Suntex: Weaving Solar Energy Into Building Skin

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Abstract

The key objective of this research project is to "create a new architectural textile, Suntex, by interweaving thin film solar cells and electrically conductive yarn into a structural technical textile, so it can generate energy while it is providing shade, structure or an aesthetic update to a building."
Textile has strong potential as a sustainable building material because it can be lightweight, material efficient, and low carbon. Moreover, its flexibility provides great design freedom and its transparency makes it very suitable for façade applications, maintaining views to the outside while providing solar shading. Suntex is a solar textile, currently in development, intended for textile architecture applications like textile façades. By combining three qualities, namely providing the building with energy generation, solar shading, and a unique aesthetic appearance, which also promotes the acceptance of solar technology, it offers a positive climate impact.
Suntex can be considered as a new type of membrane material for Building Integrated Photovoltaics (BIPV). With this innovative, constructive fabric, enormous surfaces that are still unused can be outfitted with energy-generating potential.
This paper presents a design case to analyse the potential impact of Suntex as a textile façade. Based on insights into the development process and experiment results so far, it evaluates the feasibility and impact from a technical and design perspective.

Keywords

Textile architecture, solar textile, energy innovation, lightweight structures, BIPV

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1 INTRODUCTION & OBJECTIVES

1.1 INTRODUCTION

Buildings generate nearly 40% of annual global carbon dioxide (CO2) with operational emissions (including energy used to heat, cool, and light buildings) accounting for another 28% (UN Environment and International Energy Agency, 2017). To achieve the target of the Paris Agreement, approximately two thirds of the existing building stock will need to be modernised by 2040 (Architecture 2030, 2022). Buildings must become climate-positive by producing their own renewable energy and become climate-proof through intelligent thermal management.

As stated by the International Energy Agency, solar energy is "becoming the lowest-cost option for new electricity generation in most of the world" (IEA, 2020) and thus holds great promise for a sustainable future. One of the characteristics of solar systems is that they can be decentralised with the installations for the production of energy located closer to the place of energy consumption, a factor that has become particularly appealing in light of the global energy crisis (World Economic Forum, 2022). However, photovoltaic panels on the roofs of homes and offices alone, especially in high-rise buildings, are insufficient to meet the energy demand (TNO, n.d; Middelhauve, 2021). Façades have great potential, especially in low-latitude urban areas where the low sun on the vertical surface generates greater solar potential in the winter months than on roofs (Horn et al. 2018), so long as façades are carefully selected to maximise incident irradiance and minimise shading from nearby buildings or other obstructions.

Traditional silicon solar photovoltaic modules are rigid, heavy and have a one-size-fits-all design. This makes it a challenge to integrate them both functionally and aesthetically into existing buildings. New generations of thin-film solar cells mark a turning point in solar harvesting possibilities for buildings. These solar films are lightweight and flexible and can be custom fit for many more applications, such as applying them on existing (architectural) surfaces, including low-load-capacity roofs and curved surfaces, or integrating them into other flexible materials like textiles. In comparison to other materials like steel, concrete, aluminium or glass, textile is a more sustainable building material with very low embodied carbon due to its lightweight structural properties (Van Hinte & Beukers, 2020) and low energy consumption (Shareef Al-Azzawi et al., 2021). Furthermore, its flexibility and transparency provide great design freedom and usage, also in architecture. A second skin façade, from textile for example, enables views to the outside while mitigating and controlling excessive solar radiation. In addition, these façades can save energy through their isolation and ventilation properties during the cooling or heating period of a building. (Ahriz et al., 2022).

Combining (thin-film) solar technology with textiles is not new (Smelik et al., 2016; Kuhlmann et al., 2018; Nathanson, 2021) and the solutions range from highly experimental lab-stage research to more applied approaches that are already commercially available (Satharasinghe et al., 2020). The simplest, most common approach is to attach the flexible solar panel to the surface of the textile, for example through adhesives, sewing or laminating (Mather & Wilson, 2017; Nathanson, 2021). However, these assembly processes are difficult to scale industrially and present limitations for architectural applications in terms of their mechanical properties, modularity, and design potential (Mather & Wilson, 2017). To date, this method is used commercially within an architectural context by the US-based company Pvilion.

Suntex, an architectural textile currently under development, takes a different approach. Thin-film solar panels and electrical circuits (composed of conductive yarn) are integral to the construction of the textile by being directly combined in the weaving process. With the aim of being both a standardised and easily customizable architectural textile that increases the energy-harvesting potential of otherwise untapped surface area. Intended as a (retrofitted) façade second skin, Suntex has the potential to make a building more energy efficient through thermal insulation and through harvesting additional energy with integrated photovoltaics. Additionally, it brings completely new aesthetic qualities such as colour, transparency, and texture, which can help drive the adoption of photovoltaic technology (Reinders et al., 2020). A Suntex façade, in common with other façade solutions, can become a valuable addition for energy autonomy and grid reliability. By applying Suntex to existing infrastructure it is not in competition with agricultural land, industrial estates, or housing unlike space-consuming solar farms. Further, solutions such as Suntex have the potential to improve urban habitats, by de-reflecting glass windows, a primary source of bird-building collisions (Klem, 2006).

The key objectives of this paper are to explore the feasibility of Suntex and potential impact of this new textile when applied as a textile façade. The feasibility will be investigated by evaluating the textile samples created so far, against the requirements of a type I architectural fabric. The potential impact of this new textile will be investigated through an implementation analysis, which includes a case study, wherein the quantified benefit of energy generation will be explored alongside the qualitative benefits.

It should be noted that the initial phase of the research project is currently planned to run for two years, and is at the midpoint of one year at the time of writing.

2 RESEARCH METHODOLOGY

In order to develop a smart technical textile for application in textile architecture, this research is carried out at the intersection of textile design, design engineering and textile architecture. The design process is therefore hands-on, iterative, and highly collaborative. As a result of this interdisciplinary approach, both scientific research methods and design research methods are combined in the textile development process, which follows an iterative cycle.

