The background research around the subject of solar energy harvesting textiles includes comparison of different solar cell types for textile fabrication purposes, and previous research on photovoltaic textiles.
A description of a previous related project *Energy Harvesting- Sun Powered Textiles* is also included as background for the following process.

POSITIONING & PREVIOUS WORK

Smart textiles, wearable electronics, e-textiles and functional textiles are closely connected interdisciplinary research fields. The concepts are often overlapping and from engineered fibers to textiles with integrated electronics, a whole range of materials can be bunched under the same terms. A remarkable variety of topics are connected and dependent on each other in the different stages of smart textiles and wearables creation. When progress is made in any of the related areas, it affects the whole ecosystem. (Stoppa & Chiolerio 2014)

In *Multidisciplinary know-how for smart textiles developers*, Tünde Kirstein (2013) explains that an object or textile becomes smart when its property changes are “rapid and significant”. The “level of smartness” varies depending on the objects ability to react to the surroundings. Phase-change, shape memory, and temperature-sensitive color changing materials are examples of lower level smart materials that react to the surroundings in a significant way but do not require programming or electrical stimulus to do so.

Achieving a “higher level of smartness” is possible by integrating electronics to textiles in fiber, structural, or product level. These textile electronics can be programmed to operate in various ways, collect data through sensors, communicate with the user, and even learn. With artificial intelligence, future textiles could function like a human brain: make independent decisions and solve problems. (Kirstein 2013, 1-5)

According to Elina Ilen (2015), ‘smart textile technology’ is also defined by interaction and reaction to the “external stimuli”. (p. 17) In her thesis *Decontamination of Wearable Textile Electrodes for Medical and Health Care Applications* (2015), Ilen clarifies the various terms and their relationships that are used in academia around the subjects of ‘smart textiles’ and ‘wearable technology’. The figure above is based on her structuring of the field. Similarly to Kirstein (2013), Ilen (2015) implies that smart textiles may include electronics or interact with the surroundings through other intelligent properties. If electronics are integrated to smart textiles, they become ‘textile electronics’. These include all kinds of energy harvesting textiles which can be used for both wearable uses or non-wearable applications like textile architecture. Electronic textiles with functional features such as conductivity are outside of the ‘smart textile technology’ category, in ‘functional textiles’. (Ilen 2015, 15-20)

In the **Figure 6**, woven textiles with integrated energy harvesting photovoltaics are positioned inside the ‘Electronics embedded to textile’ category which is another category under ‘textile electronics’. Because photovoltaic energy harvesting textiles include electronics and smart materials e.g. conductive fibers, but don’t necessary result in changes of properties in the textiles, they could also be categorized under functional textiles with embedded electronics. (Ilen 2015, 15-20) In textile design, ‘functional textiles’ is a common term used in connection with woven and knitted textiles and nonwovens in various industries from outdoor clothing to automotive industries. The specific function is achieved with choice of materials, production method, structures or finishing. Examples of textiles where the function is attained through design of textile structures are acoustic textiles and compression textiles. However, even in very artistic textile practices in fashion or haute couture fabrics, textiles have sought inspiration from technology and functionality.

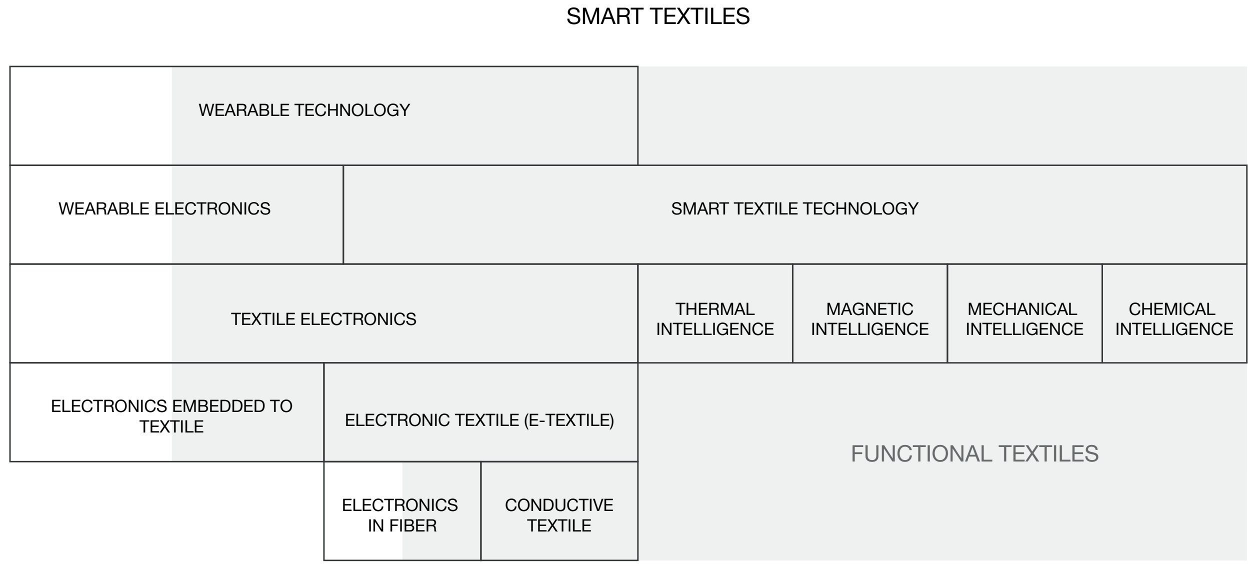


***Fig 6**: smart textiles terms and their relationships*

At Aalto University there has been research on various functional textiles. Oldouz Moslemian’s thesis *Performative Compositions/ Material Behaviour as an Active Agent in Design and Fabrication* (2016) looks into building kinetic systems by using electric activation of textiles. In Moslemian’s work, textiles and 3D printing are used for fabrication. Around textile electronics, there are two previous MA theses from Aalto University: Romyah Gowrishankar’s *Designing Fabric Interactions- A study of knitted fabrics as an electronic interface medium* (2011) and previously mentioneld Emmi Pouta’s *Worn Identities- Interactive textiles as extentions of future bodies* (2016). Gowrishankar studies integrating electronics into knitted textiles and uses the textile material as a medium for creating tangible interfaces. Emmi Pouta has been focusing on woven electronic interactive textiles. The “Heat Harvest” project (Townsend, Karttunen et al. 2017) is one example of an interdisciplinary project on energy harvesting at Aalto University. However, no work covers the topic of integrating solar cells into textiles. Related research from other sources is opened up in next chapters of this part.

organic solar tape

SOLAR CELLS

Solar cells are a 150 billion euro business and the most common technologies are decades old. The biggest potential for technical innovation is in the new technologies including thin film and polymer solar cells. Currently they only cover around 10 % of the market, but in an enormous field like photovoltaics even a small percentage can be significant. (P. Lund, personal communication, October 11, 2018)

Silicon solar cells (Mono crystalline and Poly crystalline) are the oldest and most used technology, ruling the markets with over 80%. They have been developed since the 1950s and perform at high efficiency today. Silicon solar cells are rigid and therefore usually not used for e-textiles purposes. However, because of their high efficiency, a very small silicon-based PV structure can provide good amounts of energy. (Mertens & Roth 2014, 15-21)

Thin film solar cells are described as 'second generation solar cells'. These include CIGS (Copper Indium Gallium Selenide), CdTe (Cadmium Telluride), and amorphous silicon solar cells (a-Si). Thin film solar cells are more flexible than silicon solar cells, use less material in a less energy intensive production method and therefore have a shorter energy payback time. The drawback of CIGS and CdTe solar cells is the scarcity and even toxicity of some of the used materials. Amorphous silicon solar cells are non-toxic and a very promising technology but there are challenges with the electrical output dropping significantly after some months of use. Because of their other good properties amorphous silicon solar cells are commonly used for photovoltaic energy harvesting accessories. (Mertens & Roth 2014, 108-118; Coursera 2018; J. Halme, personal communication)

'Third generation solar cells' include Polymer solar cells, which are also under the class of organic solar cells. Other organic solar cells are dye-sensitized and hybrid PV cells. Polymer solar cells are very thin and they can be printed on transparent plastic in various patterns. The energy payback time is less than three months and they can be manufactured of carbon, oxygen, sulfur and hydrogen which are abundant on earth. Even though the efficiencies are low, they are improving fast which make them an interesting future technology. (Mertens & Roth 2014, 120; Coursera 2018)

All of the previous groups include technologies that could be used and developed further for smart textiles purposes depending on the application, product and material.

<u>Pros and cons of three different solar cell types</u>

Silicon solar cells:

+ silicon material is abundant on earth (silica = sand)
+ high efficiencies: best technologies on the market over 20% → smaller area required
+ absorb a broad range of light spectrum
- energy intensive process → long energy payback time: 1.6- 4.5 years
- thick and rigid

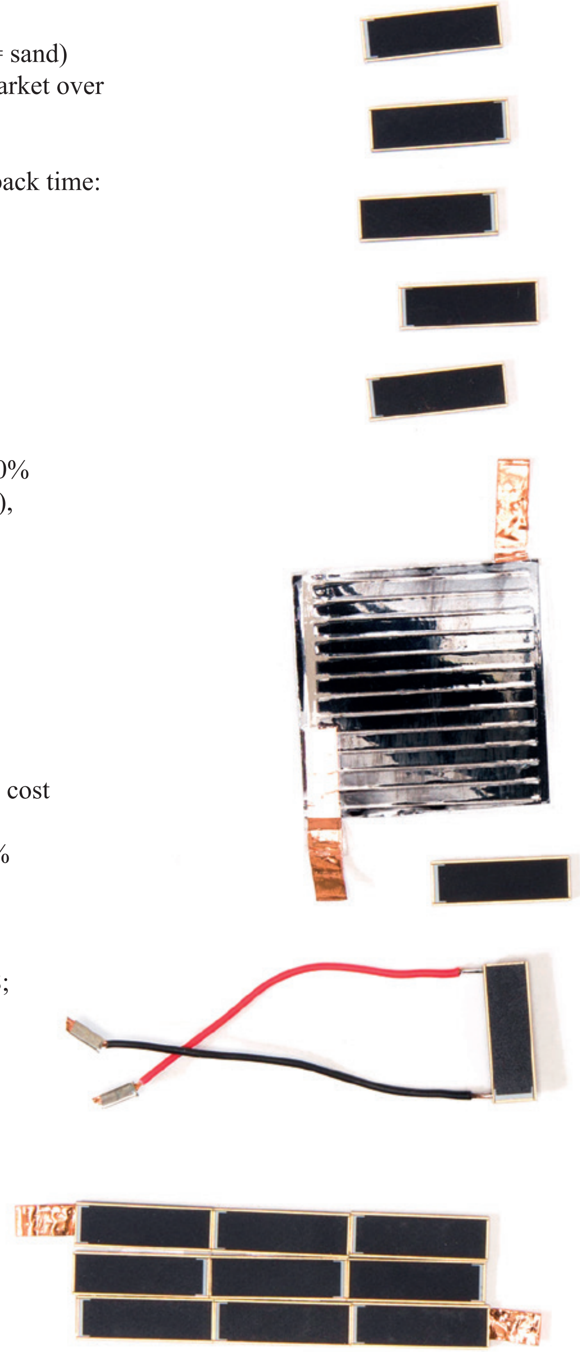
Thin film solar cells:

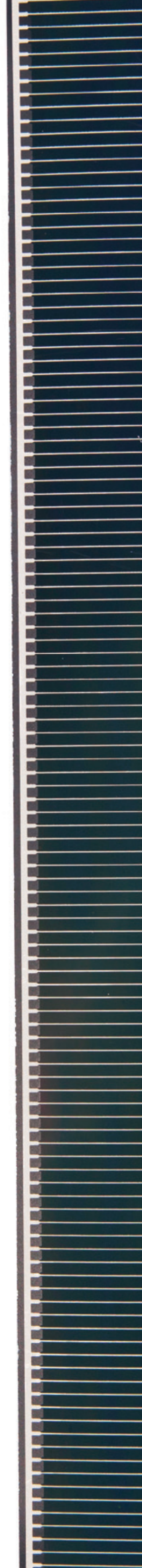
+ flexible
+ less energy intensive production
+ good efficiency, best research cells around 20%
- Cadmium is toxic and scarce (CIGS modules), Tellurium is rare (CdTe modules) → long term limitations in filling energy needs

Polymer solar cells (organic solar cells):

+ Flexible & thin
+ Low environmental impact
+ Fast manufacture & installation speed →low cost
+ possibility to print in patterns and colors
- low efficiency, best research cells around 12%
- currently only absorbs visible and UV light
- stability issues

(Mertens & Roth 2014, 15-120; Coursera 2018; NREL 2018; Fraunhofer ISE 2018)





right: flexible CIGS solar cell
from top to bottom: small silicon solar cells, customized piece of CIGS solar cell with copper tape conductors, silicon solar cells attached as a module with copper tape conductors

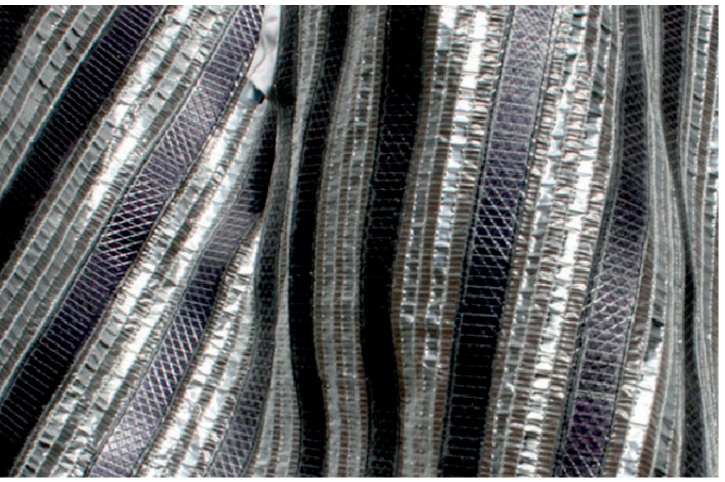
Beam backpack, 2018

Pauline Van Dongen: Windbreaker project, 2016

Ralph Lauren RLX solar panel backpack, 2011

knitted solar curtains by Petra Blaisse & Textiellab, 2015

solar-powered jacket by Junya Watanabe, 2016



woven thin film solar cells by Sheila Kennedy, 2007

Integration of solar cells to our lives: future & now

With solar panels becoming a permanent part of the living environment their aesthetics gains importance. For photovoltaics, black and very dark colors are common because they absorb light most efficiently and thus produce the most current. (PV-tech 2018) Photovoltaics can be manufactured in various colors but it has a negative effect on the performance. Still there is interest in coloring and re-designing solar cell modules. Tesla has created a solar roof that looks like regular tiles and completely blends into the architecture of the builing (Tesla 2018), and a swiss company Solaxess among others is developing colored and even white facade materials with hidden solar panels. (Solaxess 2018) An interdisciplinary project by Moor et *al.* (2017) on the other hand used textile design strategies to create repeating multicolored patterns for solar cells. In the future all new buildings could be constructed using beautiful and/or invisible photovoltaic building materials to supply residents with renewable energy. (Sciencemag 2018)

In textiles, intelligent integration of photovoltaics could make the technology invisible. Energy harvesting and other smart technology would bring additional functionality to the already usable textile. When searching solutions for energy harvesting photovoltaic textiles, three approaches for integration are most common: fabrication of ready-made flexible photovoltaics on the surface or inside textile, producing photovoltaic yarn for weaving or knitting, or to print solar cells on textile-like “flexible substrates”. (Lund et *al*, 2018; Bayramol et *al*, 2017)

The research by Yun et *al.* (2015) demonstrates a textile woven of dye-sensitized solar cells electrode components and glass fiber on a nylon and glass fiber warp. The possibility of weaving wire-shaped solar cells into a textile is also showcased in a study by Zhang et *al*. (2016). Dye-sensitized solar cells may also be printed straight on glass fiber textile. (Opwis et *al*, 2016) However, the method requires extremely high heat and can only be applied to very smooth surfaces. And even though remarkable efforts are being made to create photovoltaic fibers, they are still very bulky and resemble more an electric wire than yarn for textile production. None of these processes are yet suitable for wearable purposes.

With usable photovoltaic yarns and printing of solar cells straight on fabric still being a long way from mass-production, integrating ready-made solar cells is the most common way to create energy harvesting photovoltaic textiles and clothing. This is usually achieved by sewing solar cells on the surface of a textile, weaving or knitting them as a part of the textile construction, or inserting them in “transparent pockets”. (Bayramol et *al*, 2017) Knitted solar curtains by Petra Blaisse and TextielLab show an example of integrating ready-made solar cells to a product by designing the textile structure. (Textiellab 2018) Sheila Kennedy has done the same by weaving thin film solar cells to be a part of the curtain textile. (CNN 2018) Fabrication of photovoltaics by sewing and transparent pockets has been used in various energy harvesting clothing, accessories, camping gear, and even sails. (Solar Cloth Systems 2018; Sailmagazine 2018)

There are a couple examples of relatively seamless photovoltaics integration to product design. In Pauline Van Dongen’s ‘windbreaker’ project the photovoltaics are designed to become a part of the garment’s aesthetics. (Pauline Van Dongen 2018) Kingsons minimalistic Beam backpack promises to charge an iPhone in 2,5 hours in addition to other useful features. (Hypebeast 2018) However, the problem with most of the current products is that the solar cells are very visible and define the look of the product. When staying on the level of garment construction, the alternatives for innovative solutions wear thin quickly.

