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Optimisation of knitted fabrics as visually concealing covers for textile-integrated photovoltaics

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A B S T R A C T

Integrating solar cells in textiles offers a promising path toward energy-autonomous wearable electronics, but their design requires careful optimisation between energy efficiency and visual aesthetics. For this purpose, we present a systematic study of the optical properties of knitted textiles as visually concealing covers for textile-integrated solar cells. The study investigates microscopic and macroscopic factors that influence the optical performance of knitted textiles. A set of 175 samples was knitted, including 20 knit structures, 6 yarn materials, and 20 yarn colours. The knitted samples were studied using optical characterisation methods such as spectroscopy, microscopy, and photography. We developed metrics characterising solar cell performance and visual appearance, which can be used to optimise textiles based on desired performance characteristics. The strong correlation between the performance metrics demonstrates a design compromise between solar cell performance and concealment. By applying a proposed set of optimisation criteria to the knitted samples, 23 out of the 175 samples qualified as the best in solar cell performance and concealment. The developed metrics are also applicable to other textile configurations and light-sensing applications.

1. Introduction

As modern wearable devices develop more advanced functionalities, they increasingly demand higher power. Batteries are often recharged or replaced frequently to meet the energy requirements of wearable electronics. The high frequency of battery recharging or replacement negatively impacts the environment and the user experience and, accordingly, the product acceptance [1].

Energy harvesting presents an alternative to frequent battery charging and replacement by using energy sources in the surrounding environment, such as motion, light, or heat. Energy harvesting can make wearable electronics energy-autonomous, improving the safety and reliability of wearable devices and decreasing their lifetime costs. Self-powered electronics come in various forms, as there can be different ways to integrate the energy source into the device. Integrating the energy source and electronics in a single encapsulated unit allows the device to be self-powered, which comes with several advantages over typical battery-powered devices. For instance, integrating photovoltaic systems into portable electronics eliminates the need for bulky battery packs, external wiring, and recharging or battery replacement [2]. Fully self-powered and integrated systems improve usability due to lighter, more flexible products, and improved safety of components and washing resistance [3,4].

There are numerous energy harvesting technologies, including piezoelectric, photovoltaic, thermoelectric, or wireless harvesters, which all produce small amounts of energy that can be sufficient to power low-power devices (e.g. wearables) [5–7]. Photovoltaic modules are becoming increasingly popular for product integration due to their low cost and the abundance of solar energy resources. More specifically, they are well-suited for textile-based wearables due to their flexibility [8–10] and the large available area on the exterior of textiles. Moreover, textile-based photovoltaics can be applied to building envelopes, enabling high design freedom of building façades incorporating photovoltaic panels [11].

To harvest sunlight that is incident on a textile, the photovoltaic modules (i.e. solar cells) can either be placed on top of or integrated within the textile [8,12]. Placing the solar cells on top of the textile allows maximum exposure to sunlight but has several drawbacks. First, solar cells are exposed to environmental factors such as humidity and temperature and are prone to scratches or breaking due to contact with hard surfaces. Second, the solar cells are instantly recognisable when placed on top of the textile. This presents a challenge to designers aiming

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to make aesthetic textiles with integrated solar cells [13].

The alternative to placing solar cells on the outside of the textile is integrating the cells within two textile layers or underneath the top layer and fixing it in place. By doing so, the solar cells are protected from external factors at the cost of lower performance due to the reduced amount of light reaching them. The textile can then be freely designed to ensure aesthetic appeal by concealing the solar cells (Fig. 1) [14–16]. This approach is technically easier than integrating solar cells in textiles in the form of photovoltaic fibres or yarns or depositing them onto fabrics as thin layer films [17–19]. Integrating solar cells into textiles as pre-made components allows using commercially available solar cells that are readily available from different manufacturers in various sizes in rigid or flexible forms. It also makes the integrated solar cells durable for washing; in a previous study, crystalline silicon solar cells laminated in rigid or flexible forms. It also makes the integrated solar cells durable that are readily available from different manufacturers in various sizes.

This study investigates the suitability of knitted textiles as solar cell concealing optical covers for textile-integrated photovoltaics. A set of knitted textile samples were produced with varying knit structures, materials, and colours. Optical measurements of the textile samples were performed to identify the optimum parameters for the design of knitted textiles that effectively conceal the solar cells while allowing enough light to pass to them. The optical properties of knitted cotton textiles were previously examined in a similar study to investigate the influence of knit parameters on skin protection from ultraviolet light [20]. In contrast, this study comprehensively analyses the concealment and performance of textile-integrated solar cells (TISC) involving a wide range of yarn materials, knit structures, and yarn colours. For this purpose, this study focuses on the optical properties of the textiles in the visible (VIS) and near-infrared (NIR) light wavelengths, the spectral ranges necessary for concealment and the solar cell performance.

One of the challenges in this study was to identify the balance between the visual aspect of concealment and the optical performance of the textile as a solar cell cover. By concealing the solar cell with a knitted fabric, less light reaches the solar cell. However, a minimum amount of solar energy is required for the electronic components to function correctly. This can be met by increasing the solar cell size to compensate for the light lost due to the textile. If the textile blocks too much light, the solar cell size needed to meet the energy demands of the electronics becomes impractical. To facilitate the optimisation process, a set of metrics was developed that can be used by textile designers, engineers, and product developers to compare the optical performance of various textile samples concerning their suitability as visually concealing cover fabrics for solar cells.

2. Materials and methods

2.1. Textile materials and structures

A collection of samples was knitted to isolate the individual design parameters and examine their individual impact. The study incorporated varying yarn materials, knitting structure (i.e. pattern), and yarn colour. Six materials were used in the study: cotton (CO), hemp (CA), wool (WO), polyester (PES), polyamide (PA), and viscose (CV). The materials were chosen to represent common fibres used in the textile industry.

The origin of each yarn determines its chemical, physical, and optical properties. The yarns in this study originated from cellulose, protein, and synthetic oil-based sources. The polyester, polyamide and viscose yarns were filament yarns, whereas the cotton, hemp, and wool were staple spun yarns.

The textile samples were knitted using a Stoll CMS ADF 32 W flatbed weft knitting machine, allowing the gauge (number of needles per inch = fineness of knit) to be kept constant. The yarn size, often measured in tex, is maintained within a specific range to minimise variation in the knitted samples. Some yarns are plied to match the yarn tex of different materials (see Table 1).

Only white yarns were used for material and knit structure studies to minimise variation in the dyestuff and maintain consistency between the different materials. The shades of white have slight variations due to the material-dependent yarn finishing treatments, such as bleaching and optical brighteners (see Fig. 2). In addition to the finishing treatments already done on the yarns, the knitted samples were steamed to straighten them and to relax the knit structure to reach its final state.