As detailed in section 2.2, the textile design process follows an adapted version of the 'design thinking' approach (System Concepts, n.d) in that it is an iterative process in which testing informs the next steps. First, materials are selected according to pre-defined criteria. Next, a weave pattern is designed alongside a strategy to integrate the OPV film, and a sample is created. This sample is mechanically tested and reviewed against the textile requirements (Section 2.1). Conclusions from this process inform the first steps of the next iteration; the material selection and sample design. The latest iteration of the textile is then further evaluated through the development of a case study that reveals the potential impact of applying Suntex as energy harvesting building skin. In general, a case study combines data from multiple sources to explore a problem or scenario (Methodspace, 2021). While design cases or case studies can be built on expected, speculative data alone, this paper also shows the actual data gathered through experimental testing on woven textile samples. This process is done in an effort to contribute to the field of smart, technical textile development by sharing the details of the textile design and development process. In this case, the mechanical strength values achieved in the textile sample evaluation (Section 3.1) and the inherent nature of weaving to produce rectilinear textiles indicated that a second-skin façade would be a worthwhile design case study to investigate (Section 3.3) as an initial application. The Westraven Rijkswaterstaat building in Utrecht (The Netherlands) was selected as the particular building to explore as it is a prominent example of a textile second-skin façade and it already demonstrates the environmental benefits of retrofitting a building in this way, in terms of thermal management.

2.1 TEXTILE REQUIREMENTS FOR SUNTEX

From a structural standpoint, textiles used in architecture are required to meet strength and stiffness criteria as well as water, UV-light, and fire resistance for durable load bearing applications. Typical architecture textiles are coated fabrics such as polyvinyl chloride (PVC) coated polyester (PES) fabrics and polytetrafluoroethylene (PTFE) coated glass fabrics, where the coating provides protection against weathering agents, and the fabric weave within the coating is the load-carrying element. Uncoated fabrics are similarly used in an architectural context but to a limited extent since without a coating, achieving comparable durability becomes challenging. In terms of strength, architecture fabrics are classified into categories from type I to type V, corresponding to tensile strengths of about 3000 N/5cm to 10,000 N/5cm, respectively. The strength should be verified in both weave directions and in areas of seams using relevant standardised tensile strength tests. Type I fabric, thus, offers the minimum required tensile strength for a viable fabric. It is also necessary that the fabric does not show too much remaining strain under loading so as not to lose functionality prior to failure. In addition, architecture fabrics are required to provide a sufficient level of fire retardancy which is demonstrated by the fabric's ability to undergo combustion, the extent of smoke production, and the production of molten droplets, as indicated by the Euroclasses for fire reaction classification. A polymeric coating is considered sufficient for water and UV-light resistance; however, for uncoated fabrics, these properties should be verified.

In light of the aforementioned criteria, the Suntex fabric is designed to be a type I fabric with a strength of approximately 3000 N/5cm in both warp and weft directions. The fire behaviour objective is set to meet at least EN 13501 class B-S2, D0.

To guarantee a functional solar fabric, not only is the structural behaviour important, but the practicality and environmental impact are also crucial. These aspects were translated into the following preset objectives that have informed the R&D process of Suntex:

1. A lightweight material of up to 1200 g/m^2 with a solar panel active area to textile surface ratio of approx. 50/50;
2. A material that can be rolled up;
3. A modular system that can be put together in (differently shaped) strips to form 3D curved fabrics, whereby the various electrical circuits are connected by means of interconnects;
4. An energy yield of approximately 20 W_p/m^2 (Peak watt at STC) of composite solar textile (given this is only 50% coverage of active OPV area), which may seem relatively little compared to traditional silicon solar panels, but the characteristics of OPV mean it can be used in this context in a way traditional silicon solar panels could not;
5. A sunlight transmission factor of 20 - 30%;
6. A fully recyclable material, whereby the solar cell structures can be separated from the textile, with a lifespan of 10 - 15 years.

Deeper consideration of the textile requirements also reveals the challenges involved in developing this new material. For instance, the uniformity of the textile is being challenged by the integration of solar cells. This further complicates the general inhomogeneity and anisotropy possible in textile fabrics, meaning tensile and bending properties differ between warp and weft. Further, the integration of electrical hardware components in a soft flexible textile can cause stress concentrations and weak points. To mitigate these challenges, the textile is being developed in an iterative process using high tenacity yarns, the selection of which is informed by extensive tensile testing to meet the requirements for a type I architectural textile. In addition, when implementing the Suntex textile, certain design guidelines may need to be recommended, regarding the loading directions.

Aside from the design and construction challenges, consideration must be given to the route to mass manufacturing. In order for the textile to have maximum impact and accessibility, the production should be efficient and cost-effective. Ongoing conversations with industry partners are informing design decisions which affect the production, to ensure design for manufacture is an inherent part of the development process.

2.2 TEXTILE DESIGN PROCESS

The design process of the textile itself is informed by the requirements outlined in Section 2.1, and broadly follows these steps repeatedly (forming an iterative loop):

1. Material selection (as detailed in section 2.2.1).
   a. Photovoltaic technology selection
   b. Yarn selection
2. Textile development process (see section 2.2.2).
   a. Structure/Weave design (including solar panel integration method).
   b. Sample creation.
3. Sample evaluation (Testing, as detailed in section 3.1).
4. Analysis and review of the materials and weave design (as detailed in section 3.1), then return to the material selection stage.

2.2.1 Material Selection

A *Photovoltaic Technology Selection*

As a first step, the type of photovoltaic technology to be integrated had to be selected. Organic photovoltaic film (OPV) was chosen for a number of reasons; it is a flexible, thin-film material (as can be seen in Fig. 1) produced in a low-carbon, roll-to-roll manufacturing process, and, it is composed of organic, non-toxic materials which are abundant and can be recovered at end-of-life. Due to this composition, it is semi-transparent and can be created in different colours (see Fig. 2). Additionally, the materials and production process mean that this technology has the theoretical potential to provide electricity at a lower cost than first- and second-generation solar technologies (USA Department of Energy, 2022), and it can have an energy payback time (the time required by an application to generate as much energy as is consumed during its production) around 10 times shorter than that of other solar technologies (ASCA®, EPBT 2021).

