BYGT2900 Bachelor's Thesis Construction

# Laboratory Investigations of Polymer-Dispersed Liquid Crystal Films for Applications in Smart Windows

Laboratorieundersøkelser av polymer-dispersed liquid crystal filmer for anvendelser i smarte vindu

**Trondheim Mai 2024**


Students:
Lotta Berntsen
Isabel Borgos

NTNU supervisor:
Bjørn Petter Jelle
Tao Gao
Gabriele Lobaccaro



Project number:
2024-16

The report is PUBLIC



NTNU
Department of Civil
and Environmental Engineering

# Project description and goals

The need to improve the energy efficiency of buildings is becoming increasingly important. A major part of the energy loss in buildings occurs through the windows. Increasing the insulating properties of windows can therefore determine a considerable difference in a building's energy efficiency. New advanced window technologies are constantly being developed such as e.g. smart windows. Smart windows can dynamically adjust their properties to control the amount of solar radiation (daylight and heat) entering a building. This may reduce the need for heating and cooling systems in buildings and therefore contribute to improve the energy efficiency. Polymer-dispersed liquid crystal (PDLC) films represent one of several different smart window technologies. PDLC windows change their optical transmittance from translucent to transparent when introduced to an alternating electric current. Using PDLC windows in buildings can therefore increase the buildings energy efficiency, and the thermal and visual comfort.

This thesis will evaluate the performance of PDLC smart films provided by Fågg AS through laboratory testing of its solar radiation properties. Specifically, the transmittance and reflectance of PDLC will be investigated across a range of voltages to determine the threshold voltage for optimal transparency. With these results, advantages and disadvantages of the results will be analysed in terms of voltage requirement, dynamic solar radiation control, switching speed and user comfort. Lastly, a discussion of further work and improvements of this investigation will highlight areas where PDLC as smart window technologies can be streamlined.

To achieve these aims, two research questions will be addressed in this thesis:

1. *What is the relationship between applied voltage and solar radiation properties (transmittance and reflectance) of PDLC films?*

2. *Is it possible to operate PDLC films effectively at lower voltages, and what impact would this have on a building's energy consumption?*

**Keywords**
Smart film, smart window, liquid crystal, solar radiation, transmittance, reflectance

# Preface

This bachelor's thesis was carried out Spring 2024 within the specialisation House Building Technique, in association with Department of Civil and Environmental Engineering (IBM) at the Norwegian University of Science and Technology (NTNU). The thesis is the final requirement of the Bachelor's program in Civil Engineering and concludes our three years of study.

We were originally interested in conducting laboratory investigations on accelerated climate ageing of low-emissivity materials. However, due to a repair delay of some crucial equipment we were unable to carry out these investigations. Instead, we were advised by our supervisor to look into smart window technologies. This led us to discover the importance of these windows in fulfilling goals of more energy efficient buildings. In the bigger picture, improving these has a profound effect on reducing greenhouse gas emissions from the building sector. Having both chosen specialisations that focused heavily on sustainable constructions throughout its entire life cycle, smart window technologies were of particular interest. One type of smart window technology that we decided to research further was polymer-dispersed liquid crystals (PDLC).

We were introduced to the company Fågg AS that delivers PDLC films that are mainly used as privacy screens. From our research, we had discovered that the solar radiation properties of PDLC films allowed them to control the amount of solar radiation that is transmitted (specular and diffuse) by applying a voltage. Therefore, we wanted to test PDLC samples from Fågg to investigate how these solar radiation properties changed with different voltages. The aim would be to characterise the PDLC films by measuring their transmittance and reflectance spectra (total, specular and diffuse), find the optimal voltage for the PDLCs to maintain their transparency, and analyse how these results could contribute to energy efficiency in buildings. This led to the design of a laboratory investigation that would measure the transmittance and reflectance of PDLC at different voltages using a UV-VIS-NIR spectrophotometer covering the whole solar wavelength region including ultraviolet (UV), visible (VIS) and near infrared (NIR) radiation.