In integration of photovoltaics to textiles, the full potential of using textile structures, materials, and design hasn’t been realized yet. Even the previously mentioned solar curtain examples are very strongly focused on the function and don’t explore the possibilities of textile design strategies. Also, in all of the previous examples the design or part of the design is black due to the color of the photovoltaics. This is a major restriction, and could be one of the main reasons why photovoltaic energy harvesting textiles, clothes and accessories haven’t gained wider popularity.

energy harvesting jacket prototype

ENERGY HARVESTING-
SUN POWERED TEXTILES PROJECT

In this section I will describe the Energy Harvesting-Sun Powered Textiles- project that took place in 2017. The objective of the joint study was to start a collaboration between Aalto University New Energy Technologies Group and the Design Department, and look for future possibilities in combining the two areas. During 9 months we were meeting regularly, discussing related subjects, and brainstorming ideas on how to link energy harvesting to wearable applications.

Starting point

The project was kicked off in February 2017 by professors Peter Lund from Engineering Physics and Jaana Beidler from the Design Department. The funding was provided by the Aalto Energy Platform. Other team members were university lecturer Janne Halme, and students Sakari Lepikko & Alpi Rimppi (New Energy Technologies Group). From the Design Department, other participants were lecturers Ilona Hyötyläinen, Anna-Mari Leppisaari & Tiina Aarras, and students Eveliina Ronkainen & Sandra Wirtanen. Anni Lehtosalo (student, Department of Design) participated during the early concept design phase; postdoctoral researcher and smart textiles expert Elina Ilen and professor Kirsi Niinimäki joined the group in a later phase.

There was no specific assignment to start with, so in the beginning our team mapped out the field of smart textiles and advances around the technologies involved. The realization was, that there is a lot of research around smart textiles and wearables but the products on the market are still low level, far from the high tech promises of intelligent clothing. For example, a thermoregulating shirt by Clim8 includes a bulky battery on a very visible spot, and sensoria smart socks come with a rigid non-flexible ankle band. (Clim8 2017; Sensoria 2017) Very specific applications for workwear and professional sports are exceptions providing instant benefits for the users. A firefighters attire that reduces risks of fatal accidents is a good example of added value from wearable electronics. (Aumann, S. et *al*, 2014) However, the products aimed for regular consumers seem like extra gadgets that are not fitting for everyday use. In addition to that, one of the problems we found was the design of the existing products. Starting from the textiles and materials to the construction of garments, and encapsulation of technology, the products are mostly lacking attractiveness and a user friendly angle.

Because of the previously mentioned reasons, our student team didn't want to design another gadget. We felt that there is a bigger need for materials and products that allow building intelligent platforms with several possible applications instead of focusing on one specific use. Therefore we chose to focus on the concept of energy harvesting photovoltaic clothing and accessories. The generated energy could be used for charging and powering all kinds of wearable technologies, or devices that we carry with us.

We realized that many of the interesting technologies still require a lot of development until they can be used for clothing purposes. Especially the research in photovoltaics takes time and innovations like dye-sensitized solar cells or energy harvesting fibers are still far from usable for garment purposes. This is the reason our group ended up working with ready-made/existing solar cell technologies including small silicon solar cells and flexible thin film PV's. By focusing on the level of integration of technology into the material we could generate new knowledge by using what already is available.

Research

The Energy Harvesting-Sun Powered Textiles -project aimed to create different ways to attach solar cells to garments than the mostly used transparent pockets. Also, we wanted to test incorporating color to the design process. As a basis for the research was a hypothesis that solar cells could be used even when covered with a textile layer. The idea of enough infrared rays penetrating through fabrics to be useful for most of solar cell technology was proposed by University Lecturer Janne Halme. To prove this, our student group gathered ready-made textiles and measured how hiding solar cells with them affected the performance.

Most of the tested textile samples were functional woven fabrics or nonwovens for outdoor or sportswear purposes, but the selection also included fabrics made of natural fibers and knits. Various thicknesses, structures, and surface designs were chosen for testing. We also used multiple color selections of same textile qualities to see if there was a difference between colors. After the first test round, more detailed measurements followed with a solar cell spectral response measurement system. This method was very useful for gathering primary information about the influence of different colors and textile properties. The data helped us to choose and order suitable fabrics for the product prototypes.

Results

With the measurement data we were able to prove that covering photovoltaics with textiles allows still good amounts of visible and infrared wavelengths to pass through. Depending on the textile covering a solar cell, the harvested energy could be enough to power various applications from sensors to smart watches or mobile phones. By testing various colors of the same textile, we found that the color had a major impact on sunlight penetration through the textile. White or light colored textiles performed best but dark shades or black prevented the light to reach the solar cells.

Based on the findings our student team developed two concepts and built functioning prototypes showcasing possibilities of integrating solar cells to clothing: An energy harvesting jacket and a sun sensor accessory. The first concept, a 'Sun jacket' is an energy harvesting garment for charging smart phone or other portable small devices. The jacket functions both as a protective lightweight garment against sunburn, and an energy harvester. We used extremely light N66 Polyamide fabric and knitted Viscose mesh as textile materials. The knitted parts were produced with the industrial ADF knitting machine at Aalto University Design Department. For the PV technology we chose to customize thin film CIGS solar cell units. The solar cells were inserted to the garment construction by ultrasonic sewing.

The combination of sublimation print on the top layer textile, and arrangement of the PV modules in a geometrical shape created a solar powered design on the back of the jacket. A DC/DC converter and USB port were connected to the photovoltaics using conductive textiles to enable plugging in the device with a cable. The modular design of the jacket makes it possible to remove the energy harvesting part if needed. In theory, all parts of the technology could be made waterproof which would make washing of the whole garment possible. With the Sun jacket it is possible to charge a smart watch in only 30 minutes under full sunlight. This is a unique achievement when taking in account that the photovoltaics are camouflaged into the design and nearly invisible.

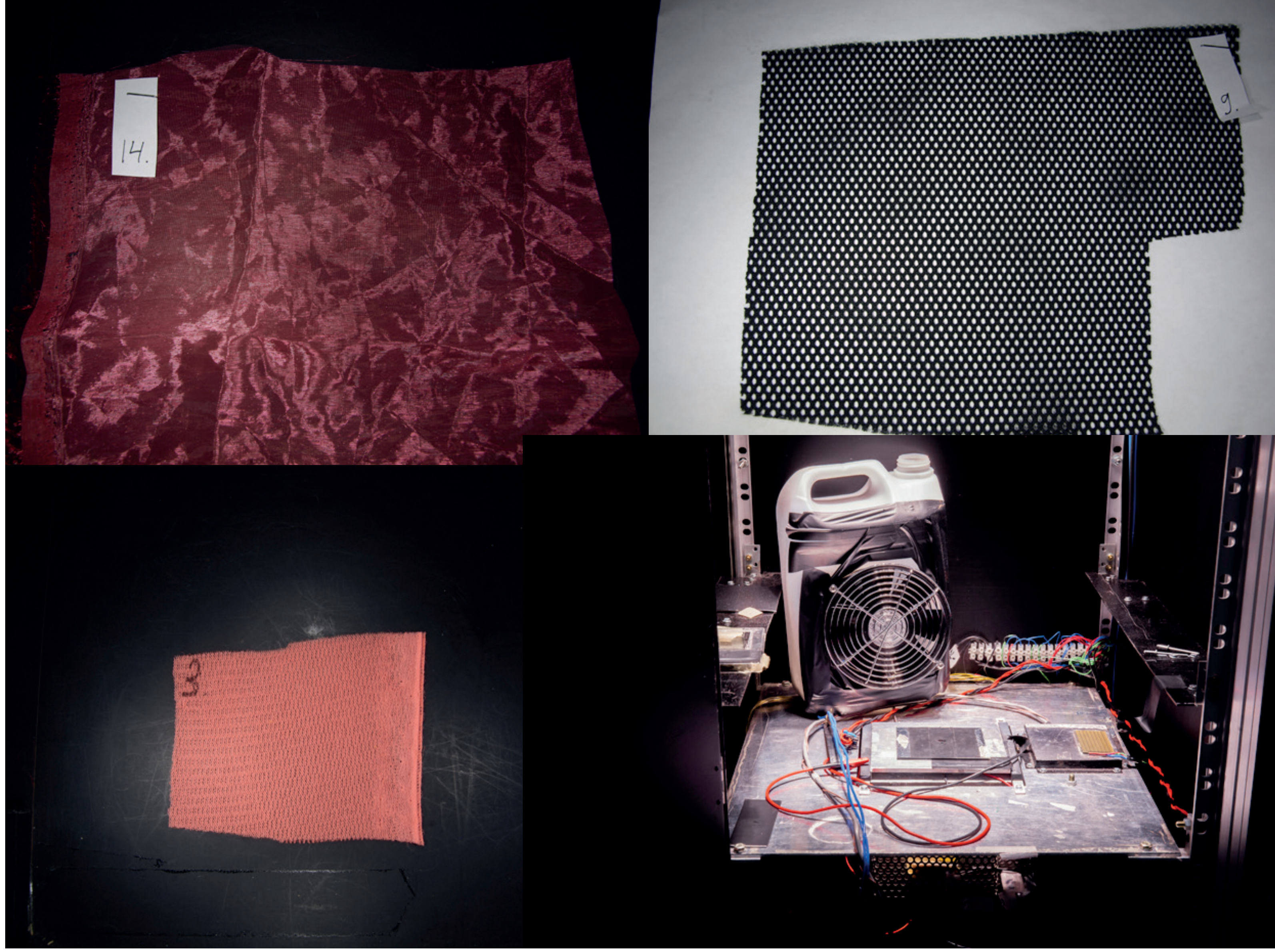
The second concept, a 'Sun sensor' is a self- powered UV monitoring system. It allows collection and communication of UV level data to the user via smartphone app. In this concept we used small rigid silicon solar cells with relatively good efficiency. (16%) The solar cells and other technology such as Bluetooth, DC/DC converter and Arduino were hidden inside a 3D printed cover. 3D printed soft filament allows creation of flexible casings to encapsulate technology and unique shapes can be created to fit the need. The same material concept for integration of wearable technology could also be used for other sensors and uses as well. Instead of standard rigid cases, electronics could be hidden inside colorful, textile-like and versatile materials.

Final thoughts on the project

During the project our group was able to use strategies from both science and design to innovate in the area of photovoltaic energy harvesting garments and materials. The concept of energy harvesting garments and accessories with hidden photovoltaics was interesting and new, and everyone was motivated to work with the subject. Most of the knowledge was gathered during conversations and spending time together working hands-on in the laboratory or design department. These were very rewarding moments and highlighted the advantages of physical presence in an interdisciplinary project. Face-to face interaction made communication easier because the different ways of working, skills and methods became visible. It was easier to ask questions and seek for answers together with everyone in the same room.

One of the challenges however was project management. Without a very clear goal and a leading figure in the project, a lot of time was spent on bouncing ideas back and forth that didn't always take the project further. This of course is a natural part of projects involving designers and explorative design-led methods. Focusing on one subject from the start gives much needed boundaries in an otherwise unfamiliar process. Also, at first it was challenging for me to understand what the possibilities of our group were because I didn't know the backgrounds and previous research that the members had done. In hindsight it would have been helpful to collect a list of our skills and create a common 'tool box'. Knowing the strengths, interests and areas of expertise of the group members could be a great source of inspiration.

The biggest difference between designers and scientists in our group was in my opinion in how we understand a prototype. Designers are used to making mock-ups that resemble the material, product or technology without necessarily functioning like the final product whereas in research the prototypes often focus on technology only and don't include an idea for a use or user. The level of compromise from both sides depends on the emphasis of the project and therefore it should be clear from the beginning.
In our conversation after the project had ended, Halme agreed that using less time on perfecting



testing process

technical functionality in the prototype allows testing the concept on users and receive valuable feedback. He expressed that 'design-thinking' could provide scientist with interesting new perspectives. (Personal communication 8.10.2018) On the other hand, designers have a lot to learn from science and technology. In my opinion, going deeper into a subject and learning about aspects that usually aren't touched by designers can open interesting new paths. Interdisciplinarity combined with a specific expertise can make us better designers.

There isn't one way to work in an interdisciplinary project and the dynamics of the group always dictate the process. However, I will sum up some learnings from the project that might be helpful in future processes that include designers and scientists:

-find a clear (but not too strict) goal, and leader/ facilitator for the project
-define the level of functionality for the prototype depending on the emphasis on design or technology
-build a tool box of all skills, interests, methods etc. to be used during the process
-ask questions and learn as much as possible from each other
-share a space

These experiences are also in line with the advice from "Recipe for Successful Collaboration" (Kääriäinen & Tervinen 2017, 17) The similarity in observations suggests that my experiences were not unique, but very common in collaboration projects. I find it very encouraging because this means similar tools and facilitating methods could be used for many kinds of interdisciplinary projects.

THEORY

In this chapter the theory behind the data collection process, and different factors affecting sunlight transmittance through woven textiles are presented. The related research together with findings from the previous project form guidelines for the following textile prototyping process.

Efficiency of a solar cell is the power output of the solar cell divided by the incoming power (from sun radiation or other illumination source)

$$\eta = \frac{P_{out}}{P_{in}}$$

The input **power density** is defined as 1000 W/m^2 which roughly corresponds to bright sunlight on a clear day when the sun is high in the sky and the solar cell is facing the sun.

The solar cell efficiency can be expressed in terms of three characteristics: the short-circuit current density J_{SC}, open-circuit voltage V_{OC}, and fill factor FF:

$$\eta = \frac{J_{SC} V_{OC} FF}{P_{in}}$$

The fill factor is related to the shape of the **current – voltage curve** of the solar cell, and is defined as

$$FF = \frac{J_{MPP} V_{MPP}}{J_{SC} V_{OC}}$$

where J_{MPP} and V_{MPP} are the current density and voltage at the current-voltage operating point where the solar cell delivers the maximum power output: $P_{out,max}=J_{MPP}V_{MPP}$. The above equations help understand how integration of solar cells into textiles affect their energy conversion efficiency. A textile covering a solar cell affects mainly its **short-circuit current density** J_{SC} by decreasing it. How big this effect is depends on how much the textile reflects and absorbs light that could be otherwise used by the solar cell. Here, spectral properties are important because both the sensitivity of the solar cell, called **external quantum efficiency** and the optical losses caused by the textile depend on the **light wavelength**. The short-circuit current density can be expressed as

$$J_{SC} = q \int_0^{\lambda_g} EQE(\lambda) S(\lambda) d\lambda$$

Where $S(\lambda)$ is the photon flux per unit area incident on the solar cell, $EQE(\lambda)$ is the external quantum efficiency of the textile-covered cell, and λ_g is the longest light wavelength that the solar cell is sensitive to and q is the elementary (electron) charge. The external quantum efficiency of a textile-covered solar cell can be written as

$$EQE(\lambda) = T_{textile}(\lambda) EQE_{cell}(\lambda)$$

where $T_{textile}(\lambda)$ is the spectral transmittance of the textile, and $EQE_{cell}(\lambda)$ is the external quantum efficiency of the uncovered solar cell. The **spectral transmittance** tells how large a fraction of the incoming light photons are able to pass through the textile at each wavelength. EQE tells how many of these photons are able to generate an electron to the external circuit connected to the cell.

The spectral transmittance of the textile depends on its spectral reflectance $R_{textile}(\lambda)$ and absorptance $A_{textile}(\lambda)$ as

$$T_{textile}(\lambda) = 1 - R_{textile}(\lambda) - A_{textile}(\lambda)$$

Textile properties affecting the performance of integrated photovoltaics

There isn’t one research that examines all textile properties and how they affect visible light and near-infrared transmittance through the fabric. However, the collected data from the *Energy Harvesting- Sun powered textiles* project suggests that at least color has a big impact on the performance of solar cells.

Most common solar cells use both infrared and visible light for energy harvesting, and even some UV. Studies around textiles and their impact on absorbing near-infrared and ultraviolet wavelengths of the electromagnetic spectrum prove that the density, weight and thickness of textile are defining factors in sunlight penetration. (Wang *et al.*, 2014; Dubrovski & Golob, 2009) In the study by Wang et al. (2014), 47 various plain fabrics were tested for the differences in near-infrared transmittance of woven textiles. The materials included 100% Cotton, 100% Silk, 100% Polyester, 100% Nylon, 100% Linen, and various combinations of these fibers. It was found that the fiber type only had a slight influence on the transmittance. “Thickness, weight per square meter and percentage cover of the fabrics” on the other hand had a direct correlation with how much near-infrared passed through the textile. (Wang et al, 2014) In textile terms these can be translated to fabric weight, yarn construction and yarn weight (Nm, denier), and warp and weft density (ends/cm, picks/cm).