The six materials in the white-coloured yarn were knitted into 20 structures, listed in Table 2. The structures were selected to represent a

![Fig. 1. Illustration of the studied concept. (a) Solar cells can be integrated underneath a semi-transparent textile layer to visually hide them while letting enough light pass through the textile to the solar cell to power wearable electronics. A suitable balance between visual aesthetics and energy efficiency can be sought by optimising textile materials, structure, and colour. (b) Photo showing three coloured knitted fabrics studied in this work: Single Jersey Light Blue, Mint and Lemon.](image-url)
sample of common knitted structures used in textiles. The structures are based on basic variations of knit, tuck, and miss stitches found in the literature [22]. Ten were knitted as single-bed structures and the other ten as double-bed structures. Some structures could not be knitted in all materials due to the characteristics of the yarns causing yarn breakage. Thus, the structures 15 in hemp and 10 in viscose are missing from the sample collection.

In addition to the structure samples, another set of samples was knitted to investigate the effect of colour. A single yarn material, cotton, was used to knit samples in nineteen different colours. The aim was to compare the impact of colour hue and lightness on the transmittance of the textile. All coloured cotton yarns knitted in this study were the same type of yarn sourced from one supplier, thus aiming to eliminate variations in dyestuff chemicals and finishing treatments.

2.2. Optical characterisation

Textiles are often optically characterised using spectrophotometry to predict their optical performance in use-case conditions for diverse applications. For instance, the optical properties can be relevant to determine the light-blocking properties of curtains. Light blocking indicates how much a textile reduces the amount of light transmitted and is particularly relevant to window coverings. As for textiles, sheerness is a more appropriate figure of merit, which corresponds to the amount of light reflected off the object covered by the fabric and transmitted through the fabric to the viewer [23]. To measure the textile sheerness, the reflectance should be measured in the use case, which could vary significantly depending on the object’s colour, textile colour, humidity, and stretching. Accordingly, visual inspection commonly evaluates sheerness in the use case conditions, producing inconsistent results.

In this study, experimental characterisation was performed to develop accurate, dedicated metrics for studying textile-integrated solar cells. The metrics were designed to be easily implementable using various setups and flexible to allow computing the metric at different use case conditions (e.g. illumination, solar cell type, etc) as needed.

The measurements began with the optical characterisation of the knitted textile samples using spectrophotometry to obtain the textile total transmittance, diffuse transmittance, and total reflectance of the textile. The optical spectrophotometry measurements were performed using the Agilent Cary 5000 UV–Vis–NIR spectrophotometer with the Diffuse Reflectance Accessory (DRA) in transmittance mode. The measurements were performed for the wavelength range of 280 nm–1500 nm, which covers a significant portion of the solar spectrum, encompassing the ultraviolet (UV), visible (VIS), and part of near-infrared (NIR) regions. Regarding calculations involving the spectral response of silicon solar cells, the studied wavelength range is limited to 280 nm–1200 nm, which fully encompasses the absorption region of crystalline silicon, the most common commercial solar cell type.

Following the spectrophotometry measurements, the absorbance for a given wavelength was derived as:

$$A(\lambda) = 1 - T_{total}(\lambda) - R_{total}(\lambda)$$

where $A(\lambda)$ is the light absorbance within the textile, $T_{total}(\lambda)$ is the total (hemispherical) spectral transmittance through the textile, and $R_{total}(\lambda)$ is the total (hemispherical) spectral reflectance by the textile and $\lambda$ is the light wavelength. The total transmittance (and reflectance) consists of diffuse and specular components, $(T_{total}(\lambda) = T_{diffuse}(\lambda) + T_{specular}(\lambda))$, which the Diffuse Transmittance Accessory (DTA) can distinguish by excluding the specular component with a light trap (See Fig. 3).

Among the measured and derived quantities, the total and diffuse transmittance of the textile are the most relevant to studying TISC. The total transmittance in the wavelength range where the solar cell produces photovoltaic response determines its photovoltaic performance when the textile covers it. The mean total transmittance ($MT$) for a given wavelength range (where $\lambda_1$ and $\lambda_2$ are the low and high ends of the range) can directly be used as a simple metric to compare different textile samples, given by:

$$MT = \frac{\int_{\lambda_1}^{\lambda_2} T_{total}(\lambda) \, d\lambda}{\lambda_2 - \lambda_1}$$

Additionally, the colour coordinates of selected textile samples were measured using digital photography against a black-and-white background, as in Fig. 4. The white background was composed of a non-fluorescent white fabric (reflectance >75% between 380 and 1500 nm), while the black fabric was a highly absorbing black fabric (reflectance <4% between 380 and 730 nm). The textile samples were illuminated with studio lamps (Lupo Superpanel Dual-Color DMX with softbox light diffuser) at a 45-degree angle and observed from the direction normal to the surface to avoid shadowing and gloss effects. The colour photography was performed under uniform, white illumination (colour temperature set to 5600 K) with a colour calibration target (X-rite ColorChecker Passport) in the picture frame to allow colour correction by creating a camera profile. Next, colour-corrected images were processed to extract the colours in the CIE 1976 L*a*b* colour space.

The spectral response of solar cells was characterised by the external quantum efficiency (EQE), which corresponds to the ratio of electrons collected at the contacts to photons incident on the solar cell. Integrating the wavelength-dependent external quantum efficiency, $EQE(\lambda)$, multiplied by the spectral photon flux, $\Phi(\lambda)$, and the elementary charge constant, $q$, over the absorption wavelength range provides the solar cell short-circuit current density ($J_{SC}$), given by:

$$J_{SC} = q \int_{\lambda_1}^{\lambda_2} \Phi(\lambda)EQE(\lambda) \, d\lambda$$

It is then necessary to develop a metric that allows optimising textiles for the specific application of TISC. A textile layer that covers the solar
Table 2
Notations and diagrams of the knitted structures.

<table>
<thead>
<tr>
<th>Structure Number</th>
<th>Name</th>
<th>Diagram</th>
<th>Structure Number</th>
<th>Name</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single Jersey</td>
<td>X X</td>
<td>11</td>
<td>Full rib</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>Cross Miss</td>
<td>X - X</td>
<td>12</td>
<td>Interlock</td>
<td>X - X</td>
</tr>
<tr>
<td>3</td>
<td>Weft Locknit</td>
<td>X - X</td>
<td>13</td>
<td>Full Milano</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Bird’s Eye</td>
<td>X - X</td>
<td>14</td>
<td>Punto di Roma</td>
<td>X - X</td>
</tr>
<tr>
<td>5</td>
<td>Mock Rib</td>
<td>X X</td>
<td>15</td>
<td>Ridge (ottoman)</td>
<td>X - X</td>
</tr>
<tr>
<td>6</td>
<td>Twill Variation</td>
<td>X - X</td>
<td>16</td>
<td>Swiss Wevenit</td>
<td>X - X</td>
</tr>
<tr>
<td>7</td>
<td>Cross Tuck</td>
<td>X</td>
<td>17</td>
<td>Full Cardigan (R)</td>
<td>X - X</td>
</tr>
<tr>
<td>8</td>
<td>Inlay Knit</td>
<td>X * X</td>
<td>18</td>
<td>Single Piqué</td>
<td>X - X</td>
</tr>
<tr>
<td>9</td>
<td>Simple Crepe</td>
<td>X - X</td>
<td>19</td>
<td>2x1 Rib</td>
<td>X - X</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>Cellular Bliister</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X X X ^</td>
<td></td>
<td>20</td>
<td>Tech Knit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>X ^ X X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>^ X X X</td>
<td></td>
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</tr>
</tbody>
</table>

Knit          Miss          Tuck          Empty Needle Rear Bed Stitch Transfer

cell reduces the incident spectral photon flux reaching the solar cell, the knitted samples.