Trondheim, 21st May 2024

Lotta Berntsen — Isabel Borgos

Lotta Berntsen

Isabel Borgos

# Acknowledgments

We would like to thank our supervisors Prof. Bjørn Petter Jelle (NTNU), Dr. Tao Gao (NTNU) and Assoc. Prof. Gabriele Lobaccaro (NTNU) for their guidance during our bachelor's thesis. We would also like to thank Mr. Lasse Veie from Fågg AS who kindly provided us with the PDLC samples that were used in this investigation.

We especially would like to thank our main supervisor Prof. Bjørn Petter Jelle who introduced us for the specific topic and problem definition for this bachelor thesis. He has taught us a lot about innovative materials and smart window technologies. We had never heard about the smart window technology or polymer-dispersed liquid crystals before, but when Bjørn Petter introduced this topic to us including a meeting with Fågg AS, we became very interested.

Furthermore, we would like to thank Dr. Tao Gao for teaching us about the instruments in the laboratory and how to use them, for always being available, guiding us and providing us with good feedback throughout this work.

We also want to thank Assoc. Prof. Gabriele Lobaccaro for his interest in our work and for the guidance, advice, and good feedback throughout this period.

# Abstract

To save energy and increase the comfort in buildings, new innovative smart window technologies can be the solution. This study focuses on the solar radiation properties of polymer-dispersed liquid crystals (PDLC) smart films. The PDLC is a controllable smart film often used on windows to adjust the solar radiation properties in order to improve the energy performance and user comfort of buildings. Some advantages of PDLC include dynamic light control, high switching speed, ultraviolet (UV) radiation protection, glare reduction and increased privacy. Disadvantages of PDLC include its need for a voltage to change and maintain a transparent state, energy consumption from the applied voltage, and aesthetics.

In this work we have tested the physical properties of polymer-dispersed liquid crystals films at different experimental conditions. More specifically, we have measured the solar radiation transmittance and reflectance (total, diffuse and specular) of a commercial PDLC smart film from the supplier Fågg AS at different applied voltages. The transmittance and reflectance of the PDLC were measured using a UV-VIS-NIR spectrophotometer with different accessories, including the normal specular (direct) transmittance detector system, an integrated sphere accessory able to measure both transmittance and reflectance (total and diffuse, thereby calculating the specular part) and a universal reflectance accessory able to measure the specular absolute reflectance at different angles of incidence.

The results showed that the total transmittance of PDLC at an applied voltage of 60 V was highest at around 900 nm with 88% transmittance. Diffuse transmittance of PDLC was highest at 0 V and 800 nm with a peak transmittance of around 67%. Total reflectance of PDLC was highest at 0 V and 450 nm with about 32 % reflectance. Diffuse reflectance was highest at 0 V and 450 nm with a peak reflectance at around 24%.

# Sammendrag

For å spare energi og øke komforten i bygninger, kan nye innovative smart vindusteknologier være løsningen. Denne studien fokuserer på solstrålings-egenskapene til polymer-dispersed liquid crystal (PDLC) smartfilmer. PDLC er en kontrollerbar smart film som ofte brukes på vinduer for å justere solstrålings-egenskapene for å forbedre energiytelsen og brukskomforten i bygninger. Noen fordeler med PDLC inkluderer dynamisk lyskontroll, høy vekslehastighet, beskyttelse mot ultrafiolett (UV) stråling, reduksjon av blending og økt privatliv. Ulemper med PDLC inkluderer behovet for spenning for å endre og opprettholde en gjennomsiktig tilstand, energiforbruk fra den påførte spenningen og estetikk.