Furthermore, OPV technology is rapidly improving. For example, the ASCA® OPV film which is currently available can produce approximately 20-50 W_p/m^2 (depending on chosen colour), but the company has recently achieved outputs of 70 W_p/m^2 in pilot scale and expect to translate that to production by year end 2022 (ASCA®, Efficiency Increase, 2021). For comparison, the most efficient monocrystalline N-Type silicon solar technology on the market can produce 220 W_p/m^2 (Clean Energy Review, 2022), but of course the characteristics of OPV technology enable it to be used in contexts where monocrystalline silicon solar panels would not be used. In addition to these promising results under Standard Testing Conditions, OPV technology has also been shown to be less sensitive to some 'real world' factors than traditional silicon solar. Especially relevant to outdoor façade applications, as shown by Dolara et al.'s (2022) research at Polimi's SolarTechLAB; OPV has high performance in lower light conditions and with light from different angles (as occurs with vertical installation on a façade), and it is not adversely affected by increased temperatures. In fact, during their five-month outdoor testing period in Milan, the OPV modules showed improved performance (shown by an increasing P_{mpp}, maximum power point) with increasing temperature in all the considered irradiance range, whereas the monocrystalline and CIS modules tested in the same conditions showed a linear decrease with the cell's temperature.
Finally, on a practical level, the nature of the OPV film technology means that custom sizes and shapes can be created, and smaller order quantities are possible which is essential for early-stage prototyping and testing. For this project, OPV strips of 45cm length and 2.5cm width were available for initial prototyping and testing, to later inform the design of a custom part.

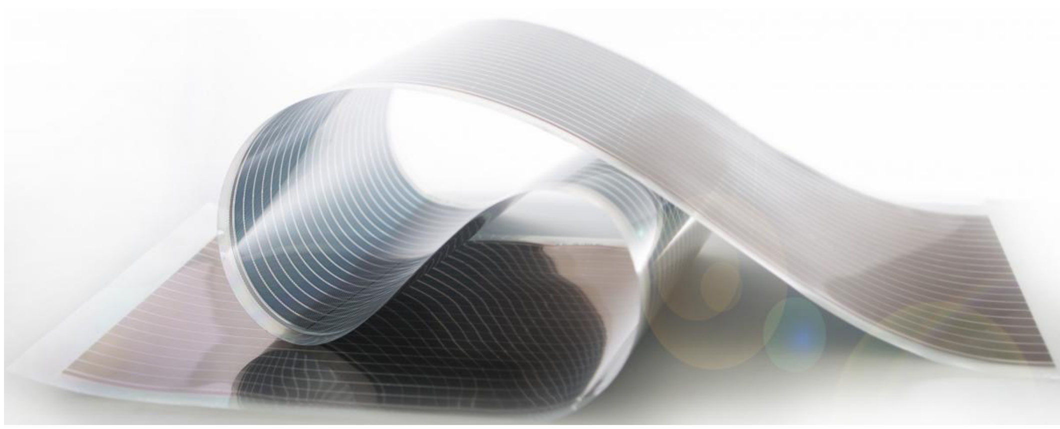

FIG. 1 ASCA Organic Photovoltaic Film, flexibility apparent. (Image courtesy of ASCA®)

B *Yarn Selection*

The continuous challenge with Suntex is the requirement to combine several "unusual" materials in one weaving process to make up the functional module. Alongside the OPV films (which mechanically, act like PET film), materials like a conductive track (that connects the solar panels), transparent monofilament (to secure the solar film), and high-tenacity yarns (that give the required tensile strength) are inevitable to use when making Suntex. All of the materials have rather different properties in terms of flexibility, elasticity, or breaking-load, which all need to be considered before, during, and after the textile has been woven. During the hands-on research, materials were assessed on how well they harmonise and complement each other so that their properties combine in the weave to make Suntex an energy-harvesting architecture type 1 fabric. The important factors for the selection of materials and structure of the fabric include:

- A high-tenacity main yarn, used in warp and weft, that is readily available and has a textile look and touch
- A high-tenacity main yarn, used in warp and weft, that when woven has a tensile strength of 3000N/5cm (criteria type 1 architectural fabric)
- A transparent warp yarn ("float yarn") in combination with a specific weave pattern to hold the OPV films in place without putting strain or load on them or covering them entirely
- A conductive yarn, used in warp and weft, that enables a functioning circuit which connects the OPV films with each other and enables a connection to transfer the energy to an outlet
- All materials complying with fire-retardancy, durability, and weather resistance standards for textile architecture

Based on these factors, examples of chosen yarns and their mechanical properties can be seen in Table 1.

TABLE 1 **An example selection of yarns to suit the set criteria, and their mechanical properties.**

	Example	Diameter (mm)	Linear Density (dTex)	Breaking Force (N)	Breaking Tenacity (cN/dTex)
Main Yarn	MSP rPET	n/a (flat yarn)	1100	84.3	7.54
Float Yarn	Filva Monofilament	0.40	1600	27.45	1.72
Conductive Yarn	Karl Grimm High Flex 3981	0.42	2325	27.468	1.181

FIG. 2 ASCA Organic Photovoltaic Film; transparency, colour and freeform possibilities apparent. (Image courtesy of ASCA®)

2.2.2 Textile Development Process

A *Weave design*

The main focus of the textile development is the weave structure which is designed strategically around the integration of the OPV film. This makes it similar to the Texenergie/Texenergy research project by Saxion University (Hurenkamp, 2020), in which OPV films were woven into a textile to make indoor window blinds (among other applications). Since these use cases differ significantly the material choices for Suntex and the weave structure are also different.
The main aim for Suntex is that the high-tenacity yarns described in Section 2.2.1 B must take the majority of the tensile load, and the “float” structures around and on top of the OPV hold the film strips in place without putting excessive load on these strips or shading them. The purpose of this is to prevent electrical efficiency losses of the OPV. Therefore, an iterative process began, in which different material combinations, patterns, and weave-set-ups were tested and evaluated regarding processability and functionality of Suntex, first on a handweaving loom and later an industrial sampling loom. As detailed in Section 3.1, these woven demonstrators and specimens were extensively tested to investigate their structural and tensile behaviour and therefore verify or eliminate material choices, weave patterns, and set-ups.