Research by Zhang et *al.* (2016) demonstrates how different woven structures affect the performance of the wire shaped photovoltaics. In their study, plain weave showed to be the best option for a single-layered photovoltaic textile prototype. Compared to twill and sating it offerend the “largest effective illuminative area” and thus the best performance. (ibid.) The research of Dubrovski & Golob (2009) on UV shows similar results. According to their research on the effect of woven structure on ultraviolet protection, plain weave allowed most radiation to pass through. The structure provides “naturally higher thread passages” which results in the radiation to penetrate more freely. Satin and twill weaves proved more effective in blocking UV because the structures make it possible to achieve a higher weft density. (Dubrovski & Golob, 2009) In the case of integrating solar cells into woven textiles, a free passage of solar irradiance through the textile is aimed for.

Color is an important factor for performance of photovoltaics as well as design when aiming to hide the technology. In UV protection of textiles the color can have an even greater influence on the level of protection than the weave structure or density of the textile. (Dubrovski& Golob, 2009)

Summary

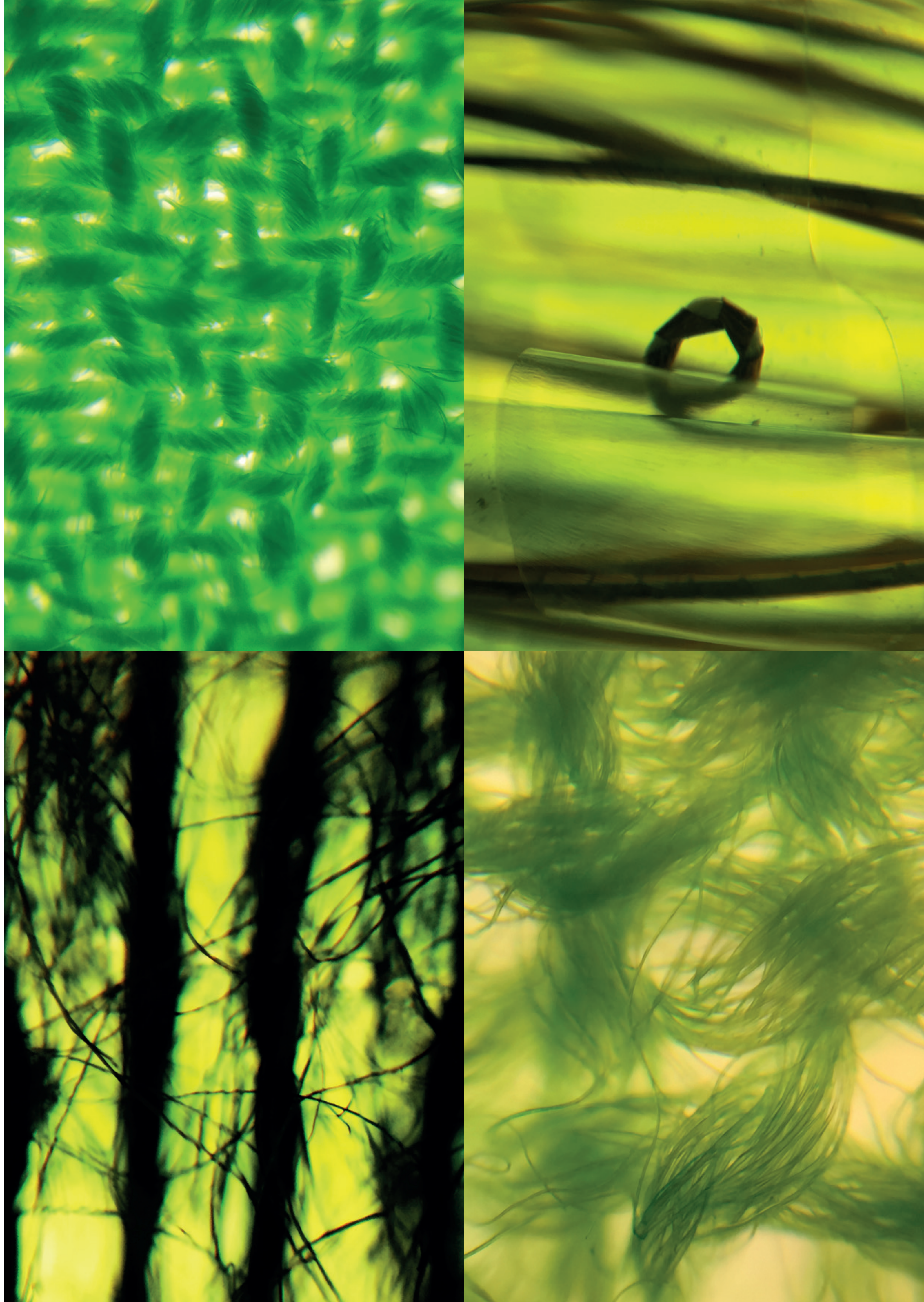
According to the previous information, the following features of a textile predict good conditions for minimum decrease in the efficiency of a solar cell:

1. transparent, white or light colors

2. small percentage cover of the fabric
- low warp & weft density
- weave structures with higher thread passages eg. plain weave

3. light materials

During the textile design and weaving process, adjusting all of the previous variables is relatively easy. In multi-layered woven jacquards it is possible to vary the warp and weft density and choose materials according to their thickness and color. In addition, surface design can be used to build texture and patterns. This makes weaving a well suitable textile method for integrating technology.



close-ups from different woven textiles

3

TEXTILE PROTOTYPING

In this chapter, I will open up the process of creating woven textile prototypes for photovoltaics integration. As mentioned before, the following project continues on the subject that was started during the Energy Harvesting- Sun Powered Textiles project and uses the data and experience as a basis. I also continued working with Janne Halme as an advisor from Department of Applied Physics, and Kirsi Niinimäki from the Design Department. Both were already familiar with the journey which made the shift to the next part of the process organic.

BACKGROUND, LEARNING & PROCESS

Energy Harvesting photovoltaic clothing and accessories had evoken my interest to dig deeper into the structure of fabric. Coming from a textile background, I saw the opportunity of improving the level of integration by using my knowledge in advanced woven fabrics and design. I realized my ignorance about solar cells was limiting me and being able to continue I had to learn more about photovoltaics. Hands-on work around the subject had already taught some things about existing solar cell technologies and what is possible, but I was missing an overall picture of the field. Taking a free web course Introduction to Solar Cells by Technical University of Denmark (Coursera 2018), helped to understand some basic principles and fill in the gaps that had bothered me earlier. During the course, I learned about history, the three generations of solar cells, and their working principles. Getting familiar with the key vocabulary was important because I could look up answers to my questions independently and read through related research.

Another realization was, that fabricating electronics for all prototypes was out of question in the given time. So, I made the conscious choice to use separate solar cells for testing, and focus on the textile structures that allow integration instead of creating fully functional prototypes. For the testing, two different solar cells were used at first: a 22 mm x 7 mm monocrystalline silicon solar cells (IXOLARtm High Efficiency SolarBIT by IXYS) and a 70 mm x 13 mm piece of flexible organic solar cell foil (Solar Tape by infinityPV). The measured average efficiency of the IXYS solar cell was 12% while the promised efficiency of infinityPV organic solar cells is 2% and up. During the first tests it became clear that the organic solar cell was difficult to measure with the used method due to stability issues. Therefore only the monocrystalline silicon solar cell was used for the testing phase. However, because organic solar cells represent possibilities of the future photovoltaics they were used for demo purposes despite their deficiencies.

Visual starting point

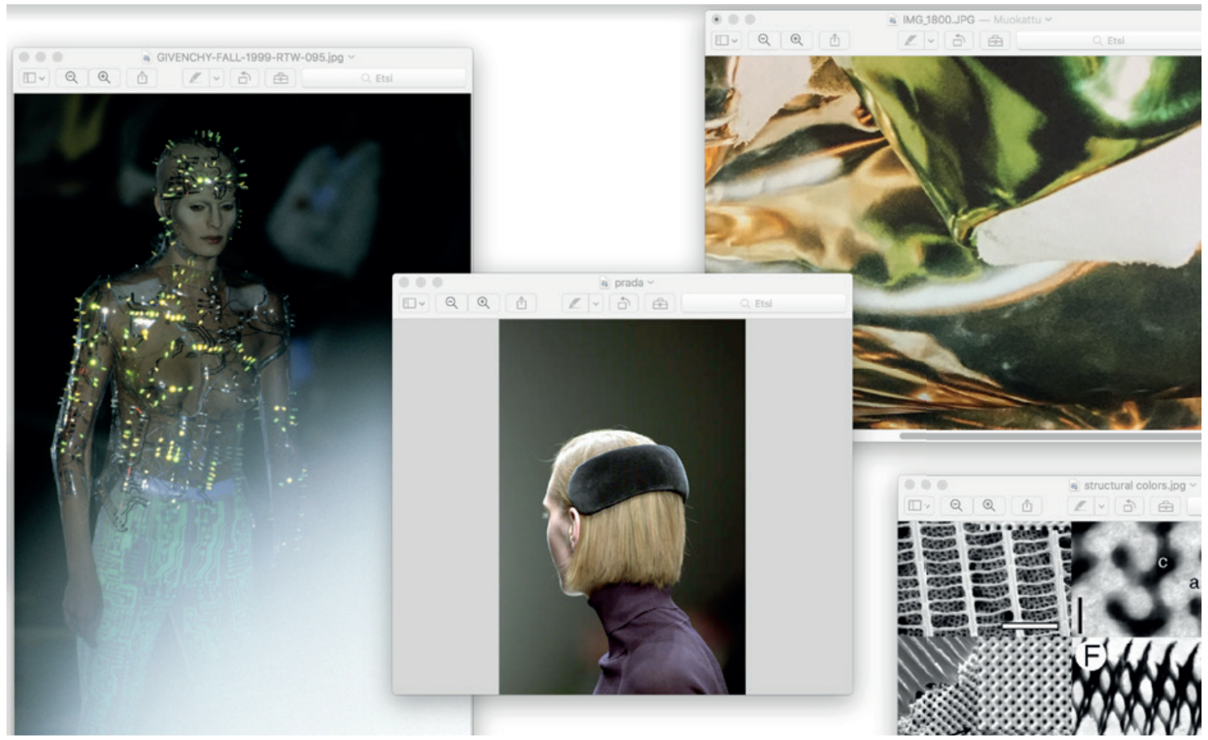
Ideas for textiles started emerging early on, but I tried not to restrict the process by thinking of the designs, collection, or end application too much. Usually I would start with visual research and making a color and material chart. This time, however the starting point was the technology rather than aesthetics, so I ended up making the aesthetic choices along the way. Still, there were some images and ideas that followed me through the process creating some boundaries, and helping to curate the final textile prototypes.

From the start, I was fascinated by the idea of combining traditional weaving patterns and techniques with future technology. Visual starting points combined traditional textile motifs like checks and diamonds to microscopic patterns from structural colors, and references from 90s technology-inspired fashion. The Alexander McQueen's f/w 1999 collection for Givenchy included 'tech couture' pieces with led lights, and fashion designs drawing from computer aesthetics. (Vogue, 2018) As inspiration for the possible product applications, I had Japanese Furoshiki and late 90s and early 00s Prada accessories. Japanese Furoshiki cloths are pieces of fabrics that are traditionally used for wrapping goods and gifts. The simple textiles can be transformed to endless, elegant shapes. (Wikipedia, 2018) I found the idea of a multi-purpose cloth that can be opened as a sheet and morphed into a carrying device interesting for Photovoltaic energy harvesting textiles, and even learned some of the folding patterns. The referred Prada accessories on the other hand play with placement and size of different purses, pockets, kerchiefs, and headbands. (Prada 2018)

Materials, weaving, dyeing

At first, I was considering knit as another textile strategy but after the first trials, weaving took over as the preferred prototyping method. I came into the conclusion that weaving suited the objectives of my research better. Weaving allows experimentation with a larger variety of materials than handmachine knitting including stiff and very light yarns. Also, woven textiles are naturally less stretchy than knits and therefore the material properties are better suitable for both rigid and flexible photovoltaics integration. With computer-aided jacquard looms it is possible to produce almost any industrial weave structure by handweaving, whereas advanced knitting requires sophisticated machinery and a professional operator.

For the explorative prototyping process, I narrowed down the material alternatives to wool, polyamide, cotton, copper and nylon. Wool is a natural fiber and it has properties which make it a good option for smart textiles purposes: It is flame resistant, anti-



moodboard images

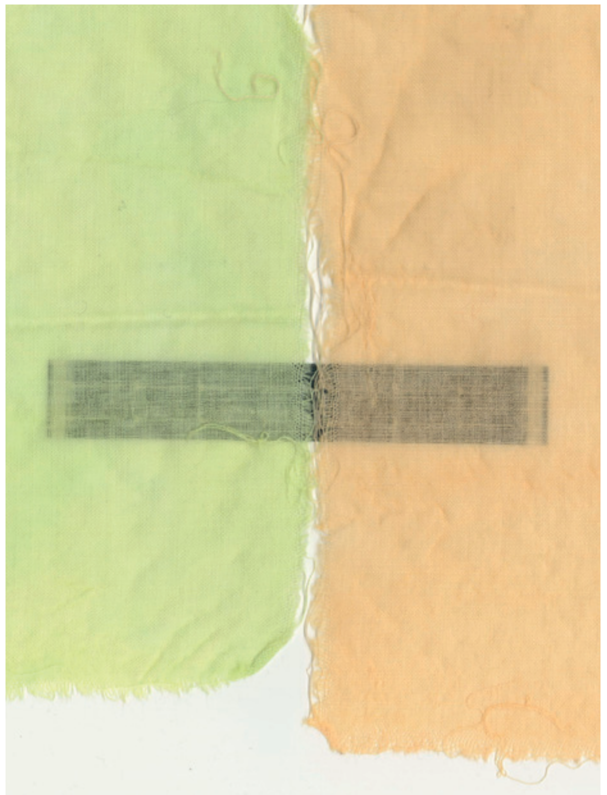
static, repels moisture and soiling, and is comfortable against the skin. Also, it doesn't require washing as often as some other fibers. (American Wool 2018)
Some of the textiles samples were hand dyed with acid dyes to be compared with similar white fabrics. Acid dyes can be used for natural protein fibers and man-made polyamides, and therefore they are suitable for wool, polyamide, and nylon. They have a relatively high lightfastness. During the dyeing process almost all of the color is absorbed to the fibers which means no waste color. (Pellonpää-Forss 2016, 195-196) Because cotton doesn't absorb acid dyes, it is also possible to design materials in which a part of the textile stays colorless/white.

Previous data from the *Energy Harvesting- Sun Powered Textiles* process suggested that dark colors are not most suitable for Photovoltaics integration by covering, so from the start mostly light and medium dyes were used. Inspired by optics I chose transparent, white, green and yellow shades. Human eyes are most sensitive to green and yellow range of wavelengths in the electromagnetic spectrum. This means that in daylight a yellowish green appears brighter and more intensive than for example blue and red colors with similar luminance. (Livingstone 2002, 12-23)

First weave structures were tested by handweaving simple tests with a shaft loom. Creating textiles for a technical purpose meant adopting a functional starting point for weaving as well. A common custom in weaving, handweaving and industrial, is to use previously made weave structures from a sample library as base, and adjust them to suit the design. This method has been adopted to *Advanced Woven Fabrics and Jacquard Workshop* course at the Aalto University Design Department which I attended during spring 2018. Because of the technical restrictions, I could not make use of the library and had to develop the structures from scratch. A lot of trial and error were required before understanding the principle of multilayered weave structures with separate or partly connected layers.

sample no. 4.10,
worsted twill, dyed green

sample no. 4.25,
voltaire wool, dyed green



wool gauze dyed light green and peach

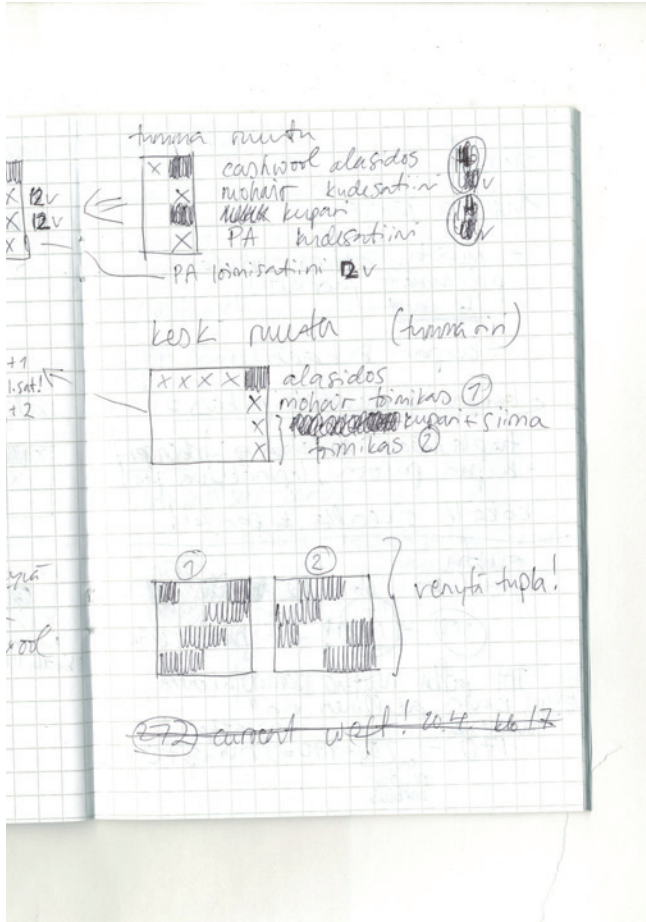
1st round of material prototyping

The first short circuit current measurements were done with ready wool fabrics with different structures and densities. I chose thick and thin wool gauzes and plain weaves, and more dense twills, satins and crepes.