I dette arbeidet har vi testet de fysiske egenskapene til polymer-dispersed liquid crystal filmer under forskjellige eksperimentelle forhold. Mer spesifikt har vi målt solstrålingens transmittering og refleksjon (total, diffus og spekulær) av en kommersiell PDLC smart film fra leverandøren Fågg AS ved forskjellige påførte spenninger. Transmittering og refleksjon av PDLC ble målt ved hjelp av et UV-VIS-NIR spektrofotometer med forskjellige tilbehør, inkludert det normale spekulære (direkte) transmitteringsdetektorsystemet, et integrert sfæretilbehør som kan måle både transmittering og refleksjon (total og diffus, dermed beregne den spekulære delen) og et universelt refleksjonstilbehør som kan måle den spekulære absolutte refleksjonen ved forskjellige innfallsvinkler.

Resultatene viste at den totale transmitteringen av PDLC ved en påført spenning på 60 V var høyest ved rundt 900 nm med 88 % transmittering. Diffus transmittering av PDLC var høyest ved 0 V og 800 nm med en topptransmittering på rundt 67 %. Total refleksjon av PDLC var høyest ved 0 V og 450 nm med omtrent 32 % refleksjon. Diffus refleksjon var høyest ved 0 V og 450 nm med en topprefleksjon på rundt 24 %.

## Table of contents

## List of tables



## List of figures

## Abbreviations

| | |
|---|---|
| EC | Electrochromic |
| GC | Gasochromic |
| HVAC | Heating, ventilation, and air conditioning |
| $IrO_2$ | Iridium dioxide |
| IS | Integrated sphere (accessory, PerkinElmer) |
| ITO | Indium tin oxide |
| LC | Liquid crystal |
| $MoO_3$ | Molybdenum trioxide |
| NIR | Near-infrared |
| NiO | Nickel oxide |
| PANI | Polyaniline |
| PC | Photochromic |
| PDLC | Polymer-dispersed liquid crystal |
| PEO | Polyethylene oxide |
| RMED | Reversible metal electrodeposition device |
| SPD | Suspended particle device |
| TC | Thermochromic |
| URA | Universal reflectance accessory (PerkinElmer) |
| UV | Ultraviolet |
| VIS | Visible |
| $V_2O_5$ | Vanadium pentoxide |
| $WO_3$ | Tungsten trioxide |
| 3D | Three detector model (accessory, PerkinElmer) |

# 1 Introduction

In an era marked by increasing concern for the effects of climate change and demands for preventative measures, the need for an emission-neutral world is more pressing than ever. The building industry has long been a major culprit of greenhouse gas emissions. Buildings require large amounts of finite energy for optimal function and are costly to maintain. In the EU, buildings account for about 40% of the energy consumption [1]. It is also estimated that the world population increased to 8 billion in the beginning of 2024 [2]. This growing population and urbanisation will require more infrastructure to sustain the expansion of cities. As urbanisation increases, so does the energy consumption of buildings.

Considering the substantial energy demand of buildings, it is important to focus on enhancing their energy efficiency. In the EU, about 75% of all buildings constructed before 2000 have poor energy performance [1]. To address these issues, there are several processes within building design and operation that can be reviewed to optimise energy efficiency and expenses. One of these is to optimise windows in the building envelope. In a building, up to 25% of heat loss is through windows and other glazing units [3]. Therefore, improving the energy efficiency of windows could substantially contribute to improving a building's overall energy efficiency by reducing energy consumption and associated costs.

Furthermore, the importance of indoor comfort cannot be overstated. It is estimated that people spend an average of 90% of their time indoors [4]. The need for increasing the comfort in buildings is therefore crucial. Comfortable indoor environments promote physical health, mental health, and productivity. Spaces that are too hot, cold, noisy, poorly lit, ventilated or visually unappealing can lead to discomfort, fatigue, and health problems such as headaches, respiratory problems, and stress [5]. Accordingly, improving the comfort of indoor spaces also emerges as another key objective in building design.