Throughout the design process, the aim was to retain a textile look and touch as opposed to a heavily coated industrial composite-like material. This is because such composite materials are difficult to disassemble, repair and recycle and, further, have limited opportunities for surface and colour design. Suntex remains uncoated, so the chosen pattern and (coloured) yarns will define the unique look and give it a tactile feel as opposed to a flat and printed coated textile. Removing the entire step of coating during the manufacturing process can compensate for the extra time needed for the more complex weaving process.
Because Suntex is unique and new, there is little (empirical) research that could be referenced when planning and anticipating the challenges of weaving, except for the above named Texenergie/Texenergy project. This makes the textile development process variable, as one change in fabric construction may affect the entire look, feel, behaviour, and functionality of Suntex.

B *Sample Creation*

In addition to the choice of materials, the weaving loom plays a major role. Industrial looms tend to be fit for one purpose only and cannot be tweaked to switch from one material to another, especially regarding the preparation of warp beams and general setup which can take months. Therefore, to facilitate a more agile development process, most Suntex samples were initially tested on a handweaving loom (Louët Erica) and later recreated on an industrial sampling loom (CCI Evergreen). On both looms a maximum fabric width of 50cm can be woven and the maximum fabric length varies, depending on the length of the warp yarns used. On the handweaving loom, the length of those yarns is chosen by the weaver and for the CCI Evergreen loom, the warping machine available for these trials automatically limits the total length of the textile to 2m. The number of shafts on the looms also differs, from a maximum of 4 (handweaving loom) to 24 (CCI Evergreen). The number of shafts (and the carefully planned warp threading through these shafts) determine the addressability of the warp yarns, and therefore more shafts can realise more complex weave structures in which several yarns need to be lifted or lowered individually. With Suntex, this is necessary for integrating the OPV film and the conductive tracks.

FIG. 3 Louët Erica Handweaving Loom

FIG. 4 CCI Evergreen Sampling Loom

Strategic use of both technologies enabled quick control and production of small samples within days that varied in complexity. A choice of these samples and the analysis thereof can be found in Section 3.1 Textile Evaluation. Further, using the CCI Evergreen sampling loom has made it possible to experiment and test solutions for weaving Suntex in an industrial setting and being able to assess the limitations that would be present in larger industrial productions like warp and weft yarn tensions, warp beam setup, gripper system, and more. Making the transition from a sampling loom to an industrial loom is the next step in the process to make Suntex widely available for use in textile architecture.

3 EXPERIMENTAL TESTING & RESULTS

As mentioned in Section 2, experimental testing is an essential part of the iterative design process. This section outlines the experimental tests and its results. More precisely, it reports textile evaluation tests and electrical and mechanical behaviour of the OPV film. A case study is then carried out in order to analyse and compare the impact of Suntex on a building façade.

3.1 TEXTILE EVALUATION

The evaluation of the textile's mechanical properties was performed using tensile strip tests in which fabric specimens, of at least 5cm widths and 20 cm lengths, were mounted onto the clamps of a tensile testing machine and stretched until failure. From these tests, the failure load, and the elongation at break can both be measured for assessing the strength and stiffness of the specimens. Additionally, the tests provide insight into the interaction between the fabric and the solar cell tape, which gives an indication of whether the solar cells will undergo stress during loading. Multiple test series were carried out on composite fabrics with different yarn strengths to examine whether the strength of the configuration meets the strength objective. See Table 2 for brief overview.

TABLE 2 **A summarised overview of Suntex iterations.**

Iteration Name	Loom	Material Combination	Weaving Pattern Notes	Evaluation Notes
Suntex V1.1	Louët Erica handweaving loom	TPU main yarn	Plain Weave with double-sided floats	Progress to machine weaving (CCI Evergreen)
Suntex V1.2	CCI Evergreen Sampling Loom (automatic)	TPU main yarn, Monofilament float yarn	2/2 Twill, Plain Weave with single-sided floats (with plain/twill backing)	Coated yarn creates an open mesh structure which is interesting for optical properties but the strength is insufficient, so must review material choices.
Suntex V2	Louët Erica handweaving loom	Twisted rPET main yarn and float yarn	Plain Weave with single-sided floats (with plain/twill backing)	Strength promising and denser weave possible with this yarn, progress to machine weaving and test with monofilament float yarns.
Suntex V3	CCI Evergreen Sampling Loom (automatic)	Twisted rPET main yarn, monofilament float yarn	Plain Weave with single-sided floats (with plain/twill backing)	Conclusive testing has not yet been completed; weave is denser than V2 which suggests high strength, but weaker monofilament material included may counteract this benefit.

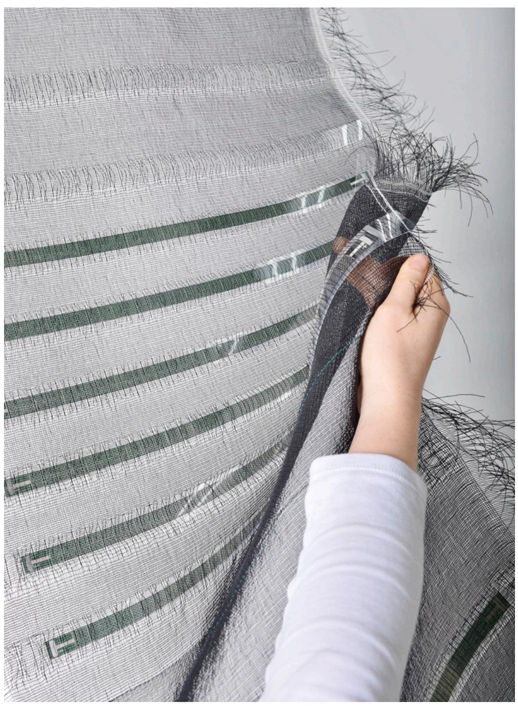

FIG. 5 Suntex V1.2 sample.

