The effect of light and heat stimuli on thermoregulatory smart textiles
Third Year Dissertation

Amrit Bath: 10899510
Department of Physics and Astronomy, University of Manchester
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This paper explores how smart textiles, fabrics that respond to their environment, can be used to harvest energy through exposure to heat and light. Specifically, it focuses on thermoelectric textiles, which generate power from temperature differences, and photovoltaic textiles, which produce electricity from solar irradiance. These two material types are modelled using real-world data from four geographically distinct locations (Tromsø, Paris, Marrakesh, and Dubai) to understand how they perform across a year of changing temperature and sunlight conditions. The aim of the study is to assess whether these materials show enough potential to justify further research and development. Results indicate that photovoltaic textiles perform best in regions with consistently high sunlight, while thermoelectric textiles are more effective in colder climates with strong temperature gradients. However, challenges remain in making these materials wearable, including issues with energy storage, comfort, and flexibility. While the findings suggest that smart textiles hold promise for future wearable technology, especially in energy-autonomous systems, practical implementation still faces several technical barriers.

1. INTRODUCTION TO SMART TEXTILES

1.1. *What are smart textiles?*

Smart textiles are 'textiles that are able to sense stimuli from the environment, react to them and adapt to them by integration of functionality in the textile structure. The stimulus and response can have an electrical, thermal, chemical, magnetic, or other origin' [1]. There are multiple categories for smart textiles. These include textiles as a carrier for integrating off-the-shelf electronics, such as conductive yarns replacing cables; where fabrics serve as sensors or actuators; and fully textile-based logic, which integrates computational functions directly into the structure [2]. Smart textiles present an alternative to conventional electronics, offering embedded flexibility and integrating their nature into dynamic lifestyles [3]. It is important to note the relevance of wearable computers, and their overlap with smart textiles. The two often work together. A wearable computer is defined as a data processing system attached to the body, with one or more output devices, the output is continuously perceptible despite task or body position. The input allows the functionality of the data processing system to be modified [4]. Smart textiles must survive mechanical, chemical and thermal treatments over their life cycle, dependant on usage requirements. This can include washing, ironing, tumbling, stretching and abrasion. They also often require power from a portable energy source such as batteries. In advanced cases they harvest energy, for example, from piezoelectric sources, where materials create electrical charge when mechanically stressed. This allows for energy conversion, however some of these technologies suffer from low energy efficiency, low flexibility and insufficient human skin compatibility, which is important for textiles to function as garments [3]. Research surrounding how to best manufacture smart textiles is ongoing, as most industrial production technologies are not compatible with smart textile manufacture [3]. Research suggests the developments in smart textiles have the potential to transform human lives and will work together with artificial intelligence and machine learning to do so. The smart textile industry is projected to grow at a rate of 1.3 USD billion per annum by 2031 [5]. The advances will be explored in the following section, and include healthcare and fitness, robotics and the internet of smart textiles.

1.2. *Where are they being used?*

Smart textiles are being implemented in a range of applications across wearables. The expected use-cases of these textiles in garment technology can be seen in Figure 1. This shows healthcare and medicine driving demand for medical monitoring and therapeutic textiles, along with safety innovations in PPE. We also explore performance-enhancing textiles in sports, and limited areas of developments in buildings and the metaverse.

1.2.1. *Healthcare and Wellness*

Smart garments, finished clothing items utilising smart textiles, are being utilised often in the healthcare industries. E.g. the Georgia Tech Wearable Motherboard (GTWM) is a smart vest which integrates metal and optical fibres to an optoelectronic device to monitor vital signs of a soldier and detect for bullet penetration[2]. It pro-

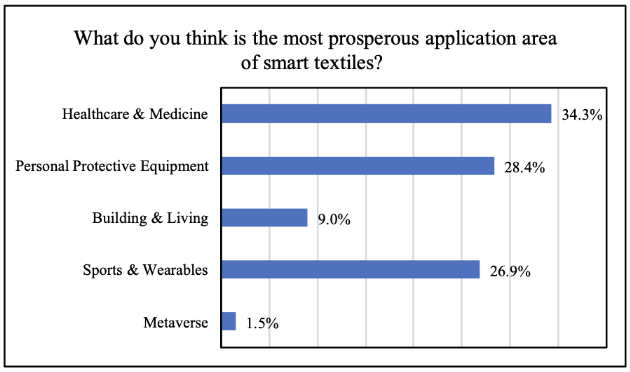

FIG. 1: Expert opinions on smart textile applications. Figure taken from [6].

vides a foundation for monitoring vitals (e.g, electrocardiogram, respiration) in medical settings using electronic textile-based wearable technology. This garment is recognised as the first smart garment of its nature to textile manufacturers nowadays [7].
More recently, the use of haptic technologies are being explored, largely in electrical muscle stimulation. Haptic technology uses tactile sensations, such as vibrations to create a sense of touch or physical stimulation. Haptic feedback can stimulate a number of different receptors in the skin, including free and sensory hair nerves and receptors for temperature, touch, pressure, and pain. Specifically, it can simulate receptors in the muscles and joints for contraction, stretching, and speed and change of the stimuli [2]. This is useful when investigating how Electrical Muscle Stimulation (EMS) can support muscle movements. Previous projects using EMS output include rehabilitation for stroke patients with object grasping, walking and actuating facial expressions [8].
Smart textiles can also implement smart wound care and smart drug delivery technologies to offer improved healing by response to stimuli. Transdermal drug delivery is possible through direct contact between skin and textile. This shows improvement compared to using bandages which limit air flow, slowing healing. Combining textile and adhesive in a patch has shown substantive results [9].
Furthermore, smart textiles can include structural health monitoring for buildings which track movement and falls of any residents [3]. From the same wellness perspective, electronic based smart textiles can configure a sensing system for movement monitoring. This can be used by emergency services to monitor urgent injuries and illnesses [7].