Fig. 4. The black-and-white background used in the photographic analysis of the knitted samples.

The specular (a) and diffuse (b) components of light transmitted through a textile. Figure not to scale.

The specular (a) and diffuse (b) components of light transmitted through a textile. Figure not to scale.

Cell reduces the incident spectral photon flux reaching the solar cell, decreasing $J_{SC}$. This effect can be calculated by multiplying the photon flux with the total transmittance of the cover textile to obtain the short-circuit current density of a textile-integrated solar cell ($J_{SC,TISC}$), as:

$$J_{SC,TISC} = q \int_{\lambda}^{\lambda_h} T_{total}(\lambda) \Phi(\lambda) EQE(\lambda) d\lambda$$

(4)

Using Equations (3) and (4), the mean effective transmittance (MET) can be derived as:

$$MET = \frac{\int_{\lambda}^{\lambda_h} T_{total}(\lambda) \Phi(\lambda) EQE(\lambda) d\lambda}{\int_{\lambda}^{\lambda_h} \Phi(\lambda) EQE(\lambda) d\lambda} = \frac{J_{SC,TISC}}{J_{SC}}$$

(5)

which is equivalent to the ratio between the short-circuit current density with and without textile coverage. The MET is a valuable metric because it accounts for both the solar cell spectral sensitivity and the textile transmittance and can therefore be used for optimising a textile for a specific type of solar cell. The MET can also be calculated for a known incident light spectrum. For instance, the MET is calculated for sunlight by substituting the spectral photon flux $\Phi(\lambda)$ with that of the global standard solar spectrum (AM1.5G) in Equation (5).

In addition to optimising the textile to maximise the solar cell performance, we also aim to maximise the visual hiding capability of the textiles and, therefore, the textile aesthetics, through experimental characterisation. Solar cells concealed by coloured textiles were implemented by Gewohn et al., where the concealment was evaluated by visual analysis [24]. In this work, we propose several quantitative metrics that allow an objective comparison between the concealment capability of various textiles.

One metric that can be used for this purpose is visible transmittance, which corresponds to the visibility through an optical film, or in this case, a textile. The visible transmittance ($VT$) only accounts for the VIS spectral range and is expressed as:

$$VT = \frac{\int_{380}^{780} T_{total}(\lambda) P(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} P(\lambda) V(\lambda) d\lambda}$$

(6)

which incorporates $P(\lambda)$ the spectral irradiance of the incident light and $V(\lambda)$ the spectral sensitivity of the human eye, defined by the CIE 1931 spectral luminous efficiency function (same as the $Y$ colour matching function). The wavelength range of the VIS spectrum is 380–780 nm, according to the International Standards Organization (ISO) International Standard ISO-20473–2007 [25].

Light transmission through textiles can either be specular, where the incidence angle is the same as the transmission angle, or diffuse, where the light ray is scattered to oblique angles. The VT is calculated using the total transmittance since the human eye can see both specular and diffuse transmitted light in the VIS range. However, as the VT does not differentiate between the specular and diffuse components, it does not tell how much the sample scatters light. Light scattering can significantly help conceal an object; the effect is well-known from fined glass and shower curtains. Therefore, a metric accounting for the light scattering effects is also needed. A suitable metric for this purpose can be determined using a spectrophotometer with a diffuse reflectance accessory (DRA).

In this case, the illumination and light detection used the 0°: d (normal:diffuse) geometry, where light is incident on the textile sample at a 0° angle from the normal to the sample surface. The diffuse component of the transmittance was measured as the light scattered to angles exceeding 5° from the normal, as shown in Fig. 3 [26].

After measuring the diffuse transmittance ($T_{diffuse}$) and the total transmittance ($T_{total}$), the light scattering capability of the textile can be characterised by the transmission haze ($H_T$) for a given wavelength, which is given by:
\[ H_T(\lambda) = \frac{T_{\text{diffuse}}(\lambda)}{T_{\text{total}}(\lambda)} \quad (7) \]

Consequently, the mean transmission haze \((MH_T)\) for a given wavelength range is given by:

\[ MH_T = \frac{\int_{\lambda_h}^{\lambda_l} H_T(\lambda) d\lambda}{\lambda_l - \lambda_h} \quad (8) \]

While a higher total transmittance results in higher visibility of the solar cell through the textile, a higher transmission haze results in a more blurred view of the solar cell due to the scattering of the transmitted light. The blurring effect highly depends on the distance between the textile and the background (i.e., the solar cell), where the effect is amplified as the distance increases. In this study, the distance between the textile and solar cell or background is fixed to zero to replicate the realistic condition where the solar cells would be integrated into direct contact with the textile layer. However, thicker textiles are expected to result in higher transmission haze due to the increased mean distance of the yarns from the solar cell surface.

Fig. 5 demonstrates the impact of transmittance and transmission haze on the visibility through different textile samples against a black and white background (top) and against a black solar cell placed on a white background (bottom). It can be observed that the contrast between the solar cell and a brighter-coloured background becomes significantly less visible to the viewer as the haze and transmittance values increase.

The transmission haze can then be used for developing a metric that specifically characterises the visibility of solar cells integrated under textiles. To develop this figure of merit, the total transmittance spectrum, transmission haze spectrum, and the spectral sensitivity of the human eye should be considered. For this purpose, we propose a new metric called solar cell visibility (SCV), which can be expressed as:

\[ SCV = \frac{\int_{780 \text{ nm}}^{380 \text{ nm}} \frac{T_{\text{total}}(\lambda)}{1 + H_T(\lambda)} P(\lambda)V(\lambda) d\lambda}{\int_{780 \text{ nm}}^{380 \text{ nm}} P(\lambda)V(\lambda) d\lambda} \quad (9) \]

To see how the SCV metric works, consider the following cases. For a completely opaque textile (i.e., \(T_{\text{total}} = 0\)), the resulting SCV value is 0%, indicating no solar cell visibility through the textile. On the other hand, for an entirely specularly transparent textile (i.e. \(T_{\text{total}} = 100 \% \) and \(T_{\text{diffuse}} = 0\)), the resulting SCV value is 100%, indicating full visibility of the solar cell through the textile. In cases where the textile partially transmits light (i.e. \(0 < T_{\text{total}} < 100 \%\)), the resulting SCV value will also depend on the transmission haze, where a higher haze value will decrease the visibility of the solar cell.