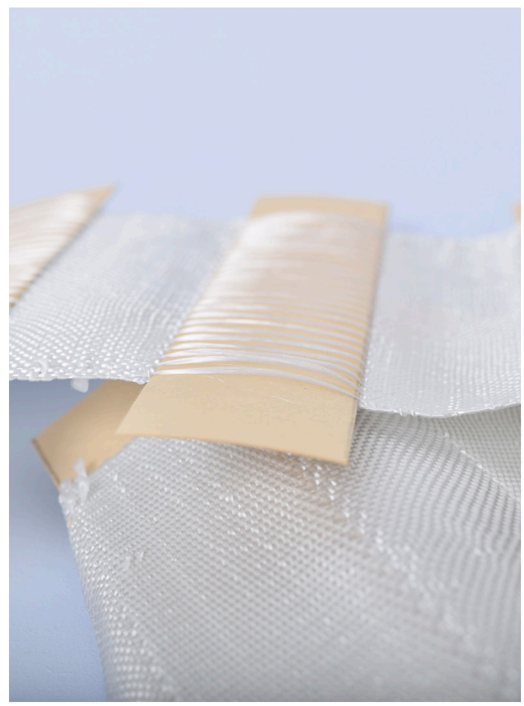

FIG. 6 Suntex V2 sample with card strips in place of solar film.

The initial fabric composite Suntex V1 (Figure 5), made with thermoplastic polyurethane (TPU) coated polyester yarns, demonstrated insufficient strength and in some cases large elongations. Consequently, the main yarn, which is the most prevalent in a weave, had to be replaced by a higher tenacity yarn in the subsequent fabric prototype. Suntex V2 (Figure 6) was, thus, hand-woven from recycled high-tenacity polyester (rPET) yarns. To acquire a quick indication of the strength behaviour and the impact on the solar film, only warp specimens were woven. The tensile tests of Suntex V2 consisted of six fabric specimens, three of which were regular plain-woven fabric (Suntex V W1 - W3) and an additional three with PET film strips inserted to mimic the presence of the solar film, hereby referred to as 'solar film' or 'SF' (for example, 'Suntex V2 SF W1' in Table 3). All specimens were coated with a speckling pattern prior to testing to enable digital image correlation (DIC) analysis during the tests. This analysis type provides the strain field over the specimens' area throughout the loading process until failure which helps identify whether the mode of failure is valid and if non-uniform stressing occurs, therefore revealing the effect of integrating the solar film into the woven textile. After specimen preparation, each specimen was mounted onto the clamps of an Instron 1122 tensile machine, and an initial 10 N prestress was applied. The initial length was then measured, and the tests carried out with an extension rate of 100 mm/min.

3.1.1 Results of Textile Evaluation

The results are summarised in Table 3, and can be seen in the graph in Figure 8. The data showed substantial failure loads, averaging 2781.4N for the regular specimens and 2545.2N for the specimens with 'solar film' (SF) integrated in 'float' structures (Figure 7). This strength reduction of only 8.49% in the more irregular 'solar film' (SF) specimens, verifies the weaving strategy of implementing single-sided floats (with plain/twill backing) to integrate the solar films.

TABLE 3 **Suntex V2 specimen information and tensile test results (as logged by Instron 1122 tensile testing machine used)**

General Information		Weave specifications			Test Results	
Category	**Specimen Name**	**Pattern**	**Warp density (yarns/cm)**	**Weft density (yarns/cm)**	**Elongation (%)**	**Failure Load (N/5cm)**
Regular Specimens	Suntex V2 W1	Plain weave	10	11	13.3	2646.23
	Suntex V2 W2		10	11	15.0	2959.46
	Suntex V2 W3		10	11	12.7	2738.56
Solar Film (SF) Specimens	Suntex V2 SF W1	Plain/Twill backing layer at SF 'floats'	10	16.6	9.7	2263.44
	Suntex V2 SF W2		10	16.6	10.6	2547.77
	Suntex V2 SF W3		10	16.6	10.2088	2542.64

FIG. 7 Suntex V2 Specimens after testing to failure. Regular specimens labelled "Twisted rPET W1-3" are referred to as "Suntex V2 W1-3" in this paper, and Solar Film specimens labelled "Twisted rPET SC W1-3" are referred to as "Suntex V2 SF W1-3" in this paper.

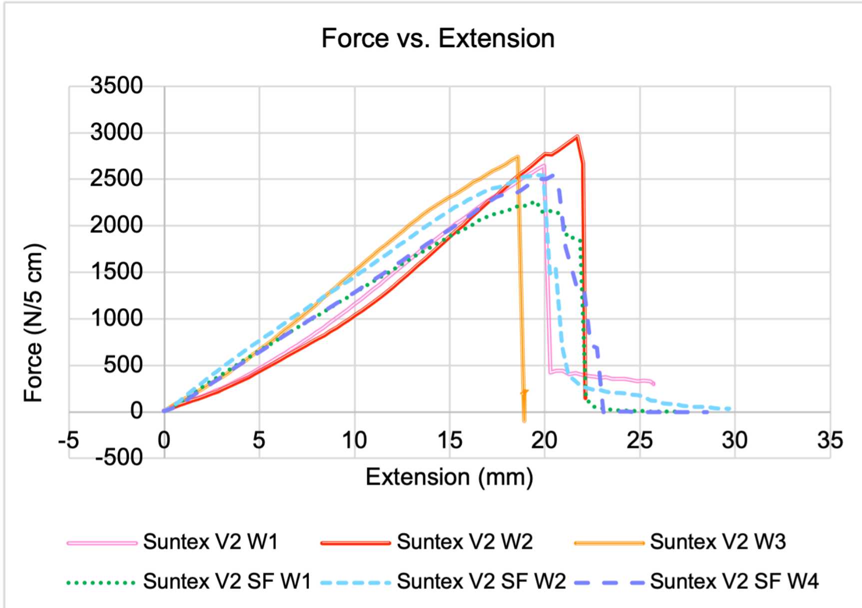

FIG. 8 Suntex V2 specimens' force-extension behaviour.