1.2.2. Fitness and Lifestyle

Smart textiles can also be integrated into a users everyday life. Including wellness and fitness related monitoring. For example: steps, heart rate and sleep tracking. Smart garments in wellness and sports have a greater potential for widespread adoption compared to the medical sector. This is largely because these markets rely on standardised products that do not demand the same level of precision in data recording. Whereas, to be successfully deployed as medical devices as in the previous section, they must first demonstrate operational effectiveness and safety to meet certification requirements [2].
Undergarments offer distinct advantages in both fitness and medical sectors. Their discreet nature allows them to be worn beneath regular clothing without interfering with non-verbal communication. Additionally, their design adheres to structural standards, ensuring they remain in use until functionality diminishes, rather than being replaced due to changes in fashion trends [2]. However, they must be extra sensitive and will require more washing since they will be worn against the skin.
From a fitness perspective, we can continue to see how monitoring can be integrated in smart textiles too. E.g, large brands Adidas and Nike have already introduced smart textile infused products to capitalise on their advantages. The Numetrex sports bra makes use of conducting knitted fibres into a sports bra, which monitors heart rate. This allows consumers to manage wellness concerns such as weight loss, physical health and energy levels [10]. In most sports, e-textiles would be beneficial for athletes due to their advancements and affordability [5].

1.2.3. Interactive Applications

Smart textiles are increasingly being used for novel aesthetic interactions. Haptic systems using EMS enable textiles to support user interaction, including rehabilitation and activity monitoring. They use computational systems and conductive yarns to control pixelation across miniature Peltier elements, which modulate temperature-sensitive textiles to produce dynamic visual effects. These are small solid-state heat pumps which work by transferring heat from one side to the other when an electrical current is applied. This enables a playful and unconventional dimension to wearable design. An example is shown in Figure 2, where a non-light-emissive display animates a heartbeat on a T-shirt [2]. This merges computational textiles with aesthetics, creating interactive and expressive garments without traditional light-based displays. This uses thermochromic inks which activate upon the use of conductive yarns. Thermochromic inks change colour with temperature making displays natural and subtle, compared to overwhelming visual animations from light emissive technologies [11]. Light emissive technolo-

FIG. 2: Non-light emissive display integrated into a T-shirt, demonstrating an animated heart using a single wearable animated pixel. Figure taken from [2].

gies are often seen as obtrusive and are used primarily to gain attention [12]. Conductive yarns integrated within the fabric heat the inks, enabling programmable patterns and dynamic designs. This technology also incorporates Peltier semiconductor modules to provide temperature control for rapid heating and cooling, allowing faster and more consistent animations throughout the garments [2].

1.3. Recent Developments

1.3.1. Energy Harvesting

Energy harvesting systems have been described by textile experts as key to the sustainable development of smart textiles. Developments in photovoltaic energy harvesting, piezoelectric and triboelectric developments [6] have allowed for energy harvesting systems to be made possible. However, challenges still remain such as flexibility, durability, moisture management and breathability. Additionally, washing the textiles pose an issue since those investing in smart textile technology want a garment enhanced with functionality rather than an extra level of care. The struggle of preserving textile properties once smart textiles have been integrated is proving to be a high cost process when mass scalability is considered.

Because of these challenges, storage of harvested energy in flexible storage systems for wearable applications is a critical new area of research. If conventional storage methods were to be used, e.g. solid state batteries and capacitors, then perseveration of textile properties would spoil. Textile based flexible batteries and supercapacitors exploit an underutilised field of study for smart textiles. These can result in a structure where energy can be generated and stored [13]. Fully flexible lithium ion batteries have a significantly lower electrochemical impedance than other membranes. By using these alongside carbon nanotubes (CNT), sodium dodecylbenzenesulfonate and anode current collectors, flexible CNT films can be researched further [2].

1.3.2. Thermochromic Fabrics

Another important direction in smart textile research involves passive thermoregulation. Thermochromic fabrics are designed to respond visually and functionally to changes in temperature and are primarily studied for their ability to regulate body temperature, independent of external conditions. While darker colours increase heat absorption, these materials also respond dynamically to temperature changes. In firefighting suits, for example, thermochromic textiles absorb heat and activate a secondary response where structural changes within the fibres enhance cooling.

Beyond visual transformations, these fabrics undergo physical shifts at microscopic levels. At high temperatures, thermochromic dyestuff fibres contract, widening the fabric's pores and allowing greater airflow to reduce body heat. Similarly, at low temperatures, the fibres are elongated and pores closed, forcing the body temperature to be maintained [14].

Research for colour changing fabrics is advancing in the areas of thermochromic fibres and microcapsules with wet spinning processes, a fibre manufacturing process using polymer solution and a spinneret which allows for good mechanical properties and excellent colour change stability. This provides an option which can be fabricated on a large scale and easily woven into various fabrics, and allows static and dynamic display imagery for information interactions in textiles [15]. For example, recent advancements in temperature regulation textiles includes the mercury jacket, which uses heating components and stretch insulation from carbon fibres [14]. Colour change is also utilised by regarding the usefulness of textile colour display in the internet of things, intelligent information interaction and information security protection [15]. An example of this is seen in Figure 3. This method enables non-emissive, responsive textile displays, with applications in interactive fashion, authentication systems, and adaptive camouflage.

1.4. Sensor Integration and Data Processing

Sensors integration in smart textiles allows for monitoring physiological and environmental parameters. These sensors operate based on physical principles such as piezoresistivity, capacitance, and electromagnetic coupling.