The emergence of smart window technologies has paved the way for innovative solutions that maximise the energy efficiency and comfort of buildings. These technologies allow for dynamic control of light transmittance, enabling features such as visual and thermal comfort. Moreover, they can reduce the energy consumption from heating, cooling, ventilation, and artificial lighting. Many smart window technologies have been developed such as electrochromic (EC) smart windows, photochromic (PC) smart windows, suspended particle devices (SPD), reverse metal electrodeposition devices (RMED) and polymer-dispersed liquid crystals (PDLC) films. These technologies distinguish from each other by their unique structural and energy features and therefore have different application scenarios.

This bachelor's thesis will explore the application potential of PDLC films in smart windows through laboratory investigations on their solar radiation properties (transmittance and reflectance). In addition, the threshold working voltage of PDLC films has been determined. This thesis will contribute to the advancement of smart window technologies for energy efficient buildings.

## 1.1 Buildings in environment and society

We are entirely dependent on using energy today, especially in urban societies. At the same time, one of the concerns is the increasing energy consumption and the related environmental problems such as global warming. As the population grows, the need for infrastructure and buildings as shelters increases [6]. It is therefore essential to take more sustainable choices when designing and constructing energy efficient buildings. As most of the heat transfer occurs through the building envelope, it is necessary to focus on this area.

The building envelope is the physical barrier that separates the interior of a building from the external environment. This includes all the components of a buildings structure that envelopes the internal space, such as walls, doors, roofs, floors, and windows. The building envelope plays a crucial role in regulating the heat transfer, and the flow of air and moisture in and out of a building. This also protects the building against external elements such as wind, rain and temperature fluctuations [7]. In summary, the structure and design of the building envelope and its components have a significant impact on the building's energy efficiency, indoor comfort, and overall performance.

## 1.2 Windows in buildings

Windows make up a large portion of a building's exterior and, as such, have a paramount effect on the regulation of a building's aesthetics and energy efficiency. The primary function of windows is to provide natural daylight, fresh air, and interaction between the indoor and outdoor environment [8]. Traditional windows can cause severe heat loss in buildings mainly due to their poor thermal insulation performance. Therefore, a lot of energy is required to maintain a comfortable indoor temperature [9]. Additionally, the U-value of windows is significantly higher than other components of the building envelope [10]. The use of energy-efficient windows allows for improved insulation and controlled temperature indoors. Moreover, this reduces the costs of maintaining manual ventilation systems and artificial lighting throughout the day. With the EU's Energy Performance of Buildings Directive, it is important to consider advanced technology within the window sector that can contribute further to the EU's goal of a climate neutral society by 2050 [11].

When ultraviolet (UV) radiation reaches windows, they will either be transmitted, reflected, or absorbed. Factors such as wavelength, incident angle and solar radiation properties of the window will affect the amount of solar radiation transmitted, reflected, or absorbed [12]. UV radiation, in particular, can cause damage to materials with elevated exposure over time. These damages can manifest in the form of material degradation and discolouration, and damage to skin [13]. Given the need for more energy efficient buildings and potential damages caused by UV radiation, there is an incentive to seek technologies capable of mitigating these effects.

Solar radiation that reaches the earth has a typical wavelength ranging from 300 – 3300 nm. These wavelengths can be divided into ultraviolet (UV), visible (vis) and near infrared radiation (NIR) [12]. The UV spectra ranges from about 4 to 400 nm, visible light ranges from about 400 to 750 nm, and NIR radiation ranges from about 765 to 3200 nm [14]. Within the solar spectrum, 3-5% of the radiation is comprised of UV-light, 42-43% is visible light and 52-55% is NIR [15]. Understanding the types of solar radiation that reach the earth is an important element of window technologies that can effectively manage heat and light transmittance. Therefore, comparing window technologies will offer an insight into the strengths and limitations of products currently on the market in terms of energy efficiency.

## 1.3 Advanced window technologies

Currently, there are several advanced window technologies available on the market. Although they have varying compositions, they all serve to maintain consistent indoor temperatures and reduce the need for heating or cooling of buildings. Examples of advanced window technologies include multilayered windows, aerogel windows, vacuum windows and smart windows.