The digital image correlation (DIC) analysis (Figures 9 and 10) data correlates with the data logged by the Instron 1122 tensile testing machine used (summarised in Table 3). The DIC analysis of the solar film specimens is particularly interesting (Figure 10); lower strain can be observed at the solar film sections compared to the adjacent woven sections, which implies that the solar cells are not under any stresses that could cause a loss of function before fabric failure. This indicates that the weave design strategy to integrate the solar film in a way that it would not be subject to large tensile loads is successful, and supports the viability of this approach and the textile itself.

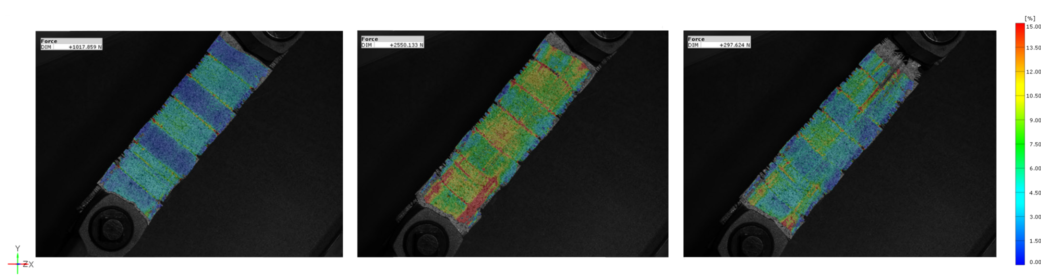

FIG. 9 Specimen 'Suntex W3' strain field along the longitudinal direction at failure (left) & directly after failure (right).

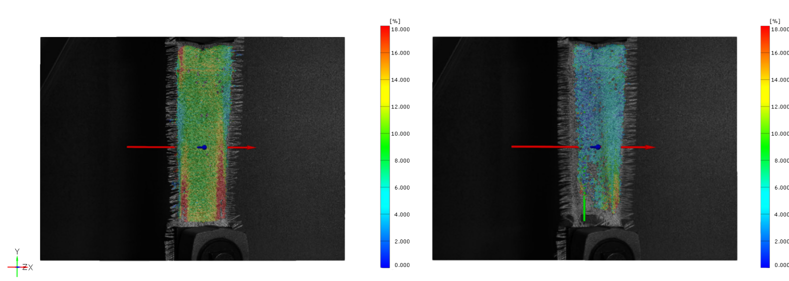

FIG. 10 Specimen 'Suntex V2 SF W2' strain field at approximately 1 kN load (left), at maximum load (middle), and after failure (right).

The results are, however, limited to the warp direction only, and to verify the fabric strength, the weft direction should also be tested. Furthermore, due to the samples being handwoven, non-uniform stressing of the specimens is most likely to happen, which might cause failure at a lesser load than potentially possible. Upcoming tests, therefore, should be performed on fabrics woven on a power loom. Nonetheless, these results show the rPET Suntex V2 is a promising configuration to achieve the desired strength, and inform the next iteration, Suntex V3.

Suntex V3 samples have been woven on a power loom (CCI Evergreen), using the same rPET yarn as Suntex V2 for the 'main yarn' but with some of these warp yarns replaced with monofilament (which is used as the float yarn to hold the solar film in place). Weaving it on the power loom facilitated a denser weave, which should result in a stronger overall textile. However, the weaker monofilament replacing some of the rPET warp yarns may counteract this effect. Conclusive mechanical testing has not yet been performed, to investigate these theories and the mechanical strength of this latest iteration.

3.2 ELECTRICAL AND MECHANICAL BEHAVIOUR OF THE OPV FILM

In addition to evaluating the tensile properties of the surrounding woven textile, certain properties of the OPV film were also investigated, to understand how it would behave within the textile. The material data sheets generally provide figures for the electrical properties, thickness, weight, flexibility, impact resistance and operating conditions. However, as the material is not intended to be tensioned (as is the case with all photovoltaic technology), tensile strength and elongation data is not provided.

The OPV film is a composite in itself; it is a laminated stack of a substrate, conductive material, printed active material within a polymer encapsulant. Fan et. al (2013) demonstrated with a certain OPV film sample that the inner laminated stack tends to be more sensitive to straining compared to the encapsulant, so it is expected electrical failure occurs at a lesser tensile force and strain than mechanical failure. However, each company producing OPV may be implementing different materials and processes and therefore there can be no standard comparisons of failure modes, for instance. This highlights the lack of empirical research in the area, and the need for testing to create practical insights. Therefore, to further understand the specific OPV material available for this research project and how it should be integrated into the textile, a number of tests were conducted to investigate both electrical failure and mechanical failure.

For these reasons, despite the design intent for the surrounding textile to carry the tensile forces as much as possible, the solar film was tested in a tensile testing machine (Figure 12). The apparatus was similar to that of the tensile fabric tests already described in Section 3.1, except a strong light source was added and the electrical performance of the solar film was also logged (using an Arduino system), while the tension was applied (Figure 11). In this way, the tensile load at which both electrical failure and mechanical failure occurred was identified.

FIG. 11 OPV strip test set-up, illuminated by bright light source.

FIG. 12 Mark 10 Instron Machine used in the testing.

3.2.1 Results of OPV Tensile Testing

The results were encouraging, showing the solar films were electrically functional up to around 500-600N tension, and 15mm extension. Mechanically, the films mostly showed a plastic mode of failure with viscous deformation of the PET encapsulant material at the yield point (at 560-680N) followed by progressive elongation and a gradual increase in tensile force. These preliminary results support the continued development of the textile, and inform the design choices. Further testing (for example, to understand the OPV behaviour when integrated into the textile, and the textile is tensioned) will be required. Finally, it should be noted that within industry, a secondary encapsulation can be added to an OPV film (in addition to the primary encapsulation present in all OPV film, including samples used in these tests) to increase the resilience of the modules to mechanical stress or environmental factors.

Integration into the textile also has an optical effect on the solar film, as certain warp yarns 'float' over the film in order to keep it in place. Preliminary tests were conducted to investigate the effect of different 'float' design strategies (varying in material and density) on the performance of the solar energy generation. These results were also encouraging, indicating that the peak performance is only reduced by approximately 10-15% with the chosen 'float' design. No optical modelling has been completed to further explain what is occurring, but it can be speculated that multiple optical phenomena are at play, not only shading (negatively affecting the irradiance on the solar film), but also reflection and scattering (positively affecting the irradiance). Further testing and analysis will inform the final design.