At this phase I was learning about pocket weaves with open layers and experimenting with contrasting materials such as conductive copper wire and fluffy mohair, transparent polyamide and fine merino wool. Sometimes the chosen materials and weave structures reacted to each other surprisingly. Unexpected shrinking occurred especially with the polyamide materials and long floats. Making the material stiffer with copper or fishing line like yarns made the properties more predictable. The looms used for prototyping with 2 warp systems were a clear polyamide Lurex warp and a 16 shaft black and white silk warp.

The testing process gave insights about the success of the choices. The data showed that transparent, white and the lightest colored textiles performed best. It was no surprise that an almost completely transparent fabric outperformed a dense darker green twill.

One observation that was made before leaving out the organic test cell was, that when hiding the organic solar cells with darker colors, the maximum short circuit current dropped remarkably more than when testing with a silicon solar cell. While covered with dark green worsted twill (no. 4.10), the maximum short circuit current of the silicon solar cell dropped to 18.39% of comparison value and the maximum short circuit current of organic solar cell to close to zero. A similar effect happened with darker green voltaire wool (no. 4.25). Both solar cell types performed badly when covered with darker textile samples, but the organic solar cell was remarkably less efficient in this situation. A solar cell that uses near infra-red rays, like crystalline silicon solar cell, can still harvest some energy through darker colored textiles, while an organic solar cell loses its efficiency almost completely. So there are advantages in using solar cells that use the near-infrared wavelengths to generate energy when covered with darker color textiles. With light colors there wasn't such radical effect. Even though the tested organic solar cell was unstable, the difference could be detected.



sketching weave structures

knitted trial with integrated photovoltaics

material test

acid dyeing process

2nd round of material prototyping

After learning the principles of designing pocket weaves, I started experimenting with ratios of top and bottom layers of the fabric. By programming a bigger percentage of the warp yarns to middle and bottom layers, a top layer with a smaller density can be created. I shifted to use the TC2 jacquard loom with a white mercerized cotton warp. The more advanced machine made it possible to do more complex designs, and weave several tests next to each other. This efficient way of weaving resulted in creating samples with different ratios and designs next to each other, keeping the weft density same through the whole row of woven textiles. I used traditional weave structures such as twill, satin, honeycomb, mock-leno, and their variations to create texture for the top layer of the fabric. (Weavestruct 2018) No remarkable differences between the effect of designs on the performance were found if the material, and warp and weft density were similar.

The first round of dyeing had made me curious if other light colors would perform in a similar way with the light green. If both dyes include the same percentage of yellow but the other some red and the other blue in addition, in theory the green shade could seem brighter to the human eye. I dyed the samples for testing using a 0,1% solution of acid dyes. Under the solar simulator, there was no difference between the two colors in how they let through sunlight. However, with the bare eye, a minimal difference in brightness of the fabrics could be detected and the orange seemed to cover the cell better. (see photo on page 33) Because the green color seemed brighter than the peachy orange, the contrast against the dark photovoltaic looked bigger than the one of orange. This implicates that not only the color of the textile, but also the color of solar cell and the contrast between the two have an impact on the illusion of coverage.

3rd round of material prototyping

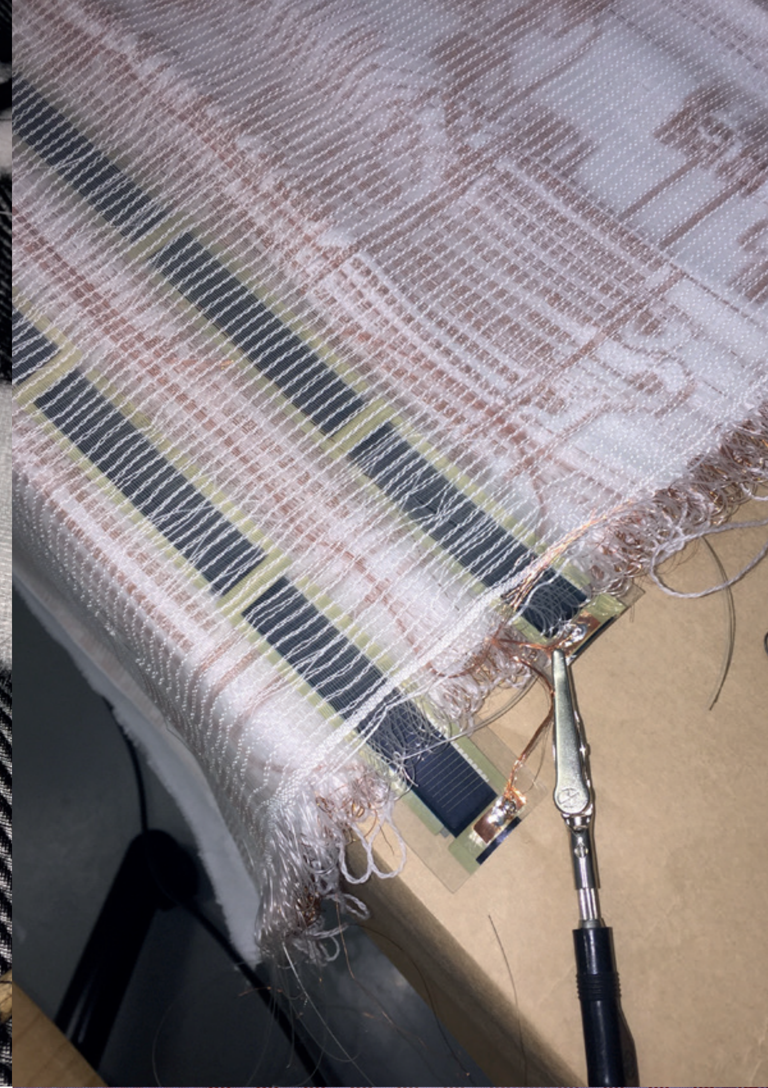
The third round followed the pattern of the previous cycles continuing with the ideas of the most interesting prototypes so far. Also, I started developing three layered pocket weaves that allow more sophisticated electronics component integration. At this point, I started gathering visual ideas for the final textile prototypes, and sketched some surface designs to be tested. I was experimenting with weft inlay, fil coupé and weft floats. Fil coupé technique means adding extra colors or materials to some parts of the design by integrating yarn floats into the weave structures that are later cut open. Weft inlay is a brocade weaving method in which the same is done without floats through partial weaving (ClothRoads 2018)

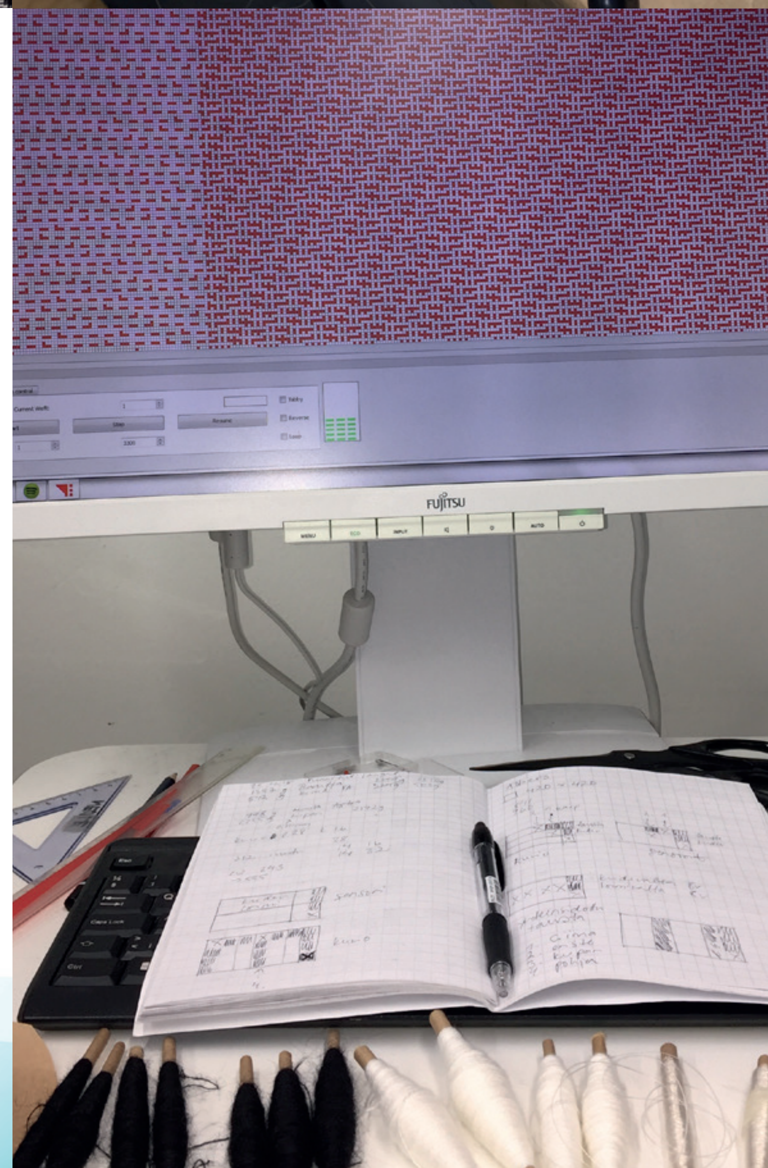
Final round

On the final round, I designed and produced 6 textile prototypes that showed ideas and concepts from different phases of the process. I mixed tested elements from previous rounds together using data and textile designers intuition. One of the prototypes was woven with a fully manual loom, and the rest with a computer-aided TC2.

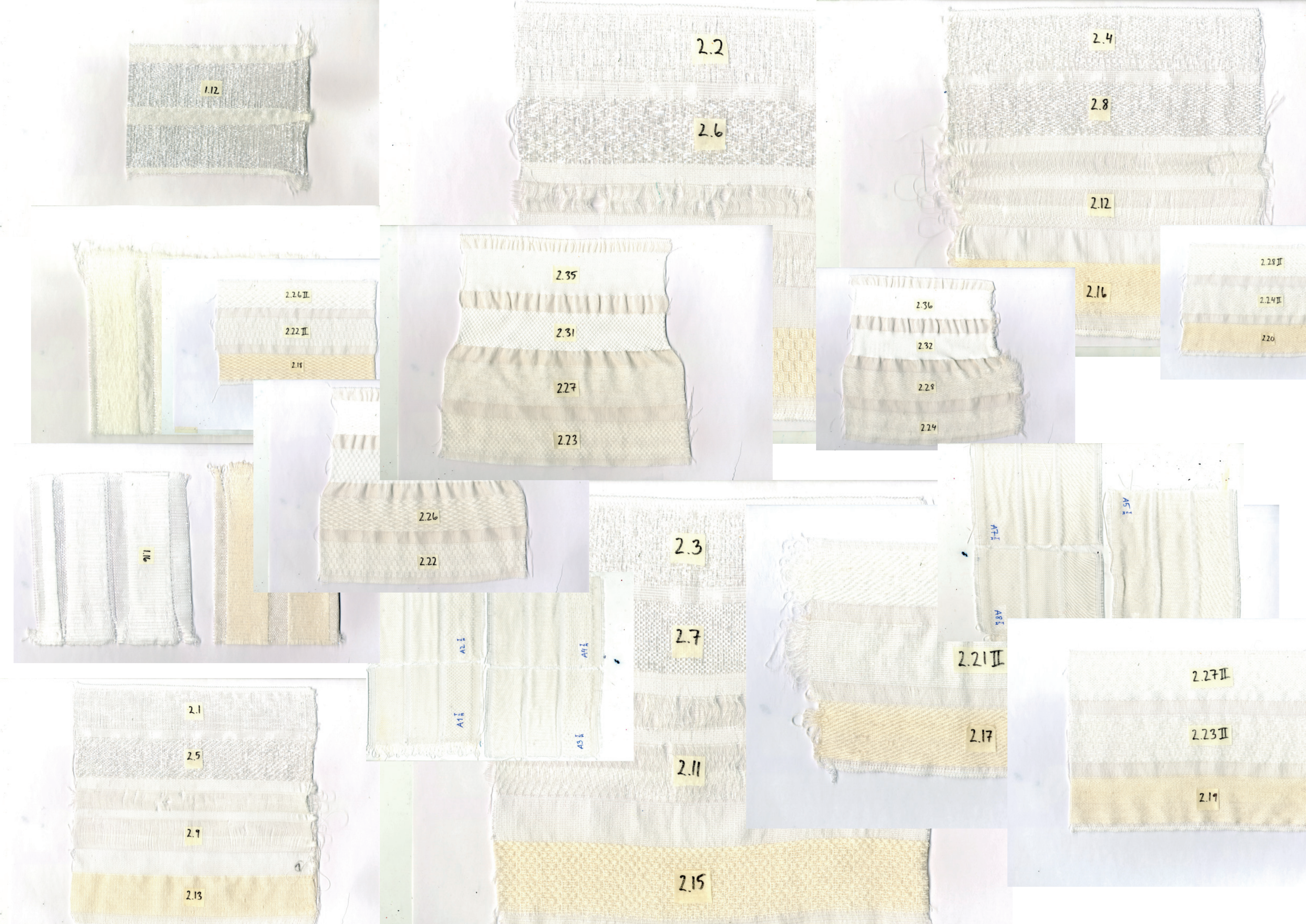
With Alpi we integrated photovoltaics to one of the woven prototypes. During the fabrication process, Alpi connected a customized flexible solar panel to the interwoven copper wires. A separate transparent top-layer, and designed internal warp floats enabled inserting the technology to the textile after the fabric was taken down from the loom. This way the electronics could also be changed later.

The final prototypes were tested twice to generate more precise data of the efficiency, current and voltage, quantum efficiency and spectral transmittance. I used the multimeter method to measure short circuit current on the first round. The second round was done together with Janne Halme using the spectral quantum efficiency measurement system, and a current-voltage measurement system for efficiency and the current-voltage curve. The results will be presented in the *Textile Prototypes: Data & Findings* part.





top left: weft inlay weaving
top right: fabrication of photovoltaics into the textile
bottom left: weaving with the TC2 loom
bottom right: preparation for weaving
pages 37 & 38: woven textiles for testing


1.12
2.2
2.6
2.4
2.8
2.12
2.16
2.26 II
2.22 II
2.18
2.35
2.31
2.27
2.23
2.36
2.32
2.28
2.24
2.28 II
2.24 II
2.20
2.26
2.22
2.3
2.7
2.11
2.15
2.21 II
2.17
2.27 II
2.23 II
2.19
2.1
2.5
2.9
2.13

Tekstiili18 exhibition

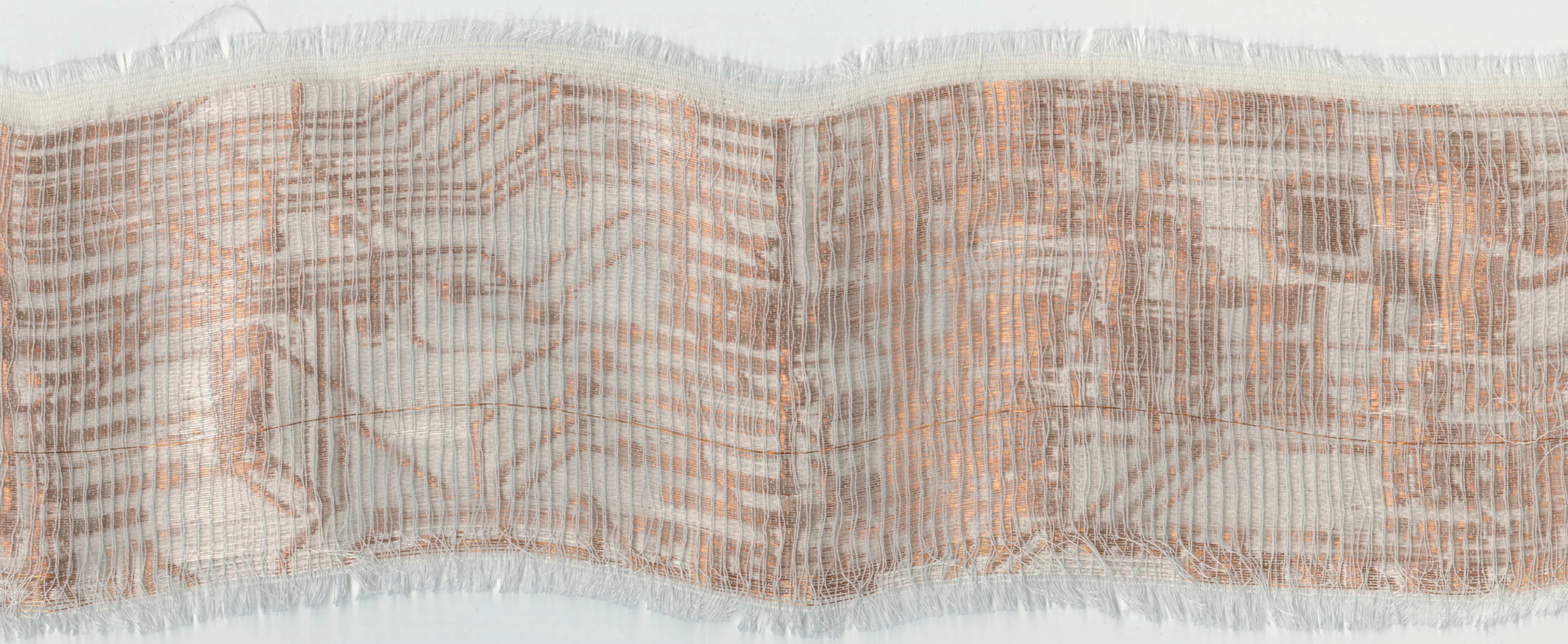
The practice-based research was presented in Tekstiili18 exhibition in May 2018 at Helsinki Cable Factory, Kaapelitehdas. Tekstiili18 focused on new perspectives to textiles in fashion, clothing, interior design and materials research from Aalto University. Tiina Härkäsalmi's 'design-driven prototypes' of cellulose based new materials were a result of a multidisciplinary research project. Another experimental work by ENG-ARTS combined technical and artistic thinking by creating holograms that were inspired by woven textile structures. (Tekstiili18 2018)

My presentation included a slideshow of process photographs taken by Eeva Suorlahti, and six of the physical textile prototypes. The photographs were taken in the laboratory testing phase, and during the weaving process of the final textile prototypes. The "Circuit Board" design included fabricated photovoltaics, and "Honeycomb Weave" demonstrated with an unconnected organic solar panel how future printed photovoltaics could be hidden inside the pocket weave structure.