1.4.1. Piezoresistive Sensors

Piezoresistive sensors detect pressure changes by measuring variations in electrical resistance caused by mechanical deformation. They are used in wearable health monitoring to track body movements or detect contact forces [5]. The Piezoresistive effect in metal conductors arises due to changes in electrical resistance under mechanical strain. When a conductive material is subjected to an applied force, its length increases while its

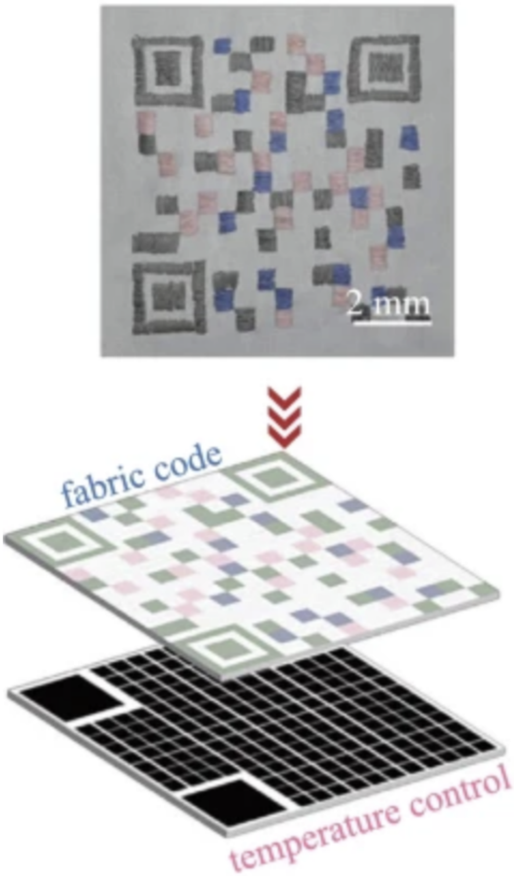

FIG. 3: Dynamic fabric display utilising a temperature-controlled heating scheme to encode and reveal information. The upper layer contains a fabric code, changing visibility based on thermal stimuli from the lower temperature control matrix. The QR code-like pattern demonstrates high-resolution, thermally-driven content variation. Figure taken from [15].

cross-sectional area decreases, leading to a redistribution of charge carriers [16].

1.4.2. Capacitive Sensors

By using the principle of capacitance, capacitive sensors measure changes in the electric field when a conductive object interacts with the textile. This is useful in touch-sensitive applications [10]. In fabric-based capacitive pressure sensors, the capacitance is influenced by the geometry and material properties of the dielectric spacer layer. The permittivity of the dielectric layers contribute to capacitance variations, this is dependant on the weighting factors of each material, which influence the dielectric behaviour of the textile under compression. The weighting factor quantifies the contribution to capacitance per material in the electric, which influences the dielectric behaviour of the textile under compression [17].

1.4.3. Electromagnetic Sensors

For wireless communication, electromagnetic sensors can leverage the textile's ability to transmit and receive electromagnetic signals efficiently [2]. In smart textiles, electromagnetic fields interact with woven conductive yarns, enabling sensing, data transmission, and actuation within the fabric structure. These textiles rely on electromagnetic coupling between conductive fibres, which can be influenced by factors such as yarn density, alignment, and material conductivity. Additionally, studies have demonstrated that conductive textiles can be designed to manipulate electromagnetic field strength and diffusion by adjusting the placement and density of conductive yarns. Electromagnetic sensors in smart textiles have potential for new expressions of woven textiles spatially and visually [18].
The integration of sensors into smart textiles enables responsive fabrics capable of detecting motion, touch, and electromagnetic signals. These sensor systems open research pathways for energy-efficient storage and energy distribution across a wearable textile.

2. THE CONNECTION BETWEEN SMART TEXTILES AND DIFFERENT CLIMATES

When considering the application of smart textiles, specifically thermochromic textiles and energy storage, it is important to understand what is currently utilised in the climates of interest. This helps provide a perspective of what the local population in each region currently utilise. Additionally, these specialised clothing aims can be implemented in smart textiles.
Humans maintain a core temperature within a narrow range that is managed by a complex thermoregulatory system. This is important for metabolic processes and major organ systems. Typically, the body strives to maintain an average temperature of 37°C $\pm$ 0.5°C, with minor fluctuations influenced by factors such as individual health, physical activity, and changing climates. However, when the thermoregulatory capacity is overwhelmed by extreme conditions such as temperature, hyperthermia or hypothermia can cause significant harm [19].

2.1. Areas of Extreme Cold

Research can be conducted on the clothes that are still made and worn by local communities. In Arctic communities, reindeer fur clothing was an integral part of the culture of the natives, due to the abundance of reindeer, along with properties of heat retention in the fur. Reindeer fur is thick

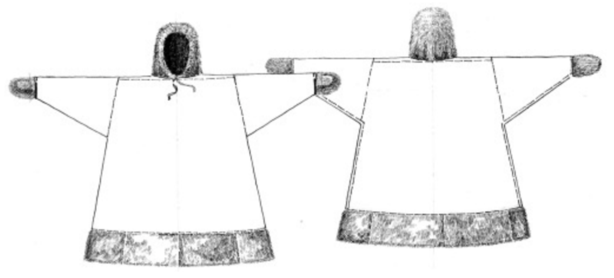

FIG. 4: Mal'tsia fur coat, a traditional outerwear garment worn by northern Indigenous communities. Designed for extreme cold, it features an attached hood and sewn-in mittens, ensuring all around insulation. Figure taken from [20].

and contains a dense underfur, this lowers movement of air within the fur, decreasing heat dissipation. Coats and boots are assembled from the fur to provide a maximum warming system for the wearer. A fur coat design, or Mal'tsia, can be seen in Figure 4. The wide, loose silhouette allows for layering, while fur trimmings enhance warmth retention. This design was made to optimise heat conservation in Arctic and Subarctic environments [20].

Smart textiles with embedded energy storage systems, such as solar-powered thermoregulation, would be cutting edge in environments with sustained low temperatures. New textile materials and research make it possible to extend research of smart textiles in this region. For example, Figure 5 shows a clothing prototype design for the arctic environment focusing on communication, navigation, environment monitoring and heating, whilst maintaining the appearance of an ordinary vest. Highlighting interest in the research of smart textiles in the arctic regions [21].

2.2. Areas of Extreme Heat

In extremely hot climates, the indigenous nomads of the Sahara preferred black cotton robes rather than reflective white clothing. We can understand this benefit from a scientific perspective too, although light clothing is more reflective, darker clothing retains less of the heat it gathers, whilst the lighter fabrics trap heat [22]. Additional studies show the black robes were effective in facilitating convective airflow beneath the fabric. This "chimney effect" occurs as the air trapped between the skin and the loose robes warms, rises, and escapes, drawing cooler air into the space. Despite the higher surface temperature of black robes compared to white robes, the convective cooling negates the additional heat absorption, maintaining comparable thermal comfort. Contrastingly to what may have been expected from the reflective properties of lighter fabrics, airflow properties must also be considered for extreme climates [23].