### 1.3.1 Multilayered windows

Multilayered windows consist of two or three glass panes separated by air or inert gases, typically krypton or argon, as shown in Figure 1. This composition serves to increase a window's insulation properties by creating barriers that reduce heat transfer [16].

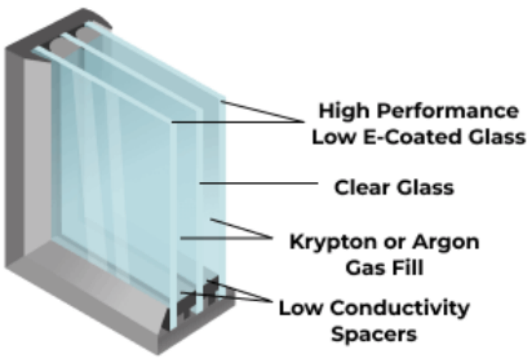



*Figure 1. Structure of triple-glazed window [17].*

## 1.3.2 Aerogel windows

Aerogel is a highly insulating material with a thermal conductivity of about 12-14 mW/(mK) [18]. They are incredibly lightweight nanostructured solids with an unusually low density, typically between 0,08-0,2 g/cm$^3$. They have a high porosity, that can be up to more than 90 % [19]. Between 90-99 % of the material consists of air [20], in mesopores, with diameters ranging from 4 to 20 nm. The combination of small pore sizes and low density is what gives aerogels the remarkable thermal insulation properties. Due to their small pore sizes, aerogels effectively limit the movement of gas molecules, reducing both conductive and convective heat transfer [19].

There are different types of aerogels, such as silica, carbon, metal oxides and organic aerogels [21] [19]. The most widely studied and commercially relevant are the silica ($SiO_2$) aerogels. Their thermal conductivity properties are determined by the conduction through the solid silica particle network at high densities, and a combination of radiation and gas-phase conduction [19]. To avoid water absorption and condensation in aerogel materials for thermal insulation applications, the aerogel material is often treated with a hydrophobic surface [22].

Aerogel windows or glazings are usually double-glazed windows where the space between the two glass panes is filled with granules of silica aerogels (see Figure 2). The thermal and solar radiation properties of aerogel windows are significantly determined by the thickness of the aerogel layer and the particle size [22]. According to research by Gao et al., if the aerogel layer thickness increases to 60 mm, a U-value of 0.3 W/(m$^2$K) can be achieved [22] [23]. It was also discovered that the visible transmittance of aerogel glazing units decreases along with the particle size of the aerogel granules [22]. Silica aerogel can be made into either transparent or translucent glazing units, based on if monolithic or granular aerogel materials are used (Figure 3). Due to the high cost and reduced strength of monolithic aerogel glazings, the most common aerogel glazings are based on granules. These aerogel glazings give high diffused lighting with reduced glare and improved sound and thermal insulating properties [24]. On the other hand, they do not provide a clear view to the outside [24]. Aerogel windows are a good option for energy-efficient windows, but they are still very expensive [21].