TEXTILE PROTOTYPES: DATA & FINDINGS

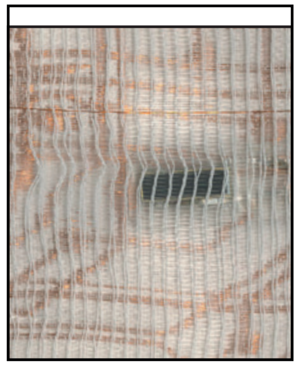
During the different phases of the thesis process, I created over 120 textile samples with varying materials, colors and surface designs. In this chapter, I present the final six textile prototypes that embody the findings and ideas that emerged during the practice-based research process. Related graphs visualizing efficiency, quantum efficiency, spectral transmittance and the current-voltage measurements are presented after each prototype image along with textile information.

Note that in the quantum efficiency measurements that were used to calculate the spectral transmittance, part of the light transmitted through the textile does not hit the underlying small solar cell, because the light beam is narrow and becomes scattered to wide range angles when penetrating the textile. The spectral transmittance results shown here are therefore underestimates of their real value. The current-voltage measurements are more representative to the real conditions, because in that case the light beam was much wider than the dimensions of the solar cell, which corresponds more closely to the the uniform direct sunlight illumination outdoors.



CIRCUIT BOARD

Inspired by a computer circuit board, this prototype resembles the possibilities of complex designs for e-textiles systems. The textile consists of three layers: one that is transparent, one that is conductive, and one that is soft wool. The top layer is open, and two other layers alternate as bottom and middle layers with space in-between. Flexible solar cells are integrated to pre-determined spots designed with internal warp floats. The solar cells are visible but designed to be a part of the design. This prototype is the key design and a bigger sample of the *Circuit Board* was woven for the Tekstiili18 exhibition with fabricated solar cells.



bare solar cell
12%

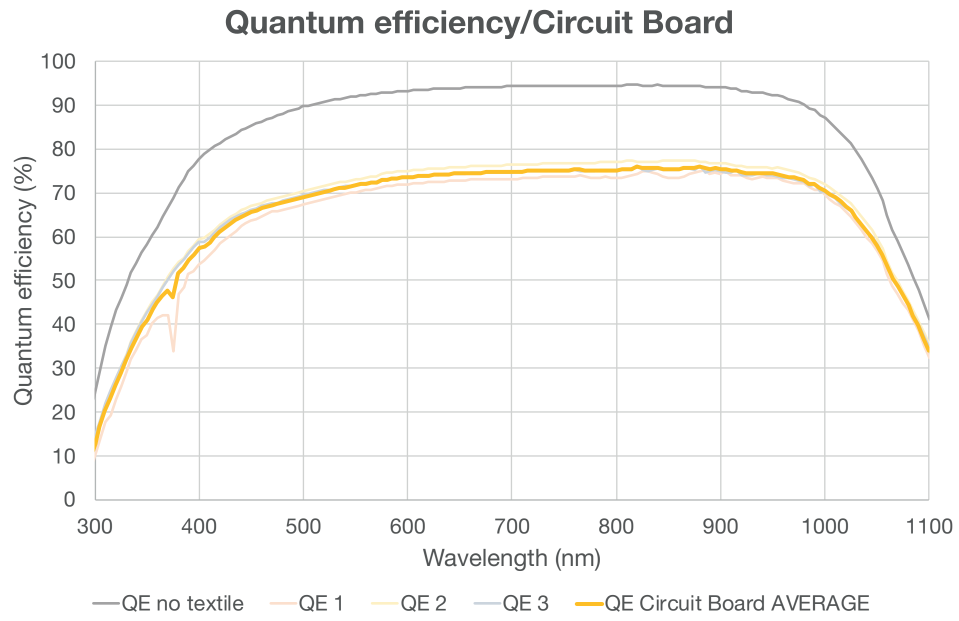
with textile
11.2%

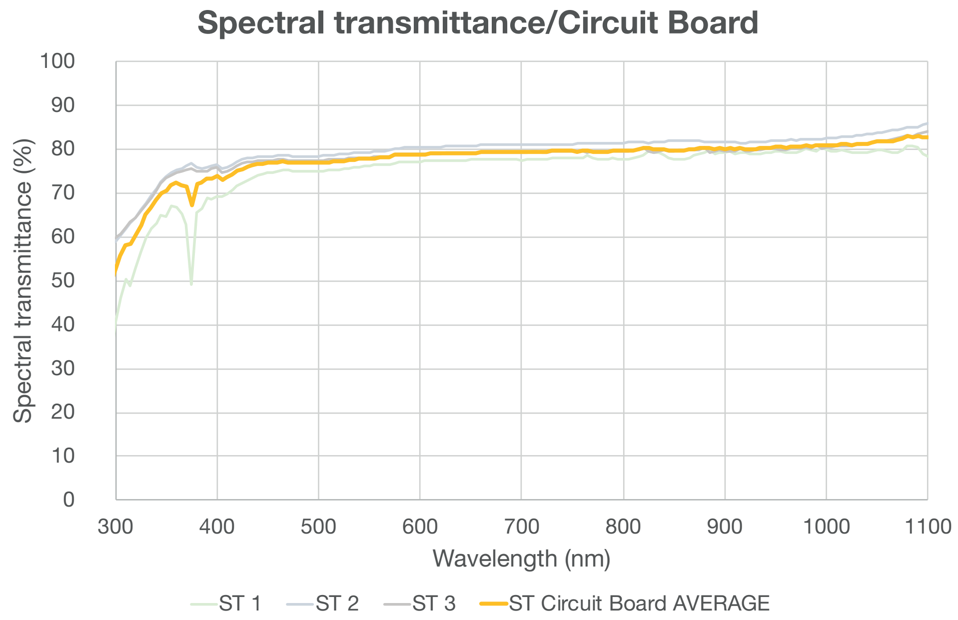
Efficiency

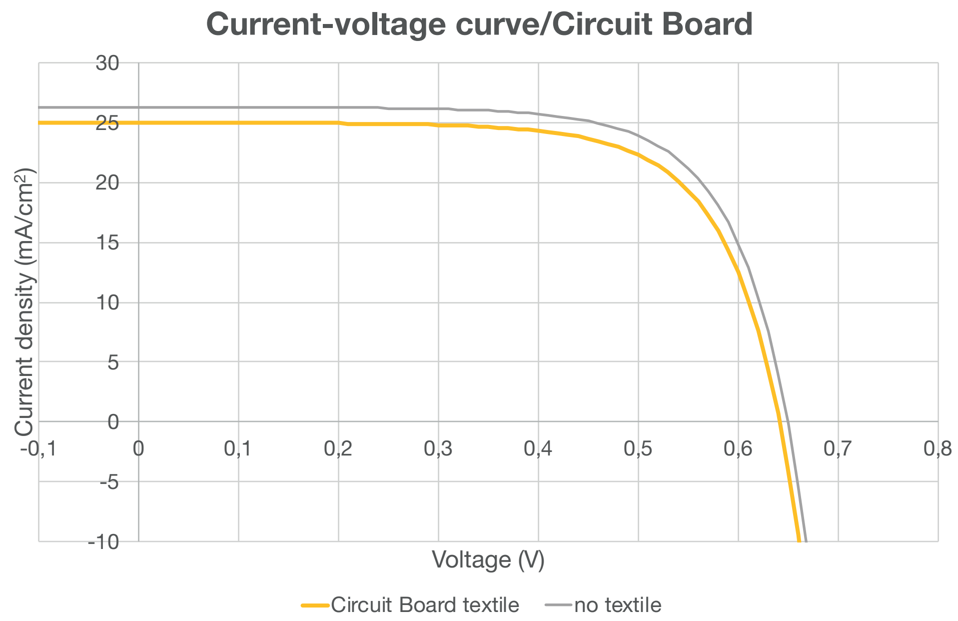
Color: Transparent, copper & white
Warp material: White Mercerized Cotton 100% CO Nm 65/2
Warp density: 30 ends/ cm
Warp ratio: Top 1:5, Middle 2:5, Bottom 2:5
Weft density: 57 picks/ cm

Weft materials
1st weft: Transparent fishing line 100% PA den 750
2nd weft: Copper wire 0,2 mm
3rd weft: White Baruffa Cashwool Nm 2/30: 100% Wool

Weave structures
Top: Weft-faced satin
Bottom: pocket weave with altering weft-faced satin layers, warp floats

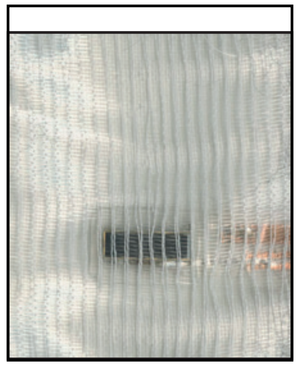






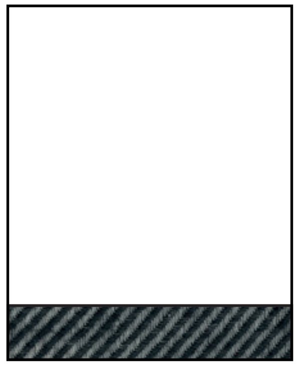
CHECK

A simple-looking check pattern is created using fil coupé and weft inlay techniques. Black areas completely cover the technology, and transparent areas allow maximum light penetration.



bare solar cell
12%

with textile (white)
11.1%



bare solar cell
12%

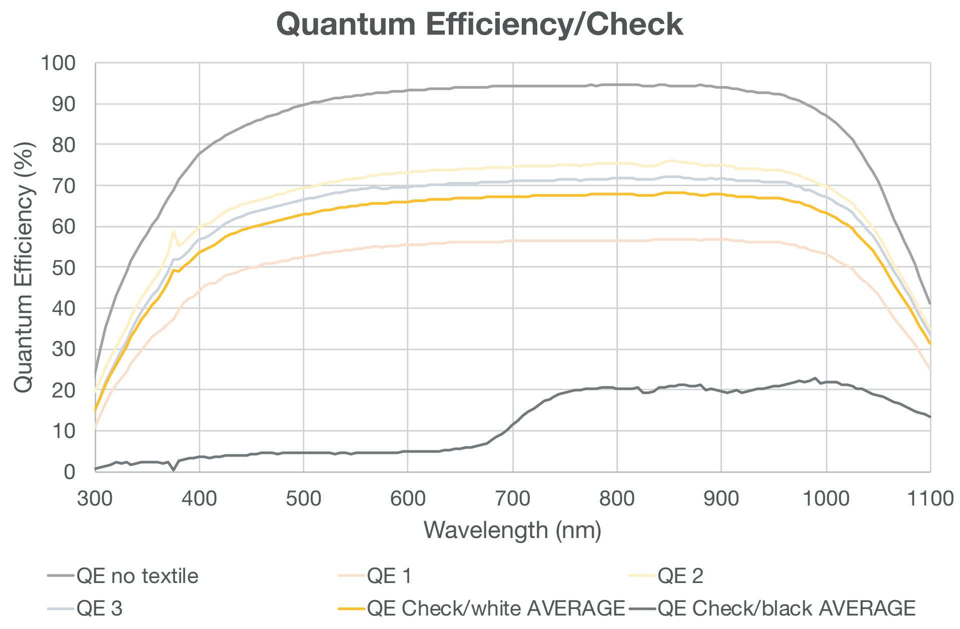
with textile (black)
1.9%

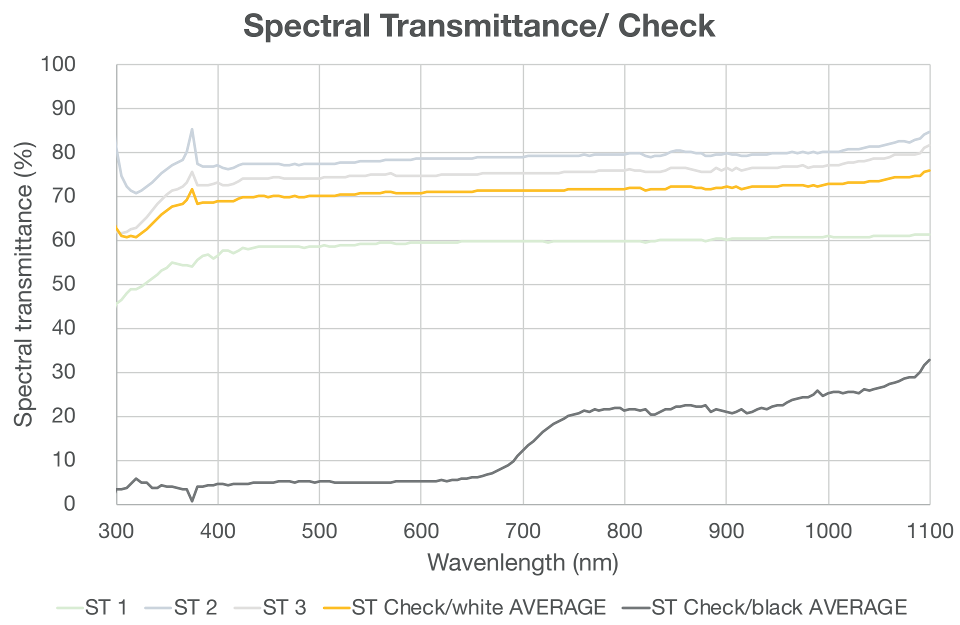
Efficiency

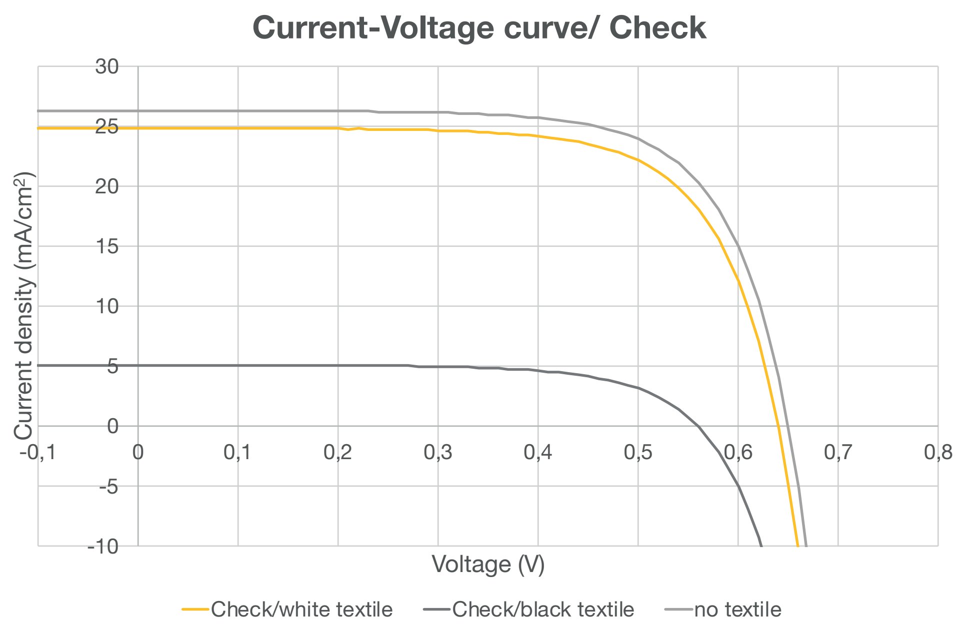
Color: black, transparent, white
Warp material: White Mercerized Cotton 100% CO Nm 65/2
Warp density: 30 ends/ cm
Warp ratio: Top 1:5, Bottom 4:5
Weft density: transparent areas: 40 picks/ cm, black areas: 46 picks/ cm

Weft materials
1st weft: Black IGEA Astro 50 Nm 15
2nd weft: Transparent fishing line 100% PA den 750
3rd weft: White Baruffa Cashwool Nm 2/30: 100% Wool