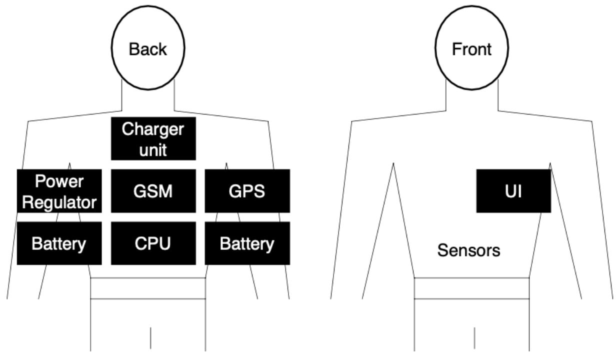

FIG. 5: Wearable prototype incorporating a dual-battery system, voltage regulator, and multiple integrated modules. The vest includes a central processing unit, global positioning system, global system for mobile communications, power regulator, charger unit, sensors and user interface. Figure taken from [21].

If traditional clothing fails to accommodate for temperature fluctuations in an environment, this can result in sweating or shivering. Traditional textiles struggle to maintain thermo-physiological comfort, therefore smart textiles have been investigated which can make use of high reflectivity and transmissivity. For example, the ZnO–PE textile has been shown to have outperformed the cotton textiles thermoregulating abilities [19]. A comparison of ZnO-PE, cotton and bare skin can be seen in Figure 6 where ZnO–PE exhibits the lowest temperatures among the textile-covered conditions, demonstrating the thermal management capabilities of this smart textile, for cooling.

3. THEORY AND PRINCIPLES OF DIFFERENT MATERIALS

The previous section discussed traditional and smart textiles responses to temperature changes in the natural environment, highlighting the roles of airflow, reflectivity, and material innovation in achieving thermal comfort. To understand how certain smart textiles actively generate heating or cooling effects, it is important to explore the physical concepts governing these functions. This section introduces the scientific foundations behind these materials, focusing on phenomena such as electrical conductivity, the Peltier effect, and photovoltaic energy conversion. These concepts allow a deeper understanding of textile functions from physical principles.

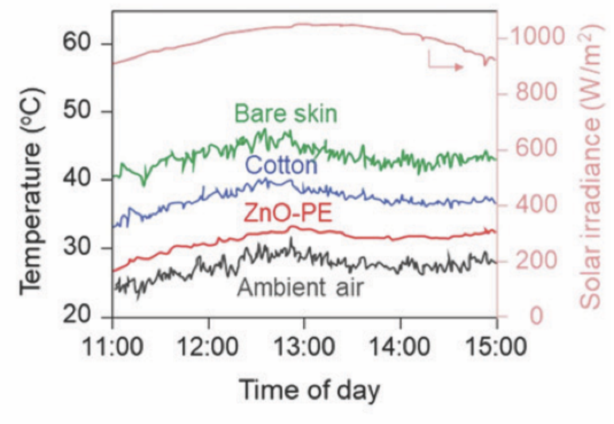

FIG. 6: Temperature variation of different materials- smart textile ZnO–PE, cotton, and bare skin-compared to ambient air under solar exposure. X-axis represents the time of day, spanning from 11:00 to 15:00, while the left y-axis indicates temperature in degrees Celsius. The right y-axis shows solar irradiance in watts per square meter (W/m²). Figure taken from [19]

3.1. *Conductive Polymers and Yarns*

Conductive yarns are important for enabling photovoltaic textiles. They act as electrodes, interconnections, and potentially even as part of the active solar cell material: allowing for flexible and wearable solar energy harvesting. Additionally, they can be integrated into thermoelectric textiles, converting temperature differences into electricity for applications such as wearable sensors and heaters.

Conductivity in smart textiles can be achieved through materials such as conductive polymers, silver coatings, and embedded metallic fibres. Polyaniline (PANI) and poly(3,4-ethylenedioxythiophene) (PEDOT) are two widely used conductive polymers [5]. Their electrical conductivity due to their conjugated double bonds enable free electron movement - mimicking the behaviour of metals. For instance, PANI achieves conductivity levels comparable to semiconductors by doping with iodine or bromine, enhancing potential for applications in sensors and actuators [3].

Electrically conductive yarns represent another key application area within smart textiles . These yarns integrate metallic fibres or CNT, which act as pathways for electrical currents [2] . The resistivity of these materials is engineered to balance flexibility with electrical efficiency, enabling applications such as strain and pressure sensing. For example, woven conductive yarns detect deformation in fabrics, with resistance increasing proportionally with applied strain and bending angle. This principle is used in motion tracking and rehabilitation devices [10].

3.2. *Solar Cells and Photovoltaic Materials*

Energy harvesting techniques, such as photovoltaic systems, are being integrated into fabrics to provide self-sustaining energy sources [5]. Solar panels integrated into textiles capture and store solar energy, enabling prolonged operation of wearable systems [2].

Efficiency, η, of a solar cell is defined as the ratio of output power density to the intensity of the incoming light. This is given by

$$\eta = \frac{I_{sc} \times V_{oc} \times FF}{P_{in}} \tag{1}$$

where I_{sc} is the short-circuit current, the maximum current generated when the terminals are directly connected with no external load. V_{oc} is the open-circuit voltage, FF is the fill factor, and describes how closely a cell's performance approaches an ideal source. P_{in} is the incident power density, determined by the irradiance [24]. The fill factor, FF, is determined using the following equation

$$FF = \frac{I_{mpp} \times V_{mpp}}{I_{sc} \times V_{oc}} \tag{2}$$

where I_{mpp} and V_{mpp} are the current and voltage at the maximum power point of the solar cell. We use this to find the maximum power output.

The increase in V_{oc} due to an increase in light intensity can be calculated using

$$\Delta V_{oc} = \frac{nkT}{q} \ln\left(\frac{J_{sc2}}{J_{sc1}}\right) \tag{3}$$

where n is the ideality factor, a dimensionless constant describing how closely the device follows ideal diode behaviour. kT/q is the thermal voltage (25.7 mV at room temperature), where k is the Boltzmann constant, T is the temperature and q is the charge. J_{sc2}/J_{sc1} the ratio between the current density at increased light level and at baseline conditions [25].