3.3 DESIGN CASE STUDY TO ANALYSE COMPARATIVE IMPACT OF SUNTEX

A preliminary overview of the quantitative and qualitative impact of installing a Suntex façade (compared to a traditional textile façade without integrated solar PV on the same building) is presented. A façade presents itself as a suitable first use case due to the rectilinear "panels" of textile required (as opposed to complicated or organic shapes) and the relatively lower loading compared to freeform tensile architecture structures as current practice is showing. Generally type I architectural textiles are used in these applications, the strength requirements for which appear to be in reach for a Suntex textile (based on the tensile strength results for the Suntex V2 samples as presented in Section 3.1.1, and calculations to predict the strength of Suntex V3).

The building in question is the Westraven Rijkswaterstaat building in Utrecht (The Netherlands), which was constructed in the 1970s and renovated to include a glass façade with a textile second skin in 2007 (the textile material was subsequently replaced in 2020). The light-weight addition of this Teflon-coated and open-weave fibre-glass textile improved the thermal management (and therefore the working environment) in the building in two ways: first, it acted as a wind baffle and allowed the employees to open their windows and thus control their own localised climate; secondly, it also functioned as a sun-shade without impeding the views, further reducing the energy required to cool the building (Hendriks, 2010). In this way, the Westraven renovation already highlights the tremendous potential of retrofitting with a second-skin textile façade to improve the sustainable credentials of existing buildings. Thus, this study will focus on the additional benefits uniquely offered by Suntex; namely the untapped potential of solar energy generation and the new aesthetic possibilities Suntex enables, and take the benefit of solar-shading as a given in this context.

The speculative design case and underlying analysis reveal some important considerations when designing a façade with Suntex, and the opportunities and challenges of applying the Suntex material as the chosen second skin façade textile. Finally, the analysis points to future improvements to make Suntex more impactful and/or attractive to the field of textile architecture.

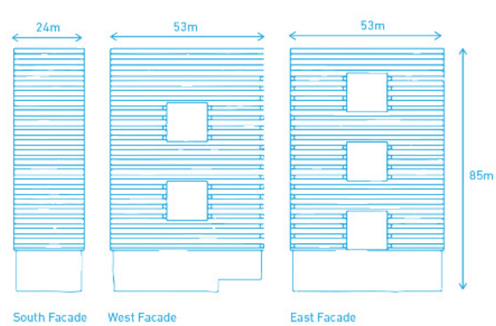

FIG. 13 Schematics of the façade surfaces in question.

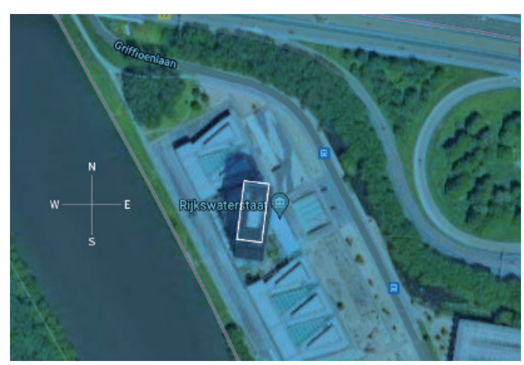

FIG. 14 Aerial view of the Westraven building, showing aspect.

3.3.1 Quantitative Benefits: Energy Generation

The first parameters when assessing the potential of any photovoltaic application are available surface area and solar irradiance as indicated by the location and orientation of a site (and the presence or lack thereof of obstacles causing shading). In the existing renovation, the north façade of the Westraven building has an additional glass layer for sound insulation from the nearby motorway, whereas the sunnier south, west, and east façades have the textile second-skin which provides solar-shading (Figure 14). The available surface area on these three sunny façades is approximately 11 152m^2 (Figure 13), and the current textile covers 10 000m^2 to allow some fully open sections (Buitink, 2020) and therefore not increase the artificial lighting requirements inside the building. In theory, Suntex would cover this same area; the façades which require shading from the sun of course have the most solar irradiance and therefore excellent potential for photovoltaic energy generation.

The aim for the Suntex material was to achieve 50% coverage of active OPV area (though it must be noted that current iteration Suntex V3 in April 2022 achieved approximately 25% coverage of active OPV area), which in this case would result in 5 000 m^2 of OPV. The output of commercially available OPV film is currently approximately 20-50W$_p$ /m^2 depending on the chosen colour (ASCA® Datasheet, 2021), and taking the peak output of the samples available for this project (approximately 40W$_p$ /m^2) indicates that this application would be a 200kW system (whereas in the near future when OPV will achieve 70 W$_p$ /m^2 in production, a 350kW system will be possible with this same surface area). In practical terms, assuming 1602 hours of sunshine in Utrecht each year according to meteorological data (Current Results, 2010; KMNI, 2020) and noting that the Westraven building is the tallest in the locality and thus receives unobstructed sunshine (and making the simplified assumption that this sunshine falls equally on these three façades), this 200kW system could produce 320.4MWh each year. Contextually, this could provide 4% of the building's total energy consumption (or approximately 1 floor), or provide lighting to the entire building, which is generally 2.5% of a non-residential building's energy usage (EU Buildings Factsheet, 2013).

For reference, the rooftop surface of the Westraven building is approximately 1 272 m^2 , roughly 11% of the surface area available on the three 'sunny' façades. Covering this rooftop area in traditional silicon solar panels could only make a system of approximately 160kW capacity (assuming 1 000 m^2 area available, and polycrystalline solar panels with a power conversion efficiency of 16% are utilised (Clean Energy Review, 2022)) thus emphasising the untapped potential of façade solar particularly in tall buildings such as this one. This example also points to the potential of third generation solar technologies such as OPV, which compensate for their lower efficiencies by being more versatile than traditional silicon solar technology.