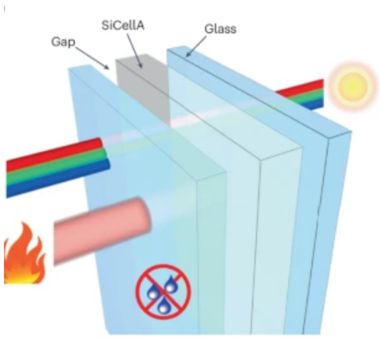



*Figure 2. Aerogel window [25].*

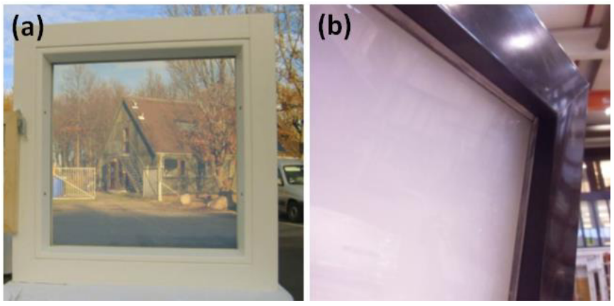



*Figure 3. Transparent (a) and translucent (b) aerogel glazings/windows [24]*

### 1.3.3 Vacuum windows

Vacuum windows, unlike traditional multilayered panes, have a vacuum-sealed gap between each glass layer, hence eliminating the convective and conductive heat transfer in gases [26]. Normally the vacuum windows consist of two glass panes separated by small pillars, but some vacuum windows can have several glasses. The edges of the glass surfaces are sealed, and the enclosure is emptied of any air or gas, creating vacuum (Figure 4) [15]. This results in low pressure between the panes which reduces the heat transfer through windows [26]. This feature of enhanced thermal insulation also makes them an ideal alternative to traditional windows. Additionally, the glass surfaces facing the enclosure are often low-emission coated, this contributes to minimizing thermal radiation. Vacuum windows may have some disadvantages as the edges can create a thermal bridge which increases their U-values [22]. Also, the vacuum windows have a higher price than the traditional double glazings, and lower impact resistance due to the micro spacers [27].

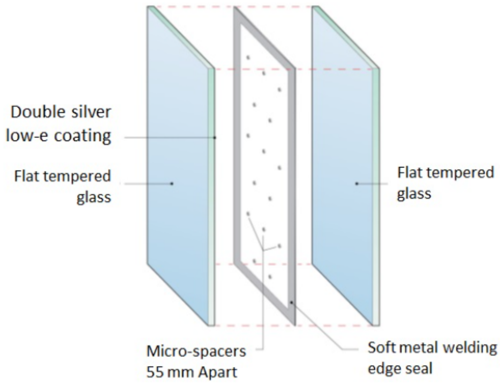



*Figure 4. Structure of a vacuum window with low-e coating [28].*

# 2 Smart windows

Smart windows are one of the most up and coming advanced window technologies. Smart windows regulate properties such as transmittance and reflectance to control the degree with which solar radiation filters through glass surfaces. They act to increase a building's energy-efficiency by reducing the amount of heat entering through windows from solar radiation. Transmittance and reflectance properties can be controlled through factors such as heat, light, or voltage amongst others [29].

Smart windows can be categorized into adaptive and controllable smart windows, depending on how the smart window dynamically changes its tinting/colouration and transmittance level, either adaptively according to the surroundings (e.g. temperature or solar radiation) or controllable by the user (e.g. by an applied voltage) [30]. Controllable smart windows can be classified into four types: suspended particle (SP), liquid crystal (LC), electrochromic (EC) and gasochromic (GC) windows. SP, LC and EC are activated by an applied voltage, while GC is activated by gases such as hydrogen [31]. Adaptive smart windows include thermochromic and photochromic windows [32]. Chapter 2.1-2.5 discusses and compares the properties of each of these smart window technologies.

## 2.1 Suspended particle devices

Suspended particle device (SPD) windows are comprised of a polymer layer of light absorbing particles coated in conductive material and inserted between two mediums of glass or acrylic [33]. The SPDs consist of light absorbing particles, usually titanium dioxide, and are dispersed within the SPD layer. The composition of SPD is illustrated in Figure 5. When there is no current applied, particles are arranged freely which leaves the glass tinted and prevents light from passing through. Once an electric current is applied, the particles will align causing the window to become more transparent as light gets through more easily [30]. This allows for control of light transmittance through windows by varying the applied voltage. The operation voltage depends on the thickness but is typically between 65-110 V [30]. The switching time is typically 1-3 seconds [30].