3.3. *Peltier Elements*

A Peltier element is an electrical component creating a temperature difference between its two sides when an electric current is applied. It consists of a thermoelectric module made up of thermocouples connected by alternating plates. They utilise temperature differences to generate power, as illustrated in Figure 7 . Peltier elements are compact and lightweight, capable of cooling well below ambient temperatures without the use of liquid coolants, making them ideal for solid-state heating and cooling applications, particularly in wearable thermoregulation and electronic cooling systems. When powered, heat is absorbed from the cold side and transferred to the hot side, generating a temperature gradient. Copper bars provide electrical connections, while ceramic bars offer structural support and thermal insulation.

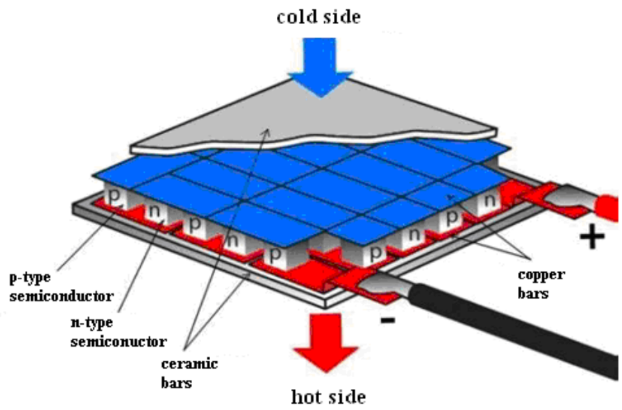

FIG. 7: Peltier element consisting of a thermoelectric cooling module composed of alternating p-type and n-type semiconductors arranged between two ceramic plates. Figure taken from [26].

When an electric current is sent through a Peltier element, it transfers heat from one side of the module to the other. Equation 4 describes the amount of heat generated by the element,

$$Q = p \cdot I \cdot t, \tag{4}$$

where Q is the heat transferred by the Peltier element. I is the current flowing through an element, and t is the flow time. p is the Peltier coefficient, which varies based on the specific metal pair and the temperature of the element.

The disadvantages of Peltier elements include their low efficiency and high power consumption. To be used for cooling, heat must be removed from the hot surface, else the efficiency will be significantly reduced. In practice, the power output is 30% of the theoretical value. The efficiency of Peltier-based cooling in smart clothing is highly dependent on the thermal resistance of both the fabric and the electrical circuit itself. Experimental studies show that the non-linear nature of heat dissipation complicates the overall energy efficiency, as a portion of the supplied electrical power is inevitably lost to internal thermal resistance within the circuit components [26].

While Peltier elements are typically used for cooling, the same thermoelectric principles can be exploited in reverse to generate electrical power from a temperature gradient. The power output of a thermoelectric generator is given by Equation 5

$$P = \frac{\alpha^2 \eta^2 \Delta T^2}{4r} \tag{5}$$

where P is the power output, η is the number of thermal couples in the series, α is the Seebeck coefficient, ΔT is the temperature difference across the material and R is the internal resistance of the system [27].

3.3.1. Thermochromic Inks and Thermal Actuation

Thermochromic inks provide a non-emissive light display mechanism by changing colour in response to temperature [2]. The physics behind this phenomenon lies in the molecular structure of the inks, which undergo a reversible change in configuration when exposed to specific thermal thresholds. These inks are actuated using conductive yarns or Peltier semiconductor modules, which generate heating and cooling through thermoelectric effects. By applying a closed-loop temperature control system, fabrics embedded with thermochromic inks display dynamic patterns or animations [5].

The efficiency depends on the thermal conductivity and heat capacity of the materials used. Conductive yarns with high thermal conductivity enable rapid and uniform heat distribution, while Peltier modules depend on temperature gradients. Thereby allowing for programmable colour changes in the fabric, with applications including ambient displays and personalised wearable designs [10].

4. SMART TEXTILE RESPONSE MODELLING

This section outlines the modelling approach used to investigate the power-generating potential of photovoltaic and thermoelectric textiles under varying environmental conditions. The aim of analysis was to understand temperature and solar irradiance effects on performance of energy-harvesting textiles across different climates.

To explore this, responses of both textile types was modelled in four geographically and climatically distinct locations: Tromsø (Norway), Paris (France), Marrakesh (Morocco), and Dubai (UAE). These sites were chosen to capture a representative spread of seasonal variation, extreme temperatures, and differing levels of solar exposure.

Modelling was divided into two main strands. Thermoelectric response was examined depending on temperature differences across the material, and photovoltaic responses were modelled on solar irradiance data. While the two technologies operate through distinct physical principles,

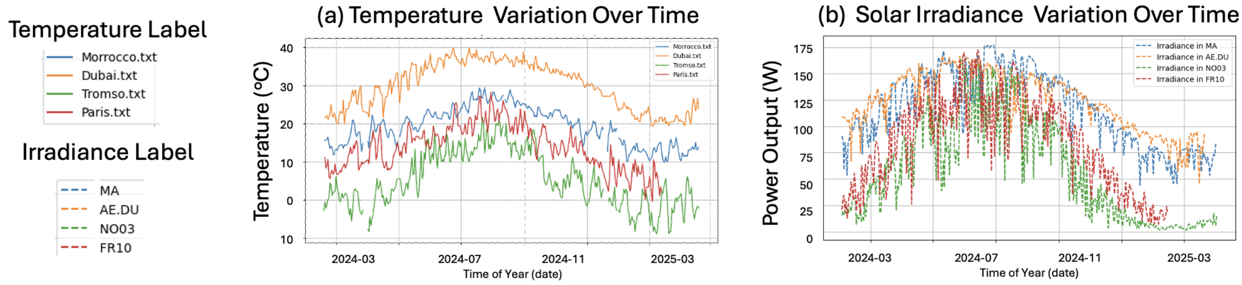

FIG. 8: Plots (a) and (b) represent the temperature and irradiance experienced by a person at ground level in different locations. The respective locations are Morocco (blue), Dubai (orange), Tromsø (green), and Paris (red). The labels for these locations are shown on the far left. Plot (a) shows the average daily ground-level temperature in each location. This represents the temperature experienced by a person in the location. Plot (b) showcases the GHI (Global Horizontal Irradiance) of a location, which measures the total amount of solar power per unit area received on a horizontal surface. Data from [28] and [29].

both models made use of publicly available environmental datasets, analysis of material properties from literature, and the theoretical equations established in the previous section.