Fig. 5. Effect of textile structure on the colour contrast and concealment of solar cells. Two textile samples (left: cotton Ridge, right: cotton Simple Crepe) with different optical properties photographed against a black-and-white background (top) and against a black solar cell placed on a white background (bottom).
Note that Equation (9) only approximately describes how haze affects the solar cell visibility through a textile. For one, it does not account for the abovementioned blurring-by-distance effect. Nevertheless, we consider that Equation (9) is both qualitatively correct and quantitatively consistent. To illustrate this, consider two hypothetical extreme cases. In the first case, the textile would be fully transparent and the transmittance fully diffuse \( (T_{\text{total}} = T_{\text{diffuse}} = 100\%) \), the transmission haze would be 100%, and therefore SCV = 50%. In this case, all VIS light would diffusively transmit through the textile and reflect from the background, 100% from a perfectly white background and 0% from a perfectly black background, resulting in maximum contrast of 100%. Minding that the colour contrast alone does not fully characterise the solar cell visibility (Fig. 5), but the haze contributes too, the 50% SCV value in this extreme case means that Equation (9) assigns at most 50% of the relative visibility to the haze effects.

In the second hypothetical case, consider a textile that acts as a perfect Lambertian scatterer that equally transmits and reflects light (i.e. \( T_{\text{total}} = T_{\text{diffuse}} = R_{\text{total}} = R_{\text{diffuse}} = 50\% \)). This corresponds to a matte white, non-absorbing, highly scattering textile. As with the previous case, transmission haze would be 100% but the transmittance would be halved, resulting in SCV = 25%. In such a case, the contrast between reflection from the black and white backgrounds would be 50%, half of that from the previous case, which the SCV correctly models: 50% visibility due to contrast times 50% visibility due to maximal haze = 25% SCV. The SCV can thus be used as a quick metric to observe general trends over many samples.

### 2.3. Textile optical properties

The optical properties of textiles depend on a multitude of textile parameters; these parameters include microscopic factors such as the physical and chemical structure of the fibre, yarn type (yarn number, staple or filament fibre, fibre amount and twist amount), chemical and mechanical finishing, as well as macroscopic factors such as the three-dimensional knit structure.

Starting with the microscopic features of textile fibres, the shape of the cross-section of a textile fibre is directly linked to how light is reflected from the fibre surface [27]. The yarn fibres of the used materials were studied using optical microscopy, with the microscope photos demonstrated in Fig. 6. Round and smooth fibres reflect light seemingly in one direction, causing lustre. Whereas fibres with an uneven surface, such as wool that is covered in scales, scatter light in different directions, resulting in a dull appearance of the fibre [28].

Moreover, the different fibre materials determine the light absorption properties. Light absorption is generally uniform over the VIS and NIR spectral regions for undyed materials. Natural fibres tend to exhibit slightly increased absorption in the UV spectral region. Alternatively, synthetic or bleached fibres may exhibit fluorescence effects, characterised by emission peaks in the transmittance and reflectance spectra when illuminated by a broadband light source [29].

As light is transmitted through the textile, it can be refracted depending on the refractive index of the textile fibres. The refractive index of individual fibres can be measured by placing them in solutions with different refractive index: the sample with a matching index makes the fibres completely disappear [30]. The refractive index of textile fibres depends on material density and chemical composition. In addition, the refractive index varies slightly based on orientation, resulting in a phenomenon known as birefringence.

Regarding light absorption by the textile fibre, most undyed fibres do not significantly absorb incoming light [30]. However, absorption also depends on the direction of light polarisation, a phenomenon known as dichroism. This results in dependence of light absorption on the fibre orientation, particularly for fibres with round cross sections. The impact of dichroism becomes particularly substantial as light passes through two dichroic fibres. If the fibres are aligned in parallel, the absorption is minimal. In contrast, fibres that are aligned perpendicularly absorb both components of the incoming light, resulting in high total absorption. Accordingly, yarns composed of parallel aligned fibres will tend to absorb less light than yarn composed of crossing (i.e., perpendicular) fibres [30].

On the yarn level, yarn size has a substantial effect on the light transmittance of the textile. Thicker yarn results in lower optical transmittance due to increased absorption and reflection by the material. In addition, the fibre processing method to form yarn has a notable impact on optical properties. Depending on the raw material and the production processes, the yarn consists of staple spun or filament fibres. The yarn can be twisted tightly or loosely, affecting the fibre alignment and yarn strength. In the case of synthetic fibres, yarns can consist of filaments parallel next to each other without a twist.

The yarns used in this study were photographed against a black background to demonstrate their thickness and hairiness (see Fig. 7). Filament yarns, such as polyester, polyamide and viscose yarns (top...
row), are smooth and show little hairiness, which is associated with lower light scattering properties. Staple spun yarns, such as cotton, hemp, and wool (bottom row), have more hairiness and therefore tend to result in higher light scattering. Further processing of yarn can alter the light scattering properties; for instance, mercerising of cotton yarn changes the cross-section of the fibre into a round shape, and singeing cotton yarn burns off the protruding fibres from the surface of the yarn making it less hairy, leading to lower light scattering.

On the macroscopic level, the different knit structures influence the optical properties of the textile depending on the thickness, density (i.e., amount of material used per area), and the knit tightness of the textile. Thicker and/or denser textiles result in lower light transmittance [31]. Structures knitted on a single-bed tend to have lower thickness and density than double-bed structures, resulting in lower light transmittance through the textile. The knit tightness, demonstrated in Fig. 8, also influences light transmittance, as light is transmitted either partially through the yarn or directly through the gaps between the yarns. The proportion of transmitted light scattered towards oblique angles therefore depends on the knit tightness and yarn hairiness.

Finally, finishing treatments of the yarn and textile can have a significant impact on the optical properties. For instance, dyed yarn will absorb more light in the VIS spectrum than undyed yarn, to generate the perceived colour to the observer. The amount of absorbed light depends on the colour chroma, hue, and lightness. Colour lightness is the main factor in determining the visible transmittance of a textile, where lighter colours transmit more visible light than darker colours. The optical performance also depends on several other factors, including the various textile dyeing and finishing methods and chemicals.

![Yarn thickness and hairiness](image1)

Fig. 7. Yarn thickness and hairiness. From left to right: polyester, polyamide, viscose, wool, cotton, and hemp.

![Knit tightness](image2)

Fig. 8. The tightness of the knit affects its light transmittance capabilities.
3. Results

3.1. Transmittance spectroscopy

To investigate the impact of the various factors affecting the optical properties of knitted textiles, the textile samples were characterized with optical methods. The total transmittance spectra of the six undyed yarn materials chosen for this study are shown in Fig. 9 and their transmission haze spectra are shown in Fig. 10. Several trends can be observed from the transmittance and transmission haze spectra. The shape of the total transmittance spectra varies greatly depending on the yarn material, while the knit structure only shifts the spectrum up or down. This implies that the material affects the microscopic optical properties of the yarn, while the knit structure mainly impacts the optical properties at the macroscopic level.

Across all the materials, the total transmittance spectra indicate generally higher transmittance values for single-bed structures (1–10) than double-bed structures (11–20). The higher transmittance of single-bed structures can be attributed to their lower material density, as they require less amount of yarn to be produced.

Another trend that can be observed is the lower total transmittance in polyamide and wool samples. In the case of polyamide, the yarn has been texturised to gain yarn elasticity. The texturisation leads to a tighter knit and decreased gap size between stitches, since the yarn is stretched in the knitting machine whilst being knitted and then contracts once the sample is released from the machine. As for wool, the yarn consists of staple fibres protruding out from the yarn, giving it a fuzzy appearance and increased coverage, see Fig. 11.