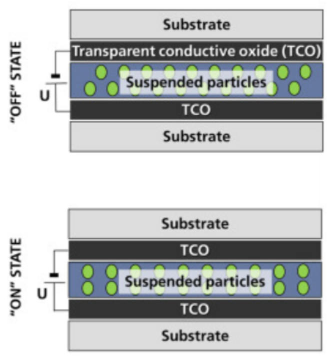



*Figure 5. Schematic of a SPD [34].*

## 2.2 Liquid crystals

Liquid crystals (LC) are substance that possess properties and structures that fall between those of conventional liquids and solid crystals [35]. LCs are organic substances (with few exceptions) with molecules that are arranged in an ordered manner like in crystals, but they can also flow like a liquid. This unique state is due to the orientation of the molecules [35] [36]. The molecules in liquid crystals typically have a long, rod-like or disc-like shape, which allows them to align themselves in a particular direction, giving rise to changes in their solar radiation properties such as transmittance and reflectance.

Depending on the alignment of the molecules, liquid crystals can exhibit in three different phases: nematic, smectic, and cholesteric [36]. In the nematic phase, the molecules are aligned in the same direction but without positional order. Due to their polarity, the direction of the molecules can be controlled by applying electricity. While in the smectic phase, the molecules are parallel but stacked in random positions within layers. These layers have long molecular axes nearly perpendicular to the flat planes they create. The primary order within these layers runs along the axis, allowing layers to slide over each other. In the cholesteric phase the molecules have a twisted structure (Figure 6) [37].

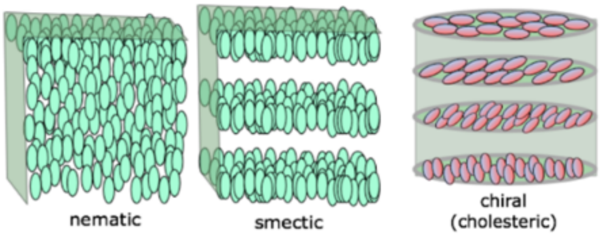



*Figure 6. The different phases of LC [28].*

Polymer-dispersed liquid crystals (PDLC) is one of many forms of liquid crystals. PDLC are made from mixtures of low-molecular-mass nematic liquid crystals. This mixture is in the form of microdroplets from 0.5 to 1 $\mu$m, dispersed in polymer films (e.g. poly(vinyl alcohol), poly(vinyl acetate), and acrylic copolymers). The mixture dispersed in polymer films is then put between two conducting glasses or polymer films typically of indium tin oxide (ITO) (Figure 7) [38]. When the PDLC film is in its original state, the liquid crystals are randomly arranged, leaving the film translucent. When a voltage is applied, the LC molecules align and the film becomes transparent (Figure 8) [38]. The typical voltage required to control the behaviour of the PDLC device is between 10-80 V, and the switching time can be 1 ms or less [38]. The PDLC films can be used for several applications such as displays, privacy control in meeting rooms, showers, and windows [38].

By using PDLC in windows and other glazings, one can dynamically control the solar radiation and shading. PDLC windows have the possibility to enhance the buildings energy efficiency by adapting to different climate conditions and improving the thermal and visual comfort for the occupants. When the PDLC is introduced to an alternating electric current the window changes its transmittance from translucent to transparent. This change can also occur gradually by using different voltages. When in an off state, PDLC film has been recorded blocking up to 98 % of UV radiation. To reduce the energy consumption even more using a smart PDLC window, it can also be combined with a light sensor to detect the sun movement and gradually adjust the transmittance [39].