It must be noted that this analysis simplifies the irradiance scenario and the methods used here are approximate, in order to quickly understand the magnitude of the impact. Detailed modelling of the irradiance, using software such as BIMsolar, would be required to optimise the positioning of Suntex solar textile in a true application. Additionally, any increased artificial lighting load would need to be quantified against the energy benefits. Nonetheless, the quantitative energy-generating potential of implementing Suntex solar textile as a second-skin façade material is clear, in addition to the solar-shading benefit it shares with many existing façade textiles.

4 FUTURE OUTLOOK

The societal value and commercial potential of Suntex does not rely merely on mechanical and electrical performance. In order to evaluate the impact of Suntex, besides the scientific results, it is relevant to include some more speculative reflections regarding the qualitative benefits and design considerations to be made in the process.

4.1 QUALITATIVE BENEFITS: AESTHETIC AND SOCIAL IMPACT

In a more qualitative sense, Suntex also presents new aesthetic possibilities for architects to explore and implement, by broadening the appearance of thin-film solar technology and the possibilities for aesthetic integration in building façades. In this way, although specific aesthetic styles are subjective and contextual, the potential for Suntex to manifest in different appearances creates opportunities for new visual perspectives on solar technology, which is a necessary step in the adoption of technologies into our everyday environment (Dongen, 2019; Sánchez-Pantoja, 2018).

In the context of the Westraven building, the appearance of the textile façade dominates the visual impact of the entire structure. The two iterations of the textile façade so far have been very dark in colour; first black PTFE-coated glass fabric in 2007 and now brown PVC-coated polyester fabric since 2020. If Suntex is created by designers with the architect's perspective in mind, more interesting colourways and gradients can be woven, with a more striking impact. Custom rolls of textile can be created to either camouflage or highlight the solar strips depending on the architect's vision. By their nature, textiles enable design freedom. The selection of yarn colour and type, and of weave pattern, can determine the colour and transparency of a textile and therefore open possibilities for new aesthetic qualities and indoor/outdoor ambiances.

Very often solar panels are out of sight on roofs or solar farms, which can make it difficult for people to engage and accept them as a necessary element of energy transition and modern energy harvesting (Reinders et al., 2020). The highly visible location of the Westraven building (conspicuous from both the A19 motorway and the busy Amsterdam-Rijn Canal) creates the perfect showcase platform for a new solar textile, with potential to not only increase awareness and acceptance of new solar technologies, but also to inspire further applications and other implementations of renewable technologies in our immediate built environment. In this way, retrofitting iconic buildings with a new solar textile could have a social impact and help accelerate the energy transition.

4.2 DESIGN CONSIDERATIONS FOR DEVELOPING AND IMPLEMENTING SUNTEX

Naturally, every innovation presents challenges, and this can be especially true in the construction industry. Creating a smart textile to meet the requirements described in Section 2.1 is difficult, and alterations to weaving machinery are required in order to accommodate efficiently weaving the solar film. The process of making robust electrical connections throughout this textile must be developed with industry; the integrated circuit must be robust and protected against the elements.

Further, the logistics of applying the finished textile, either to an existing building or to create a new structure, will present other challenges. The solar panel circuit must also be designed to be modular, so the textile could be used in different lengths with different numbers of solar panels, while minimising efficiency losses. The power outlet points and route to energy storage must be designed in tandem with the frame or tensioning system, to efficiently use minimal materials and create a multi-functional frame. Extensive ageing testing must be completed to ensure that the Suntex textile will have a useful lifetime equal to (or surpassing) that of existing architectural textiles. Finally, all materials should be separable and recyclable at end of life.

5 CONCLUSION

This paper outlined the textile design and development process for Suntex, followed by the preliminary results obtained through experimental testing of samples. These test results validated the feasibility of the textile and pointed towards façades as a potential use case. The potential impact of the textile was then evaluated through the development of a case study that explored applying Suntex as energy harvesting building skin to a pre-existing building.

The design case study presented supports the fact that façades are an untapped surface area; in tall buildings they commonly provide a surface area that is a magnitude greater than that of roofs. In many countries, like the Netherlands, there is already great competition for the usage of 'greenfield' or undeveloped land; agriculture, housing, etc; thus, space-consuming solar farms are not an optimal solution. In the Netherlands alone, there are some 1,600 square kilometres of façade surface available, which means that by 2050, at least a third of the renewable energy potential of the built environment could be on façades (TNO, n.d)

If Suntex can be developed into an industrial off-the shelf and customizable architectural textile, it can support large-scale use. However, for this to happen more research is needed to solve the challenges described in 4.2 Design Considerations for developing and implementing Suntex. Despite these challenges, the preliminary research, testing, and development process is promising and the potential impact for the Suntex solar textile is clear. Furthermore, the rapid development of organic photovoltaic technology (and other solar thin film technologies such as CIGS, which could also be integrated within the textile) suggests that the future will bring higher efficiencies at lower costs. Therefore, the iterative loops of the development process outlined in this paper will be continued until May 2023. To evaluate an industrial production of Suntex further, a dialogue with industry partners will be started with the clear aim to evolve Suntex into an industrially manufacturable type I architectural textile.

As Suntex develops into a robust industrialised product for two-dimensional surfaces like façade cladding, custom made and three-dimensional solutions for a range of applications can also be explored. By replacing traditional architecture textiles which are used to create tensile structures such as tents or canopies, Suntex can not only provide shelter and shade, but also generate energy. A particularly compelling use case for a rugged Suntex tent is in humanitarian crises, when there is an urgent need for a quickly deployable solution to provide this shelter, shade, and energy. Similarly, the potential for off-grid or self-powered tents for the events sector is clear.

The need to make the built environment more sustainable as part of the energy transition, in tandem with reducing reliance on imported energy, is high on the global agenda. The European Union Solar Energy Strategy recognises the potential of solar, and the new and novel BIPV in particular, to decarbonise our building stock. An obligation to gradually install solar energy equipment on all new and existing public and commercial buildings above a certain size and on all new residential buildings between 2026 and 2029 will accelerate this transition (European Commission, 2022). However, in order to achieve awareness and subsequently also acceptance, both by private individuals and professionals in the construction industry, new and visually attractive materials must be developed that offer a variety of integration possibilities for all kinds of surfaces. Only in this way can solar technology become both a functional and aesthetic part of our living environment and contribute to a more sustainable society.

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