In contrast to the wool, cotton is one of the smoothest yarns in this study (see Fig. 7), mainly due to its finishing treatments: singeing and mercerising. The smooth cotton yarn creates a clean defined knitted structure where the loops are distinguishable and the light passes through the gaps in the knit without being blocked by protruding fibres (see Fig. 12). This increases the specular transmittance of cotton, but also the solar cell visibility.

The transmittance spectra are affected by fluorescence due to...
Fig. 10. Transmission haze spectra of different materials and structures. The single-bed structures (1–10) are shown with lines, and the double-bed structures (11–20) with crossed lines.

Fig. 11. Surface fuzziness comparison between cotton (CO) and wool (WO) samples. The cotton yarn knits a more defined structure with distinguishable loops, whilst the wool structure offers good coverage due to yarn fuzziness.

Fig. 12. Optical microscopy of a knit fabric with three different yarn materials. The gap size is affected by yarn thickness, hairiness and knit tightness.
bleaching and optical whiteners used in the processing of the fibres and yarns. The specific chemical finishing treatments for each of the yarns in this study are unknown, hence the fluorescence of each material has been deduced from the measurement results. Due to fluorescence that likely results from yarn whitening, polyamide, viscose, and wool show increased transmittance values in the UV wavelength range because excitation of the fluorescent materials by monochromatic UV light leads to emission of light at longer wavelengths [28]. The longer wavelength light is detected by the spectrophotometer during the measurements, thereby increasing the measured value at the UV wavelength that caused the fluorescence (although the fluorescent emission occurred at longer wavelengths). The impact of fluorescence on the transmittance spectra is that it causes the data to underestimate the short-circuit current density and MET of a silicon solar cell in sunlight by approximately 14% for polyamide, 15% for wool, and 22% for viscose. In contrast, no fluorescence was observed for polyester, cotton, and hemp. These values were estimated based on spectrophotometry measurements using a photodiode array (which can detect fluorescence) and calculating the impact of the difference in transmittance on short-circuit current density using Equation (4). While the discrepancy between the measured and real transmittance can be significant depending on the fluorescence and the proportion of UV in the incident light spectrum, the impact can be disregarded when comparing samples of the same material. However, when comparing samples of different materials, the effect of fluorescence on the measurements should be considered. In addition to fluorescence effects, measurement uncertainty of up to 10% could occur due to sample handling, reproducibility of knitting, variations in the sample preparation (stretching) and experimental uncertainty.

To correctly interpret the findings in this study, certain limitations must be recognised. This study examines a limited number of yarns and materials, namely six different yarns out of all possible existing variations of yarns and materials. The optical properties of the polyamide yarn in this study are not identical to all other types of polyamide yarn on the market. The materials cannot be directly compared in terms of highest and lowest light transmitting materials as there are numerous variables affecting the optical properties of each specific sample. For instance, hemp and polyester differ in yarn count, specific gravity (fibre weight per unit volume) [27,32], where hemp is a heavier and more dense fibre, and the origin and composition of hemp and polyester yarn is different. Hemp is a natural, cellulose-based, staple spun yarn with a slight twist, whereas polyester is a synthetic, oil-based, multifilament yarn with no twist. Nevertheless, some variables impacting the light transmittance of a textile can be studied such as the knit structure as well as scattering and fluorescence properties of the various fibres.

As with the total transmittance spectra, the shape of the transmission haze spectra depends predominantly on the yarn material, while the different knit structures merely scale the haze spectra up or down (see Fig. 10). Wool and polyamide exhibit the highest transmission haze values and least variation for both single and double-bed knitted structures, showing improved light scattering properties with respect to other yarn materials. The air gaps within the wool and polyamide samples are inherently smaller due to the material, resulting in lower specular light transmission and increasing diffuse light transmission through the textile. Other materials, such as cotton, polyester, viscose, and hemp, show a trend where single-bed structures result in lower haze than double-bed structures due to the larger gaps within the material.

### 3.2. Performance metrics

Using the measured transmittance spectra, the MET and SCV can then be calculated for all combinations of yarn material and knit structure using Equations (5) and (9), respectively, to investigate the optical performance of the textile samples as visually concealing cover fabrics for solar cells. The illumination and EQE spectra used to perform the calculations are shown in Fig. 13. The calculated MET and SCV for all samples are shown in Fig. 13 (a) and (b). The MET and SCV results are also reported in Table 3. As with the transmittance spectra, single-bed structures demonstrate higher MET and SCV than double-bed structures, resulting in improved solar cell performance, but poor hiding capability of integrated solar cells. The trend is expected as both MET

![Fig. 13. The illumination spectrum, solar cell EQE, and CIE photopic luminous efficiency function V used to calculate MET and SCV for a given textile. The illumination spectrum is the global standard AM1.5G solar spectrum (in irradiance P and photon flux Φ). The EQE was obtained from quantum efficiency measurements of a monocrystalline silicon solar cell.](image-url)
and SCV are proportional to the textile total transmittance and are therefore strongly correlated, as demonstrated in Fig. 15. The strong correlation is predicted in the case of these undyed (white) textiles, because their transmittance spectra (Fig. 9) are relatively flat throughout the whole spectral range where both the solar cell is producing current with significant EQE (350–1180 nm), affecting MET, and where the human eye is sensitive to light (380–780 nm) [25] affecting SCV (see Fig. 13). As a result, the colourless textiles affect the solar cell and the human visual perception in the same proportion (see Fig. 14).

In addition to the SCV metric, the solar cell visibility can also be studied using digital photography. A set of photographed cotton samples on black and white background are shown in Fig. 16. The contrast between the black and white regions after placing the textile in front of the background sample demonstrates the visual concealing capacity of the textile (setting aside for now the additional blurring effect by haze). It also simulates the most demanding concealment challenge, i.e., the case where a black solar cell is placed between a white liner fabric and a cover textile that aims to visually hide the cell.

The CIE DeltaE2000 (dE) colour difference between the sample in front of the black and white backgrounds was determined using the photographs. The dE values strongly correlate with the SCV, as demonstrated by correlation plot in Fig. 17, indicating that both methods could be used to evaluate the visual concealment of solar cells by textiles.

![Fig. 14. (a) MET and (b) SCV results of the single-bed knit structures (top, blue outline) and double-bed knit structures (bottom, black outline).](image)

![Table 3. MET and SCV values for 20 knitted structures in 6 materials using undyed yarns.](image)

![Fig. 15. Correlation plot between MET and SCV, indicating the various structures. Design criteria (maximum SCV and minimum MET) are shown to demonstrate a possible optimisation approach.](image)
3.3. Effect of textile structure and yarn material

The different structures knitted using the same cotton yarn demonstrates how the knit structure affects the concealment, as evaluated with the two different metrics SCV and \( dE \) (Fig. 16). The overall trend shows improved concealment by structures 11–20 (i.e., double-bed structures), as evidenced by their significantly lower SCV and \( dE \) values.

As for the impact of yarn material on concealment, Fig. 18 shows samples using all six materials knitted in the same structure: Interlock. Polyamide and wool demonstrate the lowest SCV values, while cotton, hemp and viscose demonstrate higher SCV, therefore being more transparent.