4.1. Yearly Temperature and Irradiance

Comparison of real world data from different regions with properties of photovoltaic and thermoelectric textiles allowed the power output over time to be found and utilised in each region. Literature from [27], [25] and [24], allowed modelled responses of the theory and properties of the textiles under analysis. The properties of thermoelectric and photovoltaic textiles analysed can be seen in tables I and II, respectively.

Figure 8 shows the temperature and irradiance values respectively over a yearly period in Marrakesh, Dubai, Tromsø and Paris. As expected, the temperature and irradiance are positively coordinated: where higher irradiance corresponds to high temperatures, and vice versa. We can also understand the temperature profiles for each country. Irradiance levels in Tromsø, Norway drop to near zero, due to lack of sunlight hours in winter. Meanwhile, temperature values are incredibly low. We can also see hotter climates Morocco and Dubai generating larger levels of irradiance yearly, and reaching much larger temperatures, too. Urban areas such as Paris have representative winters and summers, with larger differences throughout the seasons, but still follow the consistent relationship of temperature with irradiance.

4.2. Results

4.2.1. Thermoelectric Materials

We can use thermoelectric material properties as extracted from literature, as seen in Table I. Furthermore, we can apply equation 5 to this data to process the output.

Thermoelectric power systems contain several tens to hundreds of thermocouples, depending on the size and power requirements of the system, larger modules often have hundreds of couples, e.g. commercial thermoelectric modules have 127-254. We can make use of the textile average in our methodology calculations.

Figure 9 shows power outputs using a thermoelectric power system in Dubai, Morocco, Paris and Tromsø.

The peaks occur in the winter period as the temperature difference, ΔT, is the largest between the baseline temperature of a person (310K) and the outside temperature due to the climate in this time frame. Therefore, ΔT reaches troughs in summer months. Urban climates also provide substantial power generation in the summer and winter. We can see the performance of each textile, with names and properties described in Table I. The best performing textile was found to be PbTe-SrTe-Na.

4.2.2. Photovoltaic Materials

By using material properties extracted from literature, we are able to analyse the solar cell behaviour. These properties can be seen in Table II.

The plots in Figure 10 illustrate solar power output over a yearly period across Dubai, Morocco, Paris, and Tromsø. Each plot incorporates six textile-based photovoltaic materials, along with irradiance data. The names and properties of the textiles used in these plots are described in Table II.

From the plots, there is a clear seasonal trend, with both solar power output and irradiance peaking during summer months, and declining in winter, particularly in Tromsø, where solar exposure is minimal for an extended period. The textiles

Material	Internal Resistance (Ω)	Seebeck Coefficient (α) ($\mu V/K$)
n-type SiGe	0.00054	∼200 to 300
p-type SiGe	0.00083	∼+200 to +300
PbTe	0.00765	∼150 to 200
PbSe	0.00664	∼100 to 200
PbS	0.00866	∼100 to 250
PbTe-PbI$_2$	0.00268	∼+150 to +200
PbTe-CdTe	0.00068	∼+150 to +200
PbTe-SrTe-Na	0.00058	∼+150 to +200

TABLE I: Internal resistance and Seebeck coefficient of different thermoelectric materials. Data taken from [27].

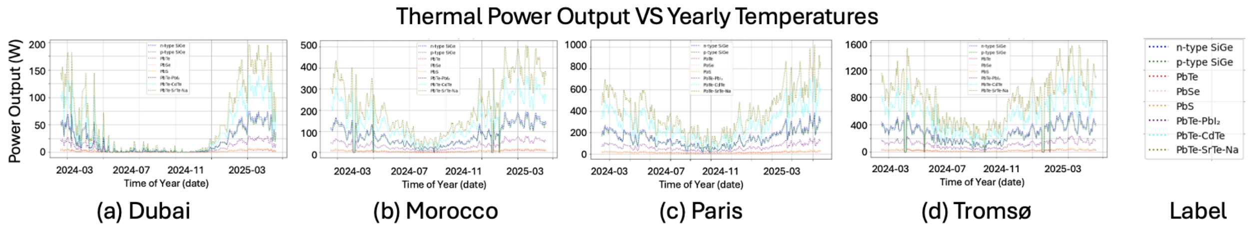

FIG. 9: Plots (a), (b), (c) and (d) show the power output using thermoelectric power system. Power is on the Y axis and defined at the far left. The figures show the textile outputs in Dubai, Morocco, Paris and Tromsø respectively. Each textile is plotted, with a label at the far right. Graphs made using Python.

following the Superstate and Substrate Configurations show relatively consistent output throughout the year but remain significantly higher than A, B, and C textiles, which are shown independently in Figure 11 so that we are able to analyse the behaviour of wearable textiles without influence of the ideal scenario of transparent conductive oxides (TCOs). Dubai and Morocco show high sustained solar power output due to their year-round sunlight, whereas Paris maintains a more balanced yet moderately strong performance.

TCOs with high conductivity enable fill factors up to 70 percent. The transmission of common TCOs exceeds 80 percent in the given wavelength region. The transmission of a 10 nm thin titanium layer was measured at 40 percent, implying that using a higher-transmission material could double the short-circuit current (J_{sc}). Consequently, J_{sc} is doubled to $7.4mA/cm^2$ in improved conditions, improving overall efficiency.

The highest-output textiles in Figure 10 use idealised glass textile structures, and are harder to optimise as wearable technology. Figure 11 gives us a more realistic idea, omitting the Superstrate, Substrate and prospects for TCO Configurations. C textile consistently outperforms A and B, particularly where the irradiance levels support photovoltaic efficiency. This provides a real-world perspective on wearable solar textiles.