Weave structures
Top: twill, fil coupé & weft inlay, weft-faced satin
Bottom: Plain weave







CLOUD

Cloud is a three-layered fluffy, soft textile with a light blue color. Solar cells could be integrated on two sides, divided with a middle-layer. Big shrinkage of polyamide led to a very thick-feeling textile that still allows solar cell to perform well . Even though the material has a color, it is so pale that it doesn't have a big influence.

bare solar cell
12%

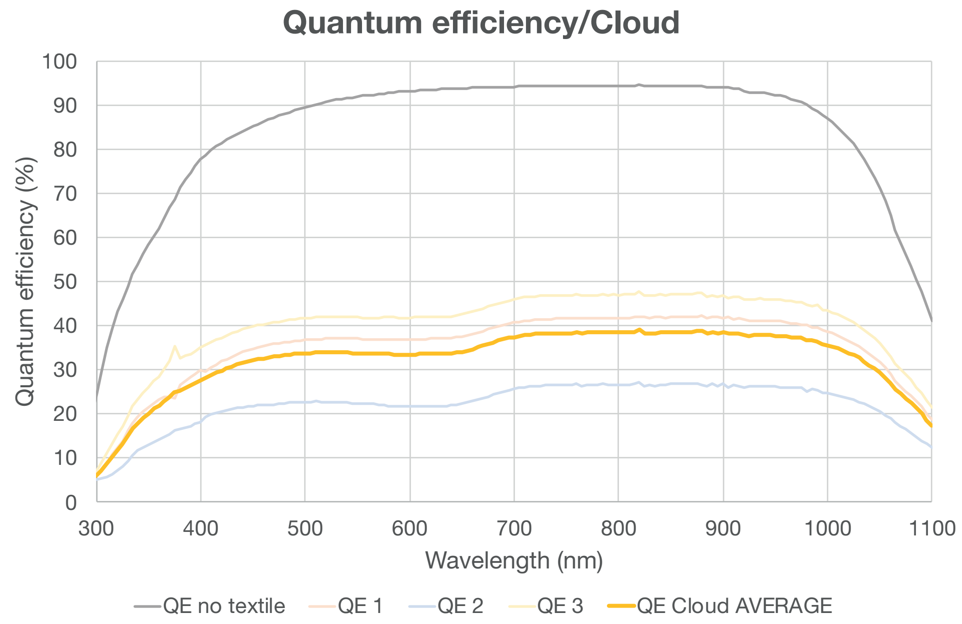
with textile
9.5%

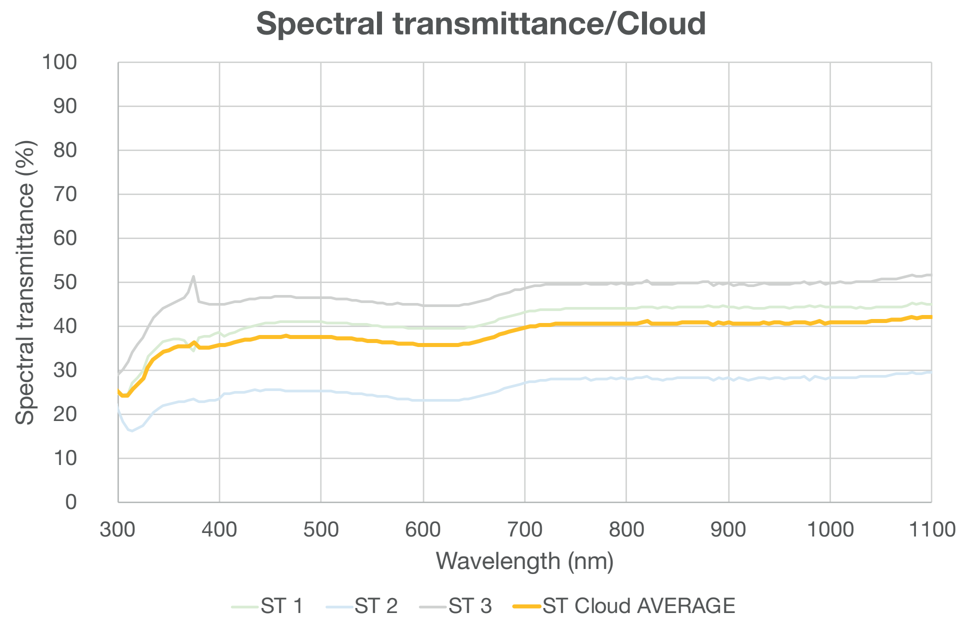
Efficiency

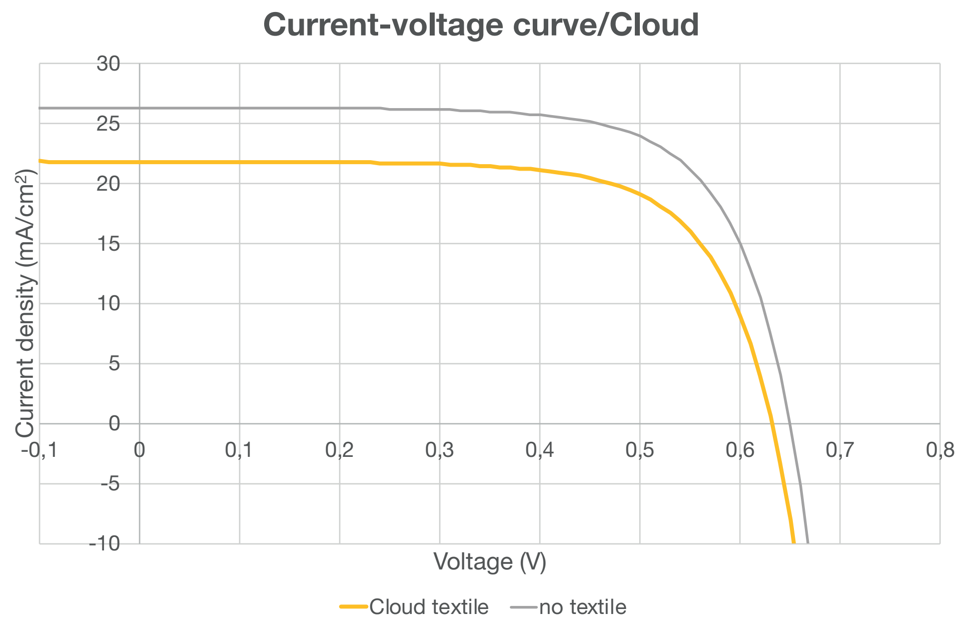
Color: light blue & white
Warp material: White Mercerized Cotton 100% CO Nm 65/2
Warp density: 30 ends/ cm
Warp ratio: Top 1:4, Middle 2:4, Bottom 1:4
Weft density: 27 picks/ cm

Weft materials
1st weft:Blue IAFIL SPIGHY 100% PA Nm 7000
2nd weft:White Baruffa Cashwool Nm 2/30: 100% Wool
3rd weft:Blue IAFIL SPIGHY 100% PA Nm 7000

Weave structures
Top & Bottom: ornamented basic weave
Middle: plain weave

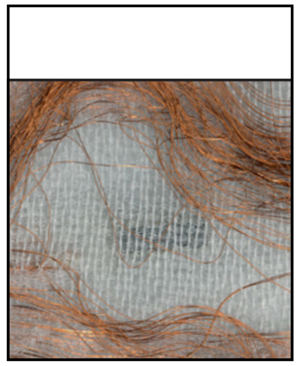






COPPER FLOATS

This textile prototype uses floats and irregularity of design as a method for covering. The copper wires float out of the way of solar cells creating more transparent areas for maximum efficiency. The long floats behave in an unpredictable way, forming a surface design on their own.



bare solar cell
12%

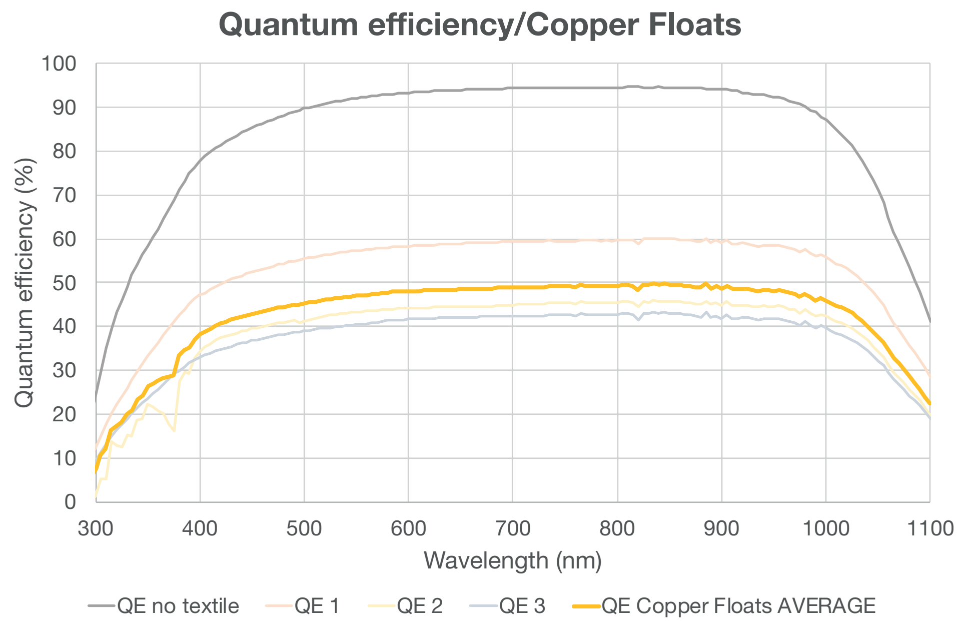
with textile
9.5%

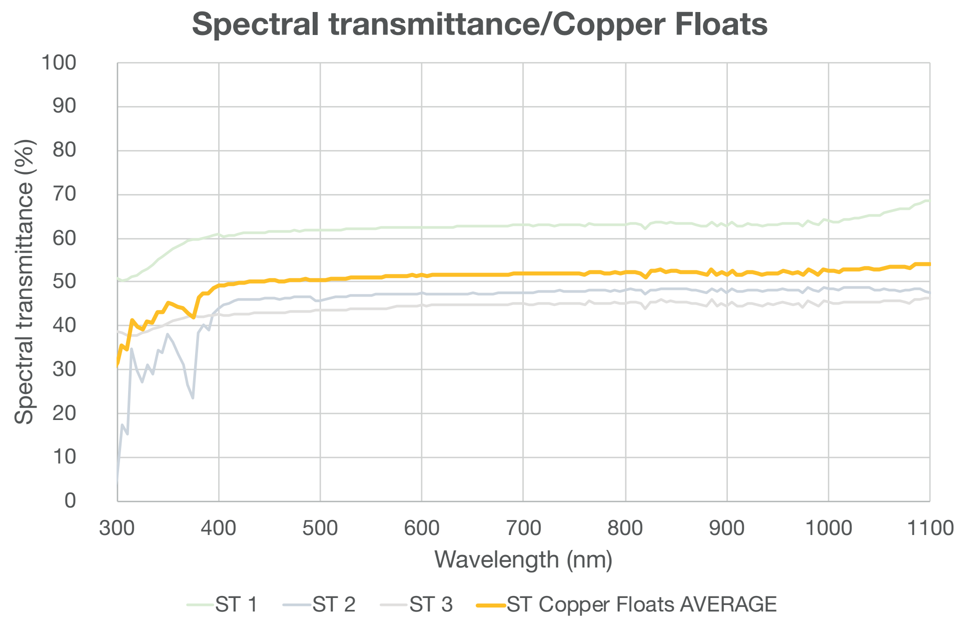
Efficiency

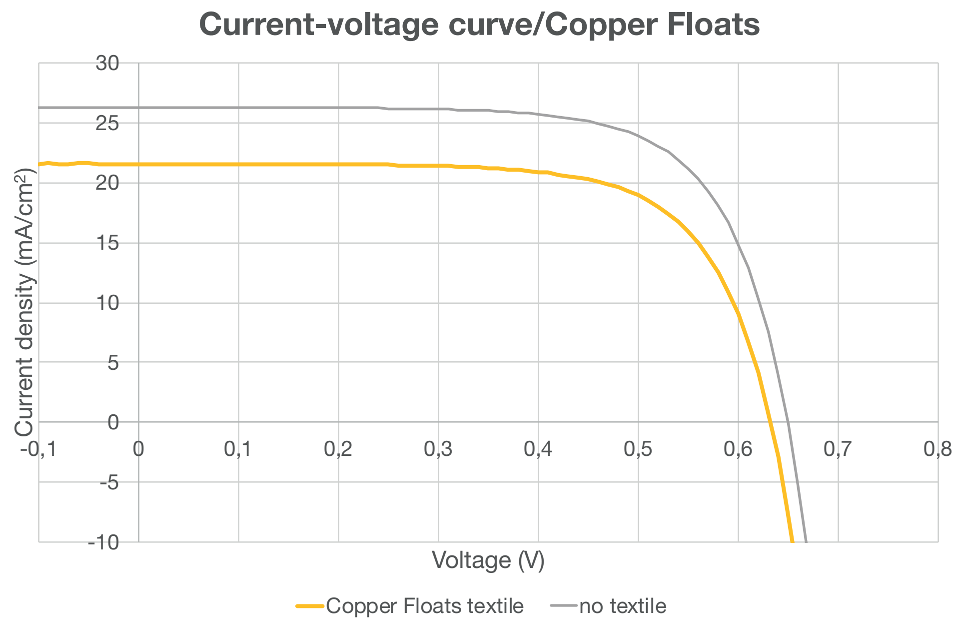
Color: Copper & transparent
Warp material: White Mercerized Cotton 100% CO Nm 65/2
Warp density: 30 ends/cm
Warp ratio: Top1:3, Bottom 2:3
Weft density: 40 picks/ cm

Weft materials
1st weft: Copper wire 0,2 mm, 2 ends
2nd weft: Transparent IAFIL SPIGHY 100% PA Nm 7000
3rd weft: Transparent IAFIL SPIGHY 100% PA Nm 7000

Weave structures
Top: floats & weft-faced satin
Bottom: modified plain weave

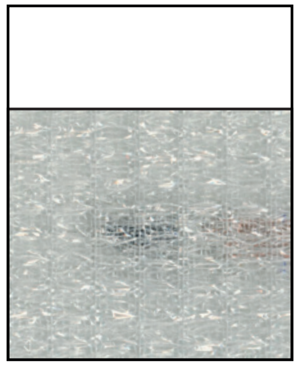






HONEYCOMB WEAVE

Honeycomb weave creates a very three-dimensional texture to the top layer. A combination of fluffy Mohair and smooth Polyamide tape result in a contrast in the feel of the fabric. The weave structure is covering the solar cell well despite the white color.