Optimising the textile optical properties for solar cell integration requires setting certain thresholds for the maximum optical power loss and solar cell visibility to filter out the useable yarn material and knit structures. An optimisation case study can be performed by first comparing the visual concealment in cotton samples (in Fig. 16) and setting the maximum SCV at 15% to filter out structures that appear too transparent. To reach a sufficient level of light energy harvesting through the textile, we choose a minimum of 25% MET as a threshold. When SCV < 15% is considered suitable from a design perspective, and MET > 25% for energy harvesting application, we get the following well-performing material – structure combinations:

1. Wool/polyamide – Mock Rib
2. Hemp – Full Rib
3. Polyester/wool/hemp – Interlock
4. Wool – Full Milano
5. Cotton/viscose – Ridge
6. Polyester/cotton/hemp – Swiss Wevenit
7. Polyamide/wool/hemp – Single Piqué
8. Wool/hemp – Tech Knit

This optimisation approach allows identifying the samples that meet the desired performance characteristics. Only 17 out of 118 samples meet the optimisation criteria, of which 15 samples are knitted in double-bed structures. Multiple double-bed structures knitted in hemp fit the requirements, making it a promising combination for the given optimisation criteria.

3.4. Effect of yarn colour

To explore the concealment of TISC through colour with the aim of designing the optimal structure, material, and colour combination,
textile samples in nineteen different colours were knitted using cotton yarn. The samples were knitted in three representative knit structures: Single Jersey, Simple Crepe, and Interlock.

The transmittance spectra of the coloured textile samples were measured, with the spectra shown in Fig. 19 for the Single Jersey knit (structure 1) using different colours. To quantify the impact of the colour on TISC, the MET was computed for the various samples using Equation (5), with the results shown in Fig. 20 and reported in Table 4. Additionally, the impact on solar cell concealment was analysed by using the SCV (Equation (9)). The metrics allow comparing the samples with varying yarn colour and knit structure in terms of their optical performance.

Lighter colours demonstrated significantly higher transmittance than darker colours in the visible region (380–780 nm), which is also expected: darker yarns absorb more light. Colours with high chroma, such as the red, blue, and green samples, also demonstrated notably low transmittance in the VIS region. However, in the mid-IR region the transmittance spectra were uniform and varied by a maximum of 10% among most samples. The same trends were observed for the Simple Crepe and Interlock knitted structures (see Table 4).

The highest MET was obtained for light colours such as rose, lemon, yellow, light blue, mint, and light grey. Similarly, lighter colours also resulted in higher values of the visible transmittance, indicating weaker concealment properties. When comparing two single-bed structures, Single Jersey and Simple Crepe, the colour has a bigger impact on the transmittance than the structure itself (see Fig. 20). Light colours such as rose, light blue, and lemon have seemingly similar high MET in both structures, ranging within 38%–41%. However, when comparing with a
double-bed structure, Interlock, it can be observed that the structure type impacts the transmittance more than colour does. All Interlock samples have lower transmittance compared to Single Jersey, regardless of colour. The lowest performing single-bed structure, green Simple Crepe, has an \( \text{MET} \) of 24.2\%, whereas the highest performing double-bed structure, lemon Interlock, has an \( \text{MET} \) of 26\%.

As with the undyed yarns, the \( \text{SCV} \) values for coloured yarns are strongly correlated with the \( \text{MET} \) values, as shown in Fig. 21, where improved solar cell performance is linked to weaker concealment. The double-bed structures have lower \( \text{SCV} \) values, demonstrating improved concealment when compared to single-bed structures. Darker colours seem to result in improved concealment due to higher absorption of visible light in the fibres. In contrast, lighter coloured fibres transmit visible light, resulting in higher \( \text{SCV} \) values.

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The \( \text{L}^* \) value in the \( L^*a^*b^* \) colour space expresses the perceptual colour lightness, studying the impact of colour lightness on transmittance is possible by plotting the \( \text{SCV} \) against \( \text{L}^* \), as shown in Fig. 22 (a). A roughly linear trend can be observed, indicating that colour lightness positively correlates with the visibility of solar cells under textiles, where darker colours result in better concealment. The colour lightness is also plotted against the \( \text{MET} \) (Fig. 22(b)) to analyse the impact on solar cell performance. Similarly, a roughly linear trend is observed, where lighter colours result in better solar cell performance. Despite the similar trends in \( \text{MET} \) and \( \text{SCV} \) vs. lightness, the slopes differ because \( \text{MET} \) benefits from the high NIR light transmittance (see Fig. 19) whereas \( \text{SCV} \) depends only on the visible light transmittance, which is low due to light absorption by the dye in the VIS region.

Consequently, a design trade-off between solar cell concealment and performance is presented, where darker colours result in higher concealment, but lower performance, and the contrary for lighter colours. The proposed metrics can then be applied to find the optimum colour, structure, and yarn material combination. When the previous optimisation approach is again implemented to Fig. 21, where samples exhibiting a \( \text{SCV} < 15\% \) and \( \text{MET} > 25\% \) are identified, the following yarn colour – textile structure combinations for cotton yarn meet the

### Table 4

<table>
<thead>
<tr>
<th>Colour</th>
<th>Structure</th>
<th>MET, %</th>
<th>SCV, %</th>
<th>MET, %</th>
<th>SCV, %</th>
<th>MET, %</th>
<th>SCV, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>White (undyed)</td>
<td>1. Single Jersey</td>
<td>46.0</td>
<td>29.5</td>
<td>47.6</td>
<td>31.9</td>
<td>33.7</td>
<td>19.8</td>
</tr>
<tr>
<td>Red</td>
<td>9. Simple Crepe</td>
<td>28.4</td>
<td>12.0</td>
<td>26.5</td>
<td>10.5</td>
<td>16.7</td>
<td>4.0</td>
</tr>
<tr>
<td>Green</td>
<td>12. Interlock</td>
<td>25.0</td>
<td>16.1</td>
<td>24.2</td>
<td>16.0</td>
<td>13.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Blue</td>
<td></td>
<td>27.3</td>
<td>14.4</td>
<td>26.3</td>
<td>14.9</td>
<td>13.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Orange</td>
<td></td>
<td>36.3</td>
<td>18.6</td>
<td>32.4</td>
<td>15.3</td>
<td>21.2</td>
<td>7.0</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td>38.6</td>
<td>23.5</td>
<td>38.0</td>
<td>22.7</td>
<td>25.4</td>
<td>13.0</td>
</tr>
<tr>
<td>Light Blue</td>
<td></td>
<td>36.0</td>
<td>20.6</td>
<td>34.2</td>
<td>19.0</td>
<td>22.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Grey</td>
<td></td>
<td>31.2</td>
<td>18.0</td>
<td>28.7</td>
<td>15.9</td>
<td>17.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Dark Brown</td>
<td></td>
<td>28.6</td>
<td>15.4</td>
<td>28.9</td>
<td>16.1</td>
<td>16.9</td>
<td>6.8</td>
</tr>
<tr>
<td>Rose</td>
<td></td>
<td>41.2</td>
<td>24.3</td>
<td>38.9</td>
<td>22.4</td>
<td>22.9</td>
<td>9.0</td>
</tr>
<tr>
<td>Coral</td>
<td></td>
<td>35.7</td>
<td>18.0</td>
<td>35.8</td>
<td>18.2</td>
<td>22.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Bordeaux</td>
<td></td>
<td>30.8</td>
<td>16.9</td>
<td>31.9</td>
<td>18.4</td>
<td>17.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Navy</td>
<td></td>
<td>27.0</td>
<td>14.3</td>
<td>30.4</td>
<td>17.6</td>
<td>17.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Mint</td>
<td></td>
<td>37.4</td>
<td>23.6</td>
<td>33.6</td>
<td>20.6</td>
<td>20.2</td>
<td>9.9</td>
</tr>
<tr>
<td>Lemon</td>
<td></td>
<td>38.9</td>
<td>25.0</td>
<td>40.1</td>
<td>25.4</td>
<td>26.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Light blue</td>
<td></td>
<td>39.0</td>
<td>22.4</td>
<td>38.6</td>
<td>22.5</td>
<td>24.4</td>
<td>11.0</td>
</tr>
<tr>
<td>Violet</td>
<td></td>
<td>34.9</td>
<td>19.0</td>
<td>36.4</td>
<td>20.6</td>
<td>19.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Light Grey</td>
<td></td>
<td>36.4</td>
<td>20.4</td>
<td>36.3</td>
<td>20.7</td>
<td>21.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Dark Grey</td>
<td></td>
<td>33.7</td>
<td>19.9</td>
<td>30.5</td>
<td>18.3</td>
<td>17.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Black</td>
<td></td>
<td>26.7</td>
<td>15.2</td>
<td>26.6</td>
<td>15.6</td>
<td>14.9</td>
<td>6.2</td>
</tr>
</tbody>
</table>