Therefore we can conclude that textile-based photovoltaic functions optimally with the most efficient energy generation in high-irradiance climates.

5. DISCUSSION

The results confirm the viability of solar textiles for continuous power generation in high-irradiance regions, while thermoelectric textiles are highly dependent on temperature gradients to function effectively. However, for either technology to be implemented successfully in real-world wearables, several key limitations must be addressed. Including challenges in material selection such as thermal stability, flexibility, efficiency, integration, comfort, and textile compatibility. Additionally, energy storage remains a critical area for development, as harvested energy must be retained and delivered in a stable, wearable form. Finally, practical performance and user experience depend on real-world factors like body movement, environmental shading, and fluctuating temperature conditions. This section evaluates each of these areas in turn, identifying both the barriers to implementation and directions for future research.

5.1. *Material Selection*

This section outlines the key thermoelectric and photovoltaic materials evaluated for integration into smart textiles, highlighting performance characteristics, limitations, and suitability for wearable applications.

PbTe-SrTe-Na outperformed other thermoelectric materials, enhancing thermoelectric performance

Devices/Schemes	V_{oc} (mV)	J_{sc} (mA/cm**2)	FF (%)	/ Eff. (%)
A (Textile-based)	360	0.08	24.9	0.007
B (Textile-based)	220	0.43	24.3	0.023
C (Textile-based)	240	0.72	25.2	0.040
Superstrate Config.	818	1.15	47.3	0.45
Substrate Config.	883	3.70	43.1	1.41
Prospects for TCO	901	7.40	70.2	4.68

TABLE II: Performance metrics of different photovoltaic devices and configurations. Data taken from [25] and [24].

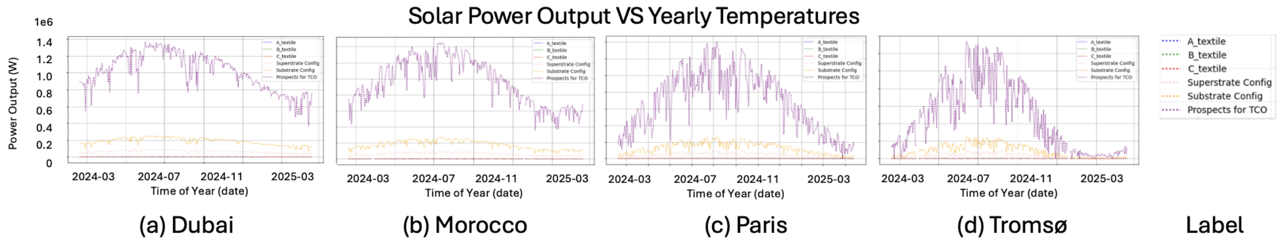

FIG. 10: Plots (a), (b), (c) and (d) show the power output using solar cell power generators, with a shared Y axis defined at the far left. This makes use of textile based materials : with textiles A, B and C using a photovoltaic textile structure that uses polyaniline/carbon nanotube composite materials. The next 3 use amorphous silicon thin-film solar cells on glass fibre textiles. These textiles are labelled at the far right. The figures show the textile outputs in Dubai, Morocco, Paris and Tromsø respectively.

by optimising carrier transport while maintaining low thermal conductivity, which is essential for the high efficiency output seen [27]. However, its efficiency remains relatively low compared to other energy conversion methods. While effective, practical power outputs are still limited for large-scale applications [27].

Organic Polymer-Based Photovoltaic Textiles are made from PANI and CNT composites. These textiles integrate a P3HT:PCBM blend, which functions as the active layer for photon absorption and charge generation. Conductive PEDOT:PSS layers improve charge transport, ensuring efficient electron flow through the textile structure [24]. Thin-film amorphous silicon (a-Si:H) solar cells deposited on glass fibre textiles present an alternative for wearables. However, transmission losses in thin metal electrode layers limit efficiency [25].

The prospects for TCO variable used extrapolated values which could be reached by possible improvements with the 10 nm thin titanium layer in the substrate and superstate being replaced by TCO, making higher conductivity of TCOs enables fill factors up to 70 percent. This allows for TCO values to reach high numerical values. Further research will be necessary to understand fully the feasibility of integrating TCO textiles, along with the two other glass based textiles. This is primarily due to the impact of cracks in the glass, which would cause shunting of the solar cell. It would be necessary to conduct an in depth investigation to understand how this could be efficiently integrated into wearable textiles [25].

Photovoltaic textiles A, B, and C show clear irradiance dependence, and are realistic estimates of performance: reinforcing the need for site-specific material choices.

5.2. *Feasibility and implementation*

Smart textiles are often developed at the material or prototype scale, whereas garments involve complex construction, wearability, and durability considerations. This hinders seamless integration into functional clothing.

Thermoelectric textiles require thin-film deposition or nano-structuring of materials such as PbTe-SrTe-Na onto a flexible, thermally conductive textile substrate. Conductive fibres or embedded micro-thermoelectric generators would be useful for efficient power extraction. However, challenges include material brittleness, temperature mismatch with human skin, and integration into lightweight, breathable fabrics [27]. These each require further research to ensure comfortability and usefulness.