bare solar cell
12%

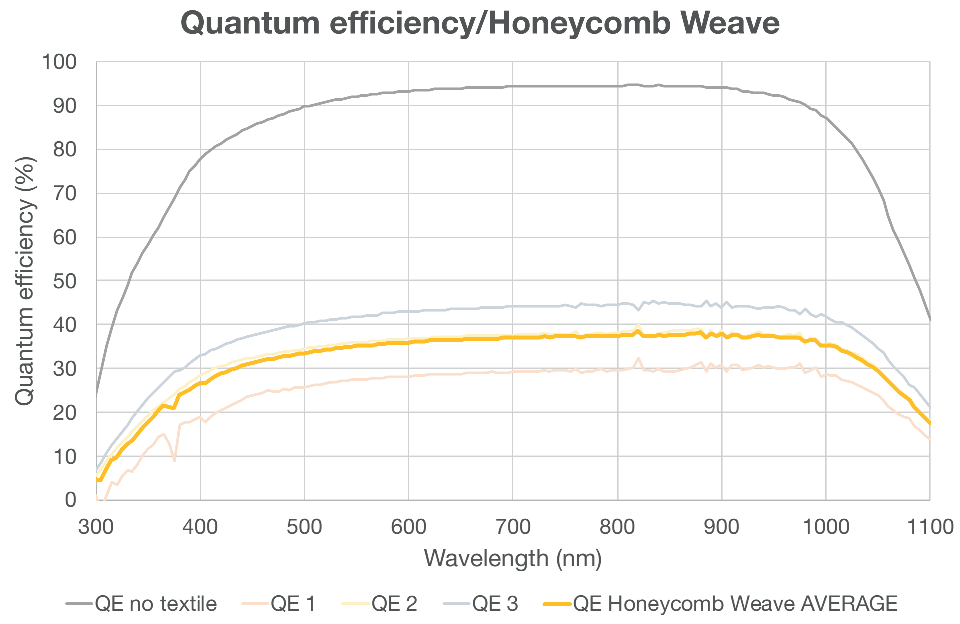
with textile
8.5%

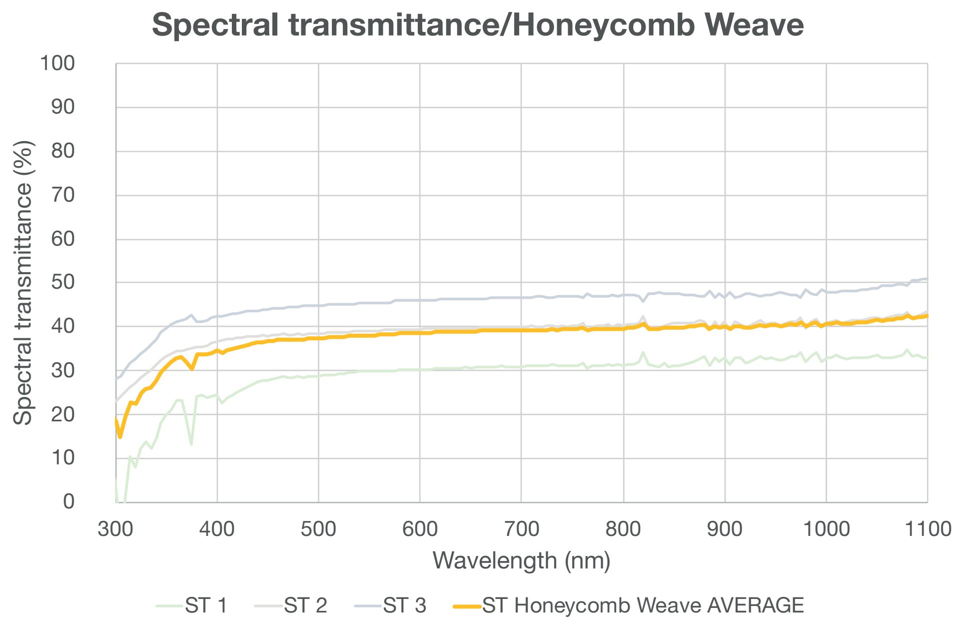
Efficiency

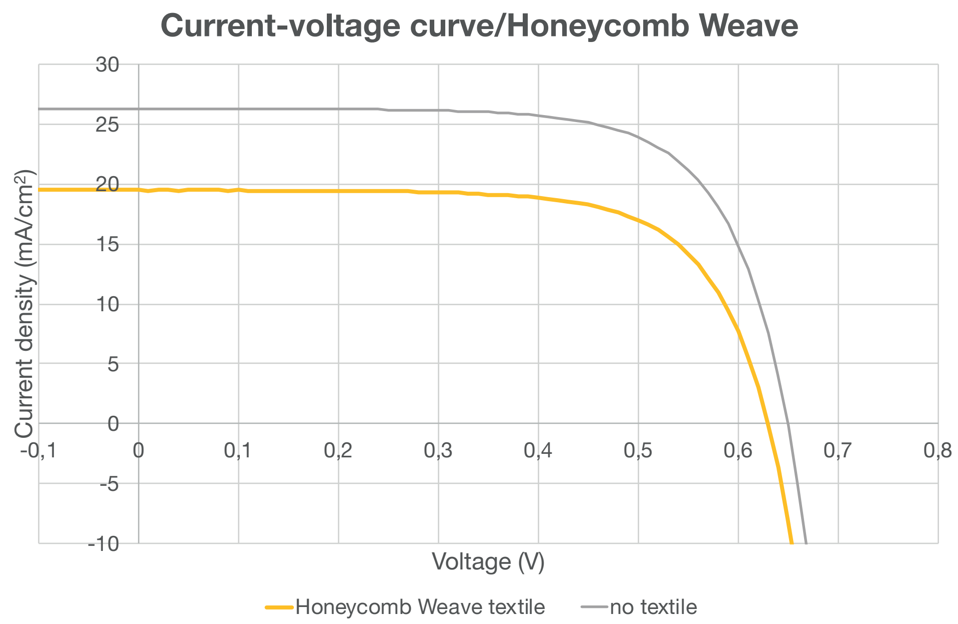
Color: White & transparent
Warp material: White Mercerized Cotton 100% CO Nm 65/2
Warp density: 30 ends/ cm
Warp ratio: Top 1:5, Bottom 4:5
Weft density: 33 picks/cm

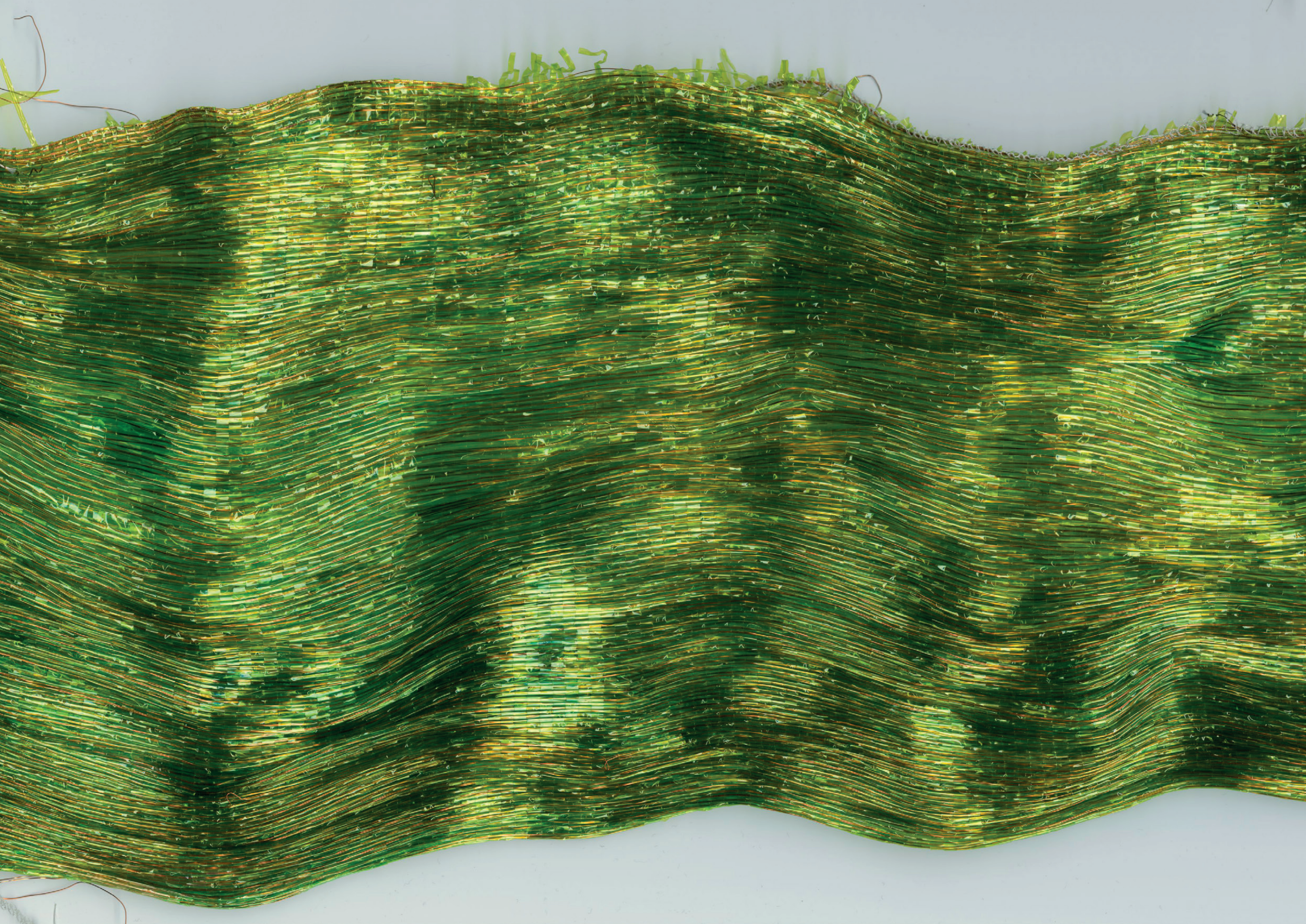
Weft materials
1st weft (woven in the same shed):
-Lurex Transparent tape Nm 18: 100% PA
-White Astro 50 Nm 15: 50% Mohair, 47% Polyamide, 3% Merino wool
2nd weft: White Baruffa Cashwool Nm 2/30: 100% Wool

Weave structures
Top: honeycomb
Bottom: plain weave



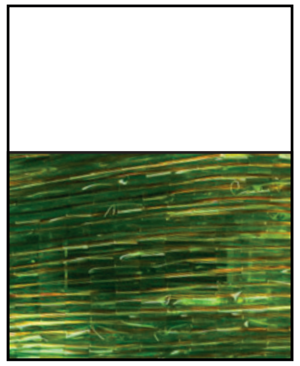






GREEN

This prototype is inspired by the color green. It is constructed of the most simple pocket weave with open layers. Copper is a conductive material that also allows shaping the textile in various forms. Transparency of both top and bottom layers highlights interaction with the surrounding light.



bare solar cell
12%

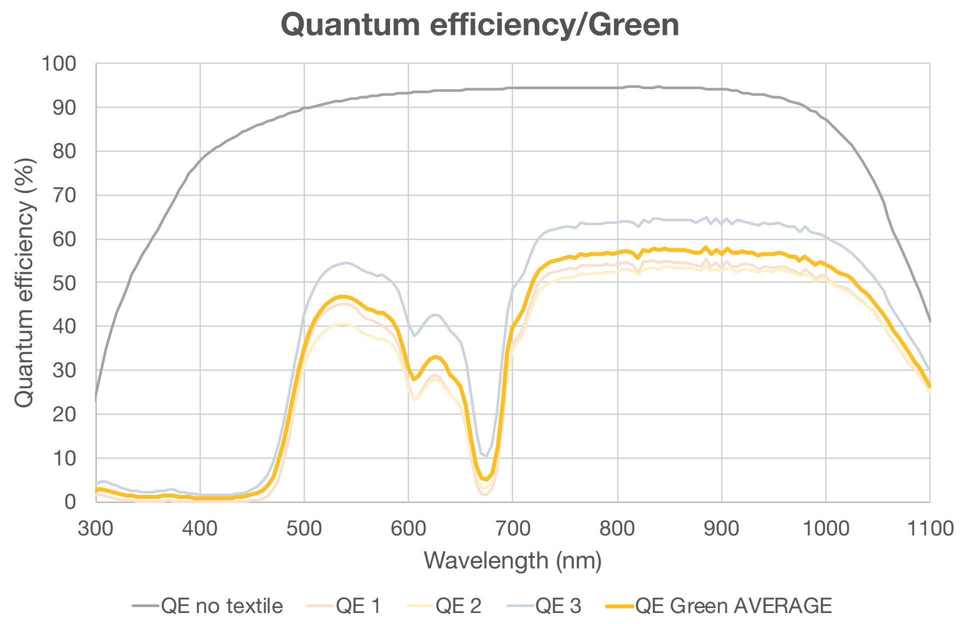
with textile
6.9%

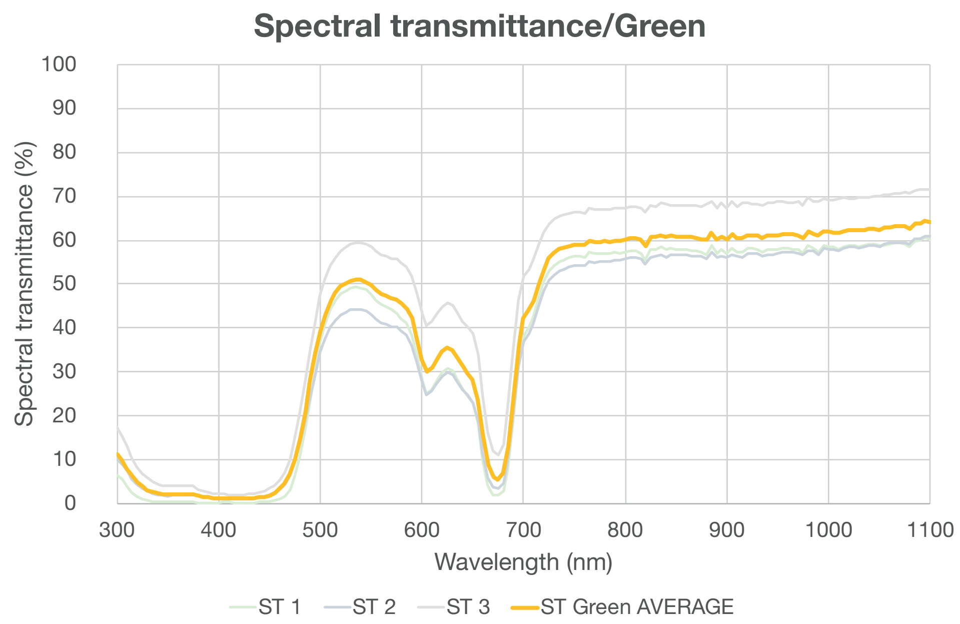
Efficiency

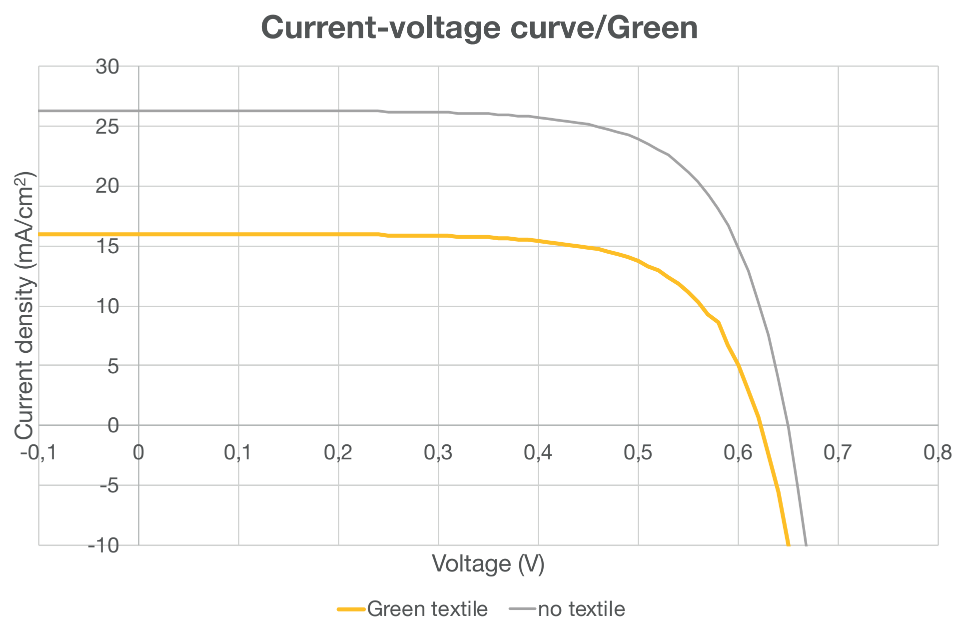
Color: Green & copper
Warp material: Lurex Transparent tape Nm 18: 100% PA
Warp density: 6 ends/ cm
Warp ratio: 1:1
Weft density: 42 picks/ cm

Weft materials
1st weft (woven in the same shed):
- Lurex Transparent tape Nm 18: 100% PA
- copper wire 0,2 mm, two ends
2nd weft (woven in the same shed):
- Lurex Transparent tape Nm 18: 100% PA
- copper wire 0,2 mm, two ends

Weave structures
Top: plain weave
Bottom: plain weave







4

CONCLUSION

This part summarizes the findings and learnings from the practice-based research and Energy Harvesting-Sun Powered Textiles project. Interdisciplinary collaboration was discussed with interviewees Peter Lund, Janne Halme and Emmi Pouta. New research questions and how to continue with the subject are also included in the reflections.

SUMMARY OF FINDINGS

This thesis work strengthens the argument that it is possible to generate good amounts of energy from the sun even when a solar cell is inserted into a woven textile. As assumed, transparent and light colors were best suitable for covering the cell. According to the data gathered from the six final prototypes, the Circuit Board design and transparent areas of the Check prototype caused the smallest drop in efficiency of the test solar cell. From 12% without a covering textile, after inserting the solar cell to the textile the efficiency was reduced to 11.2% (Circuit Board) and 11.1% (Check, transparent). Integration of the test solar cell to Cloud and Copper Floats prototypes resulted in a good 9.5% efficiency. I was expecting a slight difference because the color shade of the 100% PA material used in Cloud was pale blue, and in Copper Floats white/transparent. Honeycomb Weave with transparent PA tape and white mohair wefts reached a 8.5% efficiency. Dyed green, the same PA tape combined with copper wire resulted in the lowest efficiency of 6.8%.