---

**Fig. 20.** MET and SCV for coloured textile samples knitted in three structures.

**Fig. 21.** Correlation between MET and SCV for textile samples knitted using coloured yarn in all three structures using different marker shapes: Single Jersey (circle), Simple Crepe (square), and Interlock (triangle). The marker colours represent the individual samples knitted using these yarn colours, as in Fig. 19.
Of the 57 coloured yarn samples, only 6 combinations met the criteria:

1. Red – Single Jersey
2. Red – Simple Crepe
3. Blue – Single Jersey
4. Blue – Simple Crepe
5. Yellow – Interlock

Fig. 22. Cotton yarn using 19 different colours knitted in Single Jersey. (a) Colour lightness ($L^*$) against white background vs. SCV. (b) colour lightness ($L^*$) against white background vs. MET. The marker colours represent the yarn colours used in the sample.

Fig. 23. Photographs used to obtain the colour coordinates and to compute the $dE$ colour difference for Single Jersey knitted textile samples in the colour study.
desired optimisation criteria. The optimised samples were predominantly in dark, saturated colours (red, blue, or navy) combined with a single-bed knit structure (Single Jersey or Simple Crepe). The only exception to this observation is the yellow sample knitted in interlock, a double-bed structure. The yellow interlock sample meets the criteria due to its light colour: the light colour keeps the fabric transmittance sufficiently high despite its denser double-bed structure. The situation is the opposite with the single-bed structures: the lightest colours would be too light to conceal the solar cells effectively; only the darkest colours lower the solar cell visibility below the 15% criterion.

Next, the colour coordinates of the samples knitted in Single Jersey against black and white backgrounds were extracted using digital photography, where the photographs are shown in Fig. 23. By characterising the colour coordinates in the \( L^*a^*b^* \) colour space, the colour difference \( dE \) between the textiles placed on black and white background was calculated, with the results for the Single Jersey (structure number 1) reported in Table 5.

By examining the \( SCV \) and \( dE \) values, a positive correlation can be observed, with the correlation plot shown in Fig. 24. This indicates that in the case of coloured textiles, either metric can be used to study the solar cell concealment for coloured textile samples, allowing for flexibility in the optical characterisation methods. Samples with red hue (i.e., 1. Red, 4. Orange, 9. Rose, and 10. Coral) exhibit slightly higher \( dE \) than the general trend. Alternatively, samples with low colour saturation (i.e., 18., Dark Grey and 19. Black) exhibit lower \( dE \) than the general trend.

4. Discussion

The developed performance metrics allowed examining the samples in different materials and knit structures, using both undyed and coloured yarn, and observing meaningful trends. Of the factors influencing the optical properties of textiles, the knit structure type (single-bed or double-bed) had the strongest influence on solar cell performance and concealment, followed by the yarn colour lightness and yarn material.

Overall, the studied textiles performed well when optimisation criteria were applied, providing multiple options that enable sufficient solar cell performance (high MET) and concealment (low \( SCV \) and \( dE \)). The developed optimisation criteria can be varied for different applications; for example, an application that is restricted by the available solar cell area would place emphasis on higher MET, while another application that is restricted by the aesthetic appeal of a textile would prioritise lower \( SCV \) and \( dE \).

Two metrics were used to quantitatively evaluate the concealment of solar cells using textiles: \( SCV \) based on spectroscopy measurements and \( dE \) based on colour difference analysis using photography. Both approaches resulted in similar results and effectively represented the subjective perception of a textile concealment capacity under controlled illumination conditions. Other work on solar cell hiding using textiles involved subjective visual inspection to evaluate the concealment.