Organic solar textiles are fabricated via solution-based printing, dip-coating, or spin-coating, ensuring that conductive layers remain thin and flexible [24]. Glass fibre-based solar textiles offer higher stability and efficiency but require encapsulation to prevent wear and degradation [25]. The choice between organic polymer-based solar

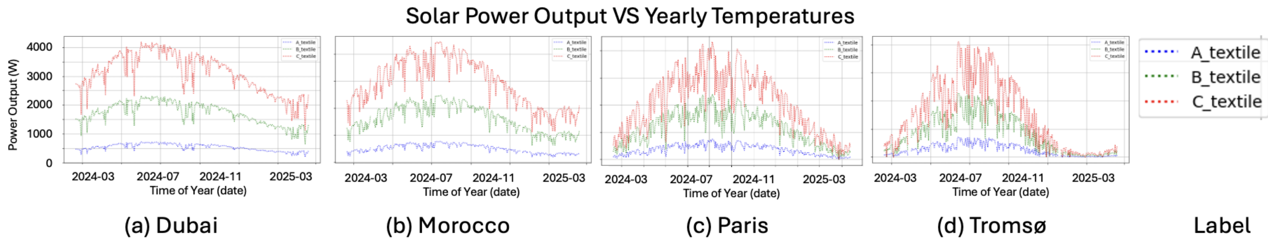

FIG. 11: Plots (a), (b), (c) and (d) show the power output using solar cell power generators, with a shared Y axis defined at the far left. This makes use of textile based materials : with textiles A, B and C using a photovoltaic textile structure that uses polyaniline/carbon nanotube composite materials with a label at the far right.

textiles and thin-film amorphous silicon solar textiles depends on the application, with Polymer-based structures using CNT:PANI composites being more adaptable. For improved efficiency and durability, amorphous silicon solar cells on glass fibre substrates offer better long-term viability.

5.3. Energy Storage

As energy-harvesting textiles become more viable, the ability to store generated energy efficiently and flexibly is essential for powering wearable devices in real-world conditions.

Energy harvested from wearable textiles could be used immediately or stored for later use, depending on the power requirements of the application. Textile-based supercapacitors are emerging as a promising solution for integrating energy storage into clothing, offering lightweight and flexible alternatives to traditional batteries. Unlike conventional power banks, which rely on bulky lithium-ion cells, textile supercapacitors are designed to be embedded directly into fabric while maintaining mechanical flexibility and durability [30].

Conductive textiles, structured in mesh geometries via embroidery stitching, function as efficient current collectors for wearable supercapacitors. These utilise materials such as graphene oxide/manganese dioxide to achieve high capacitance and energy density. These supercapacitors retain over 95% of their capacitance after 5000 charge cycles, making them highly stable for long-term use [30].

Supercapacitors enable rapid charging - some prototypes reaching full charge within seconds - making them well-suited for intermittent power generation scenarios. While current prototypes power small devices such as LEDs, ongoing advancements in nanomaterials and textile engineering could enhance capacity to sustain more energy-intensive applications like wearable heating elements [30].

A textile can store and later release energy by integrating flexible supercapacitors or thin-film batteries, which capture energy from harvesting mechanisms, store it electrochemically, and discharge it to power wearable devices [31]. Further research should be investigated to understand fully these methods of energy storage.

Additionally, phase-change materials (PCMs) and thermally emissive textiles regulate heat by absorbing excess thermal energy from the environment or the human body, storing it, and later releasing it to maintain temperature stability. Such materials can be embedded within fibres or coated onto textiles to passively modulate temperature, reducing reliance on active cooling mechanisms. Radiative cooling textiles, for instance, are designed to re-emit absorbed heat, helping dissipate excess thermal energy into the surrounding environment [32]. Research can be conducted in this area to understand the integration possibilities with the energy generating textiles discussed.

5.4. Practical Applications

Its is important to consider if these textiles can realistically power devices by comparing outputs to common power consumption benchmarks. A typical heated jacket requires 5-10W of power. A heated blanket operates between 30-50W. Electric heating pads use around 20W. Meaning most necessary heating applications operate between 0-50W [33].

Textile cooling can utilise energy stored to cool down the wearer by powering thermoelectric cooling textiles. Another use-case would include a micro-fluidic cooling systems that circulates a cooling liquid through embedded channels in the fabric [34]. Further research will be required to understand integration with solar cell textiles.

Another important factor to consider with solar cells, is the maximum power generation assumes someone is always at the maximum irradiance position, however this depends on their time spent in the shade throughout the day. These considerations must to be applied in order more realistically consider a persons experience with a wearable.

Thermoelectric textiles show extreme promise on the basis of using the temperature gradient. However, the thermoelectric plates consist of a 'hot side' and a 'cold side'. Thermoelectric energy generation works by transferring the heat from the hot side to the cold side hence, the current manufacture of thermoelectric textiles would be ineffective at generating energy from the temperature difference alone [27]. A more effective approach may involve redistributing body heat rather than generating new heat. By capturing excess warmth from the torso and transferring it to extremities, such as gloves or shoes, thermoelectric wearables could improve thermal comfort without requiring significant external power input. Further analysis must be conducted to gain understanding of how these textiles can best be utilised and manufactured into wearables.

The results suggest that solar textiles could generate up to 2000W or even 1MW, which significantly exceeds typical expectations for wearable energy generation. To contextualise, a standard solar panel typically produces around 300W per hour, leading to a maximum daily energy production of 7200Wh (7.2kWh) under ideal conditions [35]. A small wind turbine can generate between 400W-1000W per day, depending on wind speeds [36]. These benchmarks suggest that the reported values for solar textiles are several orders of magnitude higher than conventional energy harvesting sources, indicating an unusual efficiency assumption. This means that further analysis must be done on the theoretical maximum power, and the actual maximum power when activities of the textile wearer and random effects are considered. It would be useful to compare the maximum potential power output of solar panels under theoretical values with the maximum potential power outputs of textile solar cells to understand this inconsistency.

6. CONCLUSION

This dissertation has demonstrated the potential of smart textiles to harvest and store energy across a range of climates, with photovoltaic materials best suited to sunny environments and thermoelectric materials offering limited but valuable data in colder settings. Despite promising laboratory performance, widespread adoption remains constrained by durability, scalability, and comfort requirements. Additionally, further research is required to reflect the power output of each material to the true nature of the wearer. Theoretical maximum outputs suggest significant potential, but real-world application must account for variable irradiance, temperature fluctuations, and wearer activity. Future research should focus on improving the integration of flexible storage systems, addressing efficiency losses in wearable scenarios, and exploring how excess heat or light could be redistributed across garments. As interest in wearable technology grows, smart textiles offer a viable route towards energy-autonomous systems, particularly when aligned with advances in nanomaterials, phase-change systems, and machine learning-based adaptability. However, careful consideration must be given to their feasibility beyond the lab - particularly in terms of comfort, power demands, and long-term sustainability.

Generative AI Disclosure: I used ChatGPT 4o to assist in feedback on grammar.

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