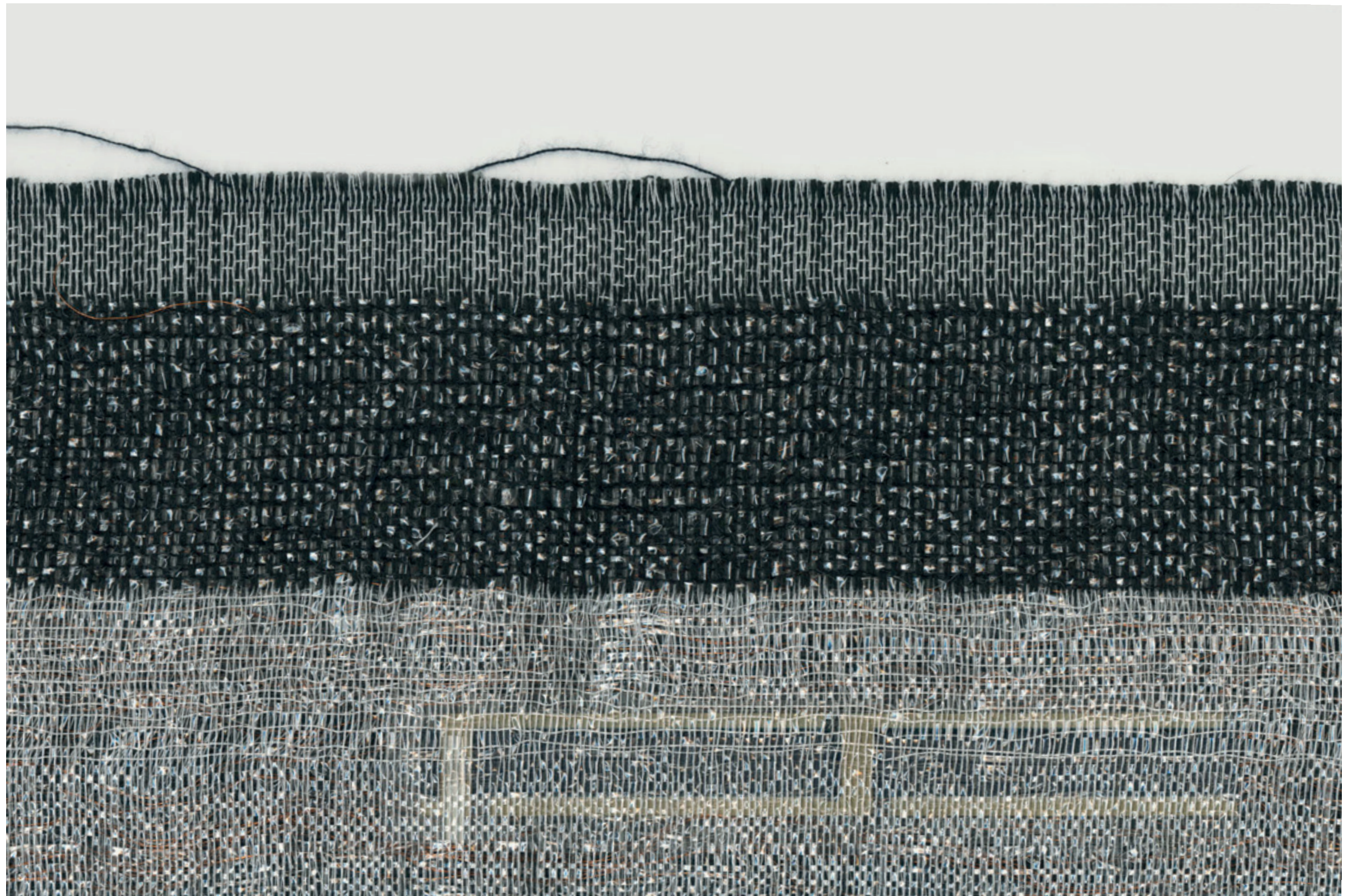
By using the fil coupé or weft inlay technique, it is possible to completely optically cover the technology while exposing it on different parts. As seen in the twill parts of Check woven with black mohair, even opaque weaves let through some light. An efficiency of 1.9% was reached with the test solar cell even though un-optimal materials, weave structures and black color were used because of the use of near-infrared light.

Afterwards I realized that I could have focused more on contrast during the prototyping process. A woven test from the first round shows how the black color in the layer behind the solar cell completely hides the cell by camouflaging it. (see image on page) Only the lighter contacts are seen, and they could easily be colored black as well. I had dropped the idea because a black textile seemed a too obvious solution. However, I didn't think at the time that dark colors could be used in some parts of the background to hide the cell. This is a good example of how ideas evolve throughout the process, and why it is impotant to document the process.

Simple tests that are done with intuition might surprisingly include answers to later questions. It would be an interesting next step to use all of the gathered realizations and start a new development cycle. In addition to contrast, optical mixing of colors between the layers could be another step to explore. A colored transparent material on the top layer interacts with the background colors toning them. This is only possible because of the use of transparent materials and pocket weave structures. Also, it would have been interesting to develop prototypes on a jacquard loom with a transparent warp material because the test results of samples woven with the transparent PA tape warp (shaft loom) were very good. Unfortunately developing a special warp for this project wasn't possible but for a more comprehensive study it would make sense.

The conclusion is that it is possible to create woven fabrics that are itself visually interesting, and allow integration of photovoltaics technology. The handmade textile prototypes show different ideas how to approach integration through the use of multilayered weave construction. A large variety of textures can be created combining and varying simple textile structures and materials. Patterns and colors can blend the technology in while adding value to the textile design. A stimulating visual and haptic expression in smart textiles could make them easier to approach and more appealing to a wider audience. This of course is an interesting opportunity for a textile designer designing photovoltaic energy harvesting textiles, or other smart textiles.

solar cell hidden inside weave structure



<u>**Key observations**</u>

-it is possible for solar cells to perform very well when covered with textiles, even with color and optically well hidden

-transparent or light-colored materials worked best but even dark textiles pass through solar irradiance

-the contrast of the top and bottom layer textile color with the solar cell has a big impact on optically hiding the solar cell

-different materials with similar yarn thickness (Nm, denier) performed quite similarly

-adjusting warp ratio and density of top layer of pocket weave has a big impact if the warp material is opaque

-brocade weaving and fil coupé can be used to produce areas that are completely covering the solar cell or other components

-a large variety of three-dimensional structures on the top layer can be made, and if color, material and density are similar the differences in solar cell performance are relatively small

LIMITATIONS

A lot of effort is still needed to develop photovoltaics and related technology further to completely suit textile design purposes. Even though lightweight and bendable, the current solar cells don't stretch well, and the color and look of the modules are problematic from the designers and users perspective. Integrated electronics must add value to the material without reducing the good properties of textiles like softness and flexibility. (Ilen 2015, 13) By choice of textile materials, colors and weave structures we can compensate the defects of the photovoltaics but it is not yet possible to reach the same, or improve the natural textile properties through integration of solar cells.

For energy harvesting textiles to make sense, they need to serve human needs. During our conversation, Peter Lund said: "Nobody is interested in the plug." We are interested in the "light that allows us to read our favorite book", or central heating to stay warm, or electricity to power our devices and machines that make our lives better. In a similar manner, we are not interested to having a textile with electronics inside if it doesn't bring us extra value, and look and feel good

at the same time.

Another challenge of energy harvesting photovoltaic textiles is the sustainability of such materials. Can a textile with interwoven technology be sustainable? Even though generating renewable energy, the entire lifecycle of the material should be considered, and the benefits should outweigh the used resources. What is the combined energy payback time of the textile production and all of the required technology? Replacing and repairing parts should also be possible to ensure a long lifecycle for the material, and enabling reuse and recycling. But mixing textile fibers and technology requires a lot of effort to disassemble and recycle. Therefore design of every component should be considered, and it would only make sense to produce extremely high-quality materials that would be maintained through services. The potential up-market price range would make such materials best fitting for 'tech couture' or for rental models for companies or public services.

Energy harvesting textiles and other e-textiles could be a part of a broader conversation about our consumption and constructing the future. They could become a paradigm of a new, sustainable way of consuming textile materials, clothing and accessories. If photovoltaic energy harvesting textiles can contribute to the physical and emotional needs of humans, and be the most sustainable option, there is no stopping of them.

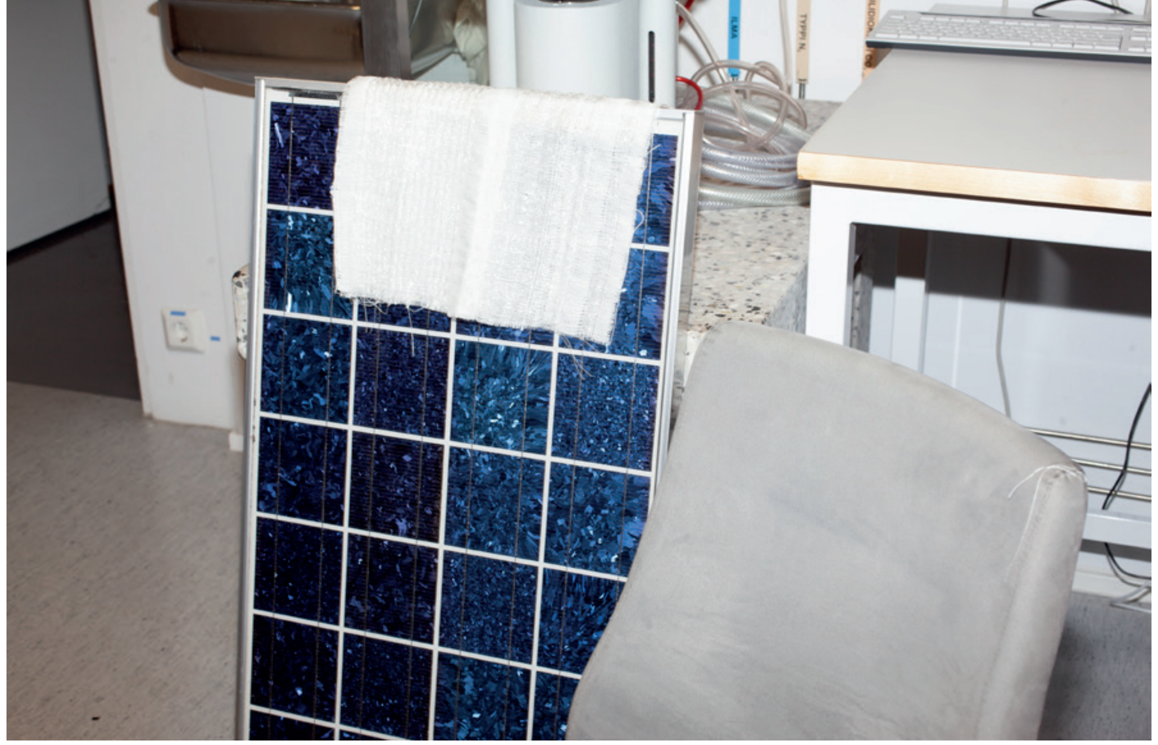
REFLECTION ON INTERDISCIPLINARITY

The interviewees Peter Lund, Janne Halme, and Emmi Pouta, agreed that there is great potential in interdisciplinary research between science, technology and design. Pouta & Lund emphasized the meaning of trust and communication skills during the process. All agreed that group dynamics are a crucial part of such projects and therefore working together in the same physical environment is important.
(E. Pouta, personal communication, February 14, 2018; J. Halme, personal communication, October 8, 2018; P. Lund, personal communication, October 11, 2018)

Because learning about a completely new subject was fascinating to me, sometimes I had to remind myself that I don't have to try to learn or understand everything. The balance of knowledge to enhance and not restrict creativity, was mentioned too during the interviews. How to learn enough so that a common language for communication is built, but not spend too much time on learning skills and knowledge that the other team members already have?

During our conversation, Lund highlighted the meaning of funding and how we need to little by little change the organizations to become more open to non-linear design-technology collaborations. He said that we also need to actively work towards breaking "stereotypes" and acknowledging each other's expertise despite the differences in our practices.

Being open and curious about topics outside of own expertise, and seeking interdisciplinary opportunities on ones own initiative are changes a designer can do to connect with other fields. In my opinion, the scientific way of generating new knowledge for the sake of material research could partly be adopted to textile design. Instead of designing fabrics only for end applications such as clothing, accessories or interior design purposes, textile designers can harness their skills for research in for example applied physics, chemistry, and biology. This way new tools and solutions could be created for our common toolbox to be used when the day comes that we need them. Projects around nanocellulose have already successfully established the practice (Kääriäinen & Tervinen 2017) and hopefully more and more fields realize the potential of using textile designers or designers from other fields in their research groups.



CONTRIBUTION & NEW RESEARCH QUESTIONS

Approaching energy harvesting smart materials from a textile designers point of view using handweaving practice is a unique starting point for research. A design-led process applying interdisciplinary knowledge from technology and science as backgrounds for explorative prototyping, differs from the 'linear' structure of scientific practice. Nevertheless, I believe this thesis contributes to textile design and e-textiles as well as photovoltaics fields introducing some ideas to all of them. In traditional textile design practice, prototyping and testing interweaving photovoltaics hasn't been done before in a similar way *Solar Cells Inside Woven Textiles* does. Integration of photovoltaics to a multilayered weave structure, on the other hand, is a new concept for electronic textiles which could be developed further and used for other applications as well. And in photovoltaics field, this is the first time the technology has been integrated to a multilayered woven textile to become a part of the aesthetics as well as the function of a fabric. During the process I found techniques to visually hide the solar cell into the weave structure. Also, the project was brought to an exhibition context focusing on textile design and creativity.

In addition to developing photovoltaics itself more stretchy and visually attractive, and continuing with the aesthetics of woven textiles, more research questions emerged. In this work, almost no time was put on the fabrication process of electronics. Very early on the focus shifted to textiles and textile properties because I realized it was too much to do both during the given time period. Fabricating electronics to textiles is an interesting subject of interdisciplinary research itself, and the technical integration of photovoltaics and other needed components to multilayered woven textiles would be a fascinating subject to continue with in an engineering-design team. Also, it would be interesting to follow the example of architecture in integrating solar cells optically using nanotechnology.

The next big question is how to design the photovoltaic energy harvesting textile in a way that benefits both design and technology, making the whole more than the sum of its parts. How to increase the intelligent and aesthetic properties of a textile through the use of photovoltaics? And what if the yarns and textile structures would be constructed in a way that focuses the light on the solar cell? Instead of decreasing the efficiency, could textiles be designed to enhance the function of photovoltaics?

All of the previously mentioned subjects could make use of combining textile strategies and explorative prototyping with scientific methods. From nano-level surfaces to the electronics, and exquisite products designed of the materials, designers could contribute with their knowledge to the different stages of research. Keeping the user and lifecycle of the product in mind at all phases would help setting clear goals for the whole team.

FINAL WORDS

In this final section, I compile the main findings to answer the research question.

Covering the solar cells with a textile layer always affects the performance negatively. By choosing transparent or light materials, and creating structures that allow as much light to pass through as possible, it is possible to find a compromise that doesn't exclude functionality or aesthetics. Traditional textile strategies like surface design, weaving techniques, and creating texture or decorative patterns can be used to support the technology.

In the *Energy Harvesting-Sun Powered Textiles* project the main findings were in the area of collaboration, along with important data that was gathered for further continuation. Working in a junction between different fields requires a lot of learning, communication, patience, and an open mind. In a hybrid environment it is important for a textile designer to be an expert in their own field but simultaneously stretch to also study topics and learn skills outside of the familiar practice. This versatility can be learned by bravely making mistakes, hands-on work, and being present through different stages of the process. Positive experiences and addressing challenges might help in planning upcoming projects and facilitating future fruitful processes.

Developing a deeper practical knowledge in multilayered weave structures and adapting scientific testing methods to the design process, resulted in several tangible proposals to answer the research question "how to design woven textiles that enable integration of existing solar cell technology". Ideal textiles depend on the end application and the other wanted properties of the textile. One option is to completely hide the technology, or it can be camouflaged to become a part of the design. The final textile prototypes include complex weave structures that can be adapted for photovoltaics integration, and are a great addition to the textile designers skillset. Multilayered woven textiles can be used in both artistic and technical work of the future including other fields of functional textiles and e-textiles.

Having technical boundaries can certainly lead to interesting textile design. Balancing in-between creativity and functionality required problem-solving that led to new research questions, and resulted in new ideas for woven textiles. Working in iterative cycles formed a constantly evolving learning process that encourages developing ideas further. The future of energy harvesting photovoltaic textiles is open for endless exploration from nano-level to global systems, and time will show to which directions it will evolve. There need to be clear benefits for developing and using such technology, and I don't think we can imagine all of the possibilities of energy harvesting or smart textiles yet. However, it has been a fascinating journey to expand my own views on what textiles can be and do, and in what kinds of projects and environments a textile designer may work in the future.

During the Tekstiili18 Exhibition, I received a lot of positive feedback about the work. Many visitors were curious to hear more, and got inspired by the subject. Several people came to tell me that the project was something new and meaningful. It was encouraging to realize that there is interest in interdisciplinarity and collaboration, and that textile designers have their part to play in it. I believe that through interdisciplinary projects designers could help resolving enormous global issues like climate change and overconsumption. In the end, complex problem solving requires a lot of creativity and collaboration. Being a part of creating something unique is in my opinion worth the time and struggles. I feel privileged to have had the opportunity to work across different disciplines, and seeing a glimpse of possible textile futures in science, technology and design.

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7 Fig. 4: multilayered weave structure, Pouta, E. (2016) Worn Identities-Interactive Textiles as extensions of Future Bodies. MA thesis. Helsinki, Finland: Aalto University School of Arts, Design and Architecture. pp. 85
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16 Fig. 6: smart textiles terms and their relationships, Sandra Wirtanen. Based on: Ilen, E. (2015) Decontamination of Wearable Textile Electrodes for Medical and Health Care Applications. Tampere University of Technology. Publication, Vuosikerta. 1305, Tampere University of Technology, Tampere. pp. 15 Figure 2
17-18 Photography: Eeva Suorlahti
19 Pauline Van Dongen: Windbreaker project, 2016. Pauline Van Dongen. Windbreaker Project. [online]. Available from: http://www.paulinevandongen.nl/project/solar-windbreaker/ [22 October 2018]
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