### Table 5

<table>
<thead>
<tr>
<th>Reproduced colour</th>
<th>Sample</th>
<th>Colour coordinates</th>
<th>( dE )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Black background</td>
<td>White background</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( L^* ) ( a^* ) ( b^* )</td>
<td>( L^* ) ( a^* ) ( b^* )</td>
</tr>
<tr>
<td>Background (BG)</td>
<td></td>
<td>16 1 -2 94 -2 1 78 1</td>
<td></td>
</tr>
<tr>
<td>1. Red</td>
<td></td>
<td>35 59 32 37 61 31 2 0</td>
<td></td>
</tr>
<tr>
<td>2. Green</td>
<td></td>
<td>26 -19 7 29 -19 7 2 3</td>
<td></td>
</tr>
<tr>
<td>3. Blue</td>
<td></td>
<td>18 4 -20 21 4 -20 2 1</td>
<td></td>
</tr>
<tr>
<td>4. Orange</td>
<td></td>
<td>46 48 49 51 54 52 5 3</td>
<td></td>
</tr>
<tr>
<td>5. Yellow</td>
<td></td>
<td>81 0 60 89 5 72 6 7</td>
<td></td>
</tr>
<tr>
<td>6. Light Blue - Grey</td>
<td></td>
<td>62 -7 -2 68 -9 -2 5 3</td>
<td></td>
</tr>
<tr>
<td>7. Grey</td>
<td></td>
<td>42 5 1 45 5 0 2 9</td>
<td></td>
</tr>
<tr>
<td>8. Dark Brown</td>
<td></td>
<td>14 5 0 18 4 0 2 9</td>
<td></td>
</tr>
<tr>
<td>9. Rose</td>
<td></td>
<td>67 15 6 75 21 9 7 3</td>
<td></td>
</tr>
<tr>
<td>10. Coral</td>
<td></td>
<td>54 56 37 60 65 43 6 1</td>
<td></td>
</tr>
<tr>
<td>11. Bordeaux</td>
<td></td>
<td>15 16 2 19 15 2 2 8</td>
<td></td>
</tr>
<tr>
<td>12. Navy</td>
<td></td>
<td>16 1 -11 19 1 -11 2 0</td>
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</tr>
<tr>
<td>13. Mint</td>
<td></td>
<td>74 -24 1 82 -29 2 6 2</td>
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<td>14. Lemon</td>
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<td>15. Light Blue</td>
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<tr>
<td>16. Violet</td>
<td></td>
<td>60 9 -11 64 10 -12 3 6</td>
<td></td>
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<td>17. Light Grey</td>
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<td>73 1 5 79 3 6 5 1</td>
<td></td>
</tr>
<tr>
<td>18. Dark Grey</td>
<td></td>
<td>19 4 -3 22 4 -3 2 1</td>
<td></td>
</tr>
<tr>
<td>19. Black</td>
<td></td>
<td>12 2 -2 14 2 -2 1 3</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 24.** Correlation plot between \( SCV \) and \( dE \) colour difference for Single Jersey knitted textile samples in the colour study.
effectiveness [24]. However, the quantitative metrics proposed in this work offer a more objective approach, which includes multiple characterisation techniques that enable flexibility in evaluating the aesthetics of TISC. The proposed experimental metrics can be supplemented in future work by numerical modelling approaches, such as the digital prototyping model proposed in Ref. [33], which results in highly accurate prediction of the colour and short-circuit current density of BIPV modules coloured using printed textiles.

The photographic analysis of the concealment effect was evaluated here using a rather extreme test: how much the textiles reduce light to the underlying solar cell. This test represents the ultimate challenge: how well the textile would hide a black solar cell against a white background. However, in the practical textile design, the concealment can be considerably improved by using a dark liner fabric behind the solar cell. In general, the best concealment is obtained by matching the colour of the liner fabric to the colour of the solar cell, i.e., to camouflage the cells against the background. In this case, the role of the cover textile could be to blur the shape and remove glossy appearance of the solar cell – and the associated electronic components and wires – and tint the matched solar cell and liner colour lighter (Fig. 23). This strategy has the advantage that much more transparent textiles (higher MET and SCV) can be used to reach effective concealment, which would allow more light to pass to the solar cells. On the other hand, the disadvantage is that the resulting colour would be a mixture of the cover and theliner fabric, as Fig. 16 well demonstrates. This would restrict the range of possible colours by ruling out the lightest and the most chromatic ones. Nevertheless, this effect and its optimisation for the design of TISC could be a topic for further research.

Although the study contains experimental uncertainty due to multiple sources, the degree of uncertainty does not affect the conclusions derived from the measurements. The significant variance in the data is a combined by-product of fluorescence effects and sample preparation and handling inconsistencies. Fluorescence was estimated to cause a 14–22% systematic error for MET for polyamide, wool, and viscose samples (See Section 3.1). Fluorescence affects the spectral data only in the UV and visible wavelength range in a way that depends on the yarn and the dye. The sample-to-sample variance in the correlation plots (Figs. 15, 17, 21, 22 and 24) is most likely due to sample handling and the knitting process affecting the knit structure density. This can be seen well in Fig. 19, where the samples have the same yarn material and knit structure but different colours. The textile dyes do not affect the transmittance above 1000 nm wavelength, yet the data shows transmittance varying between 40% and 47% around 1000–1100 nm from one sample to another. Therefore, the 7 %-unit variance can be ascribed to the knitting process and sample handling. The uncertainty from the optical measurement instruments was negligible in comparison. This means that ca. 7 %-unit uncertainty must also be considered when interpreting the differences between the knit structures in Figs. 9 and 10. Textile is not an entirely well-defined optical material but a malleable soft material system and structure whose optical properties cannot be fully specified technically or exactly reproduced in experiments. Therefore, this study’s main conclusions are based on the data from different textile materials, structures, and colours as a whole, showing good correlations between the studied parameters. A large number of samples and abstaining from individual sample comparisons validate the observed trends across the measured dataset.

5. Conclusions

A systematic study of the optical properties of knitted textiles was presented from the perspective of their use for textile-integrated photovoltaic applications. The study used experimental characterisation with optical and photographic methods and developed dedicated performance metrics to describe the capacity of the textile to visually conceal a solar cell underneath it while allowing certain amount of light to pass through it to the underlying solar cell.

The scope of this work encompassed a set of microscopic and macroscopic factors that influence the optical performance of textiles, thereby providing an overview of the various influencing factors at multiple length scales. For instance, the effect of the inherent chemical properties of fibres, the yarn shape, and the knit structures was studied. Additionally, the impact of processing steps, such as bleaching and colouring, was discussed.

Performance metrics were developed to compare various knitted textile samples. Knitted samples performed well when the metrics were used towards simultaneous optimisation of solar cell performance and concealment using a textile. By imposing a minimum mean effective transmittance (MET) of 25%, enough light is guaranteed to pass through the textile – the reduced amount light reaching the solar cell can be compensated by increasing the solar cell area. As for solar cell concealment, a maximum threshold of 15% for solar cell visibility (SCV) was suggested, which roughly corresponds to ΔE colour difference values less than 4 and therefore results in nearly imperceptible differences in colour due to the solar cell underneath. Using the proposed criteria, 23 out of the total 175 samples (14% of undyed and 10% of coloured samples) met the requirements, thereby providing the optimal design compromise between solar cell performance and concealment.

Although applied here only for knitted textiles, the developed metrics are expected to apply to any textiles in knitted, woven, or non-woven configurations. Moreover, the metrics apply to diverse solar cell colours and technologies. However, unlike monocrystalline silicon, amorphous silicon and organic solar cells primarily utilise visible light. Therefore, using a coloured textile would have a stronger impact on their performance.

The metrics act as a guide for textile designers and engineers, supplementing their subjective design insight in the process of optimising the optical performance of textiles as visually concealing covers for solar cells. Among the studied metrics, the solar cell visibility (SCV) and the colour difference (contrast) ΔE, measured against a black and white background, can be employed towards the design and optimisation of textiles for concealing also other objects such as other textile electronic components.

The high contrast due to using a black solar cell represents the most challenging case of solar cell hiding, whereas using different types of coloured solar cells would most likely be less challenging to conceal. The concealment metrics could also be applied to other solar cell covers including optical films or coatings. Despite being defined for solar cells, the mean effective transmittance (MET) could be employed for other light sensing applications by replacing the spectral sensitivity (EQE) of the solar cell with that of the light sensing device in question.

CRediT authorship contribution statement

Farid Elsehrawy: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Bettina Blomstedt: Writing – original draft, Visualization, Validation, Resources, Investigation, Data curation. Elina Ilen: Writing – review & editing, Supervision, Funding acquisition. Elina Palouvieri: Writing – review & editing, Project administration. Janne Halme: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.
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