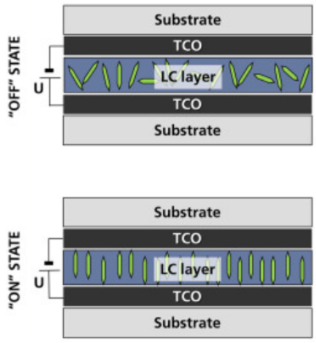



*Figure 7. Schematic of an PDLC device [34].*

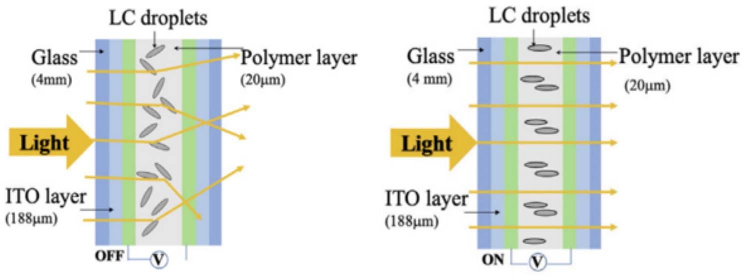



*Figure 8. The alignment of the PDLC particles when power is OFF (left) compared to when power is ON (right) [38].*

## 2.3 Chromogenic materials

Chromogenic materials are substances that change colour or transparency in response to certain stimuli such as light, temperature, pH, mechanical pressure, voltage, or the presence of specific chemicals. These materials are designed to exhibit reversible or irreversible colour changes, making them useful in various applications such as sensors, indicators, displays and smart windows [40].

### 2.3.1 Electrochromic

Electrochromic (EC) materials are substances that change colour and transparency in response to an applied electric voltage. The main materials in electrochromic devices are metal oxides of transition, commonly $WO_3$, $MoO_3$, $IrO_2$, NiO, and $V_2O_5$, or organic materials such as polyaniline (PANI) and Prussian blue [41]. The switching time depends on the size of the window [42]. Typical switching time is between 5-12 minutes, and the voltage needed is about 1-5 V [30] [43].

The components of an EC device usually include five functional layers (Figure 9). The innermost layer consists of electrolytes that provide the ions necessary for the electrochemical oxidation and reduction of the electrochromic material, and redox-active layer. The electrolyte layer can for example be polyethylene oxide (PEO) saturated with lithium chlorate. The redox-active layer often consists of a conductive polymer (e.g. $Li_xV_2O_5$) and supports the electrochemical reactions and works as an ion-storage layer [44]. On one side of the electrolytes is an electrochromic layer and on the other side is a redox-active material. Lastly, the outer layer consists of transparent electrodes on either side of the electrochromic layer that applies a voltage. This layer is typically made of transparent conductive materials such as ITO.

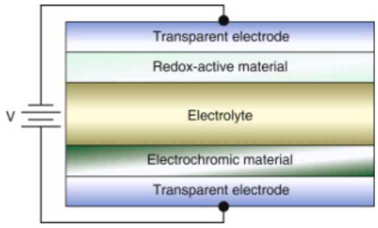



*Figure 9. Illustration of an electrochromic device [44].*

Electrochromic windows can help regulate the indoor temperature in buildings by reducing solar heat gain during hot weather and allowing more natural light to enter during colder weather. By dynamically adjusting the transmittance of the windows, buildings can reduce the need for heating, cooling and artificial lighting, and therefore improve the energy efficiency.

### 2.3.2 Thermochromic

Thermochromic (TC) materials are substances that change colour and optical properties in response to changes in temperature. TC materials are used in various applications including temperature indicators, textiles, colour-changing coatings and inks, thermal indicators for food packaging, and films. The mechanism behind thermochromism involves changes in the molecular structure or arrangement of the material at a certain critical temperature [45]. The most common TC material is vanadium dioxide ($VO_2$). What determines the colour can often be a cyclic ester. TC materials are often used in coatings used on the building envelope, and particularly on roofs. In summer at higher temperatures, the colour becomes brighter to reduce the need for cooling down the building. In the winter, the colour of the coating becomes darker as the temperature drops, which increases the heat absorption and reduces the heat load [46]. TC materials are also used in films for glazings (Figure 10). In this way TC materials can contribute to both saving energy and increasing the visual and thermal comfort in buildings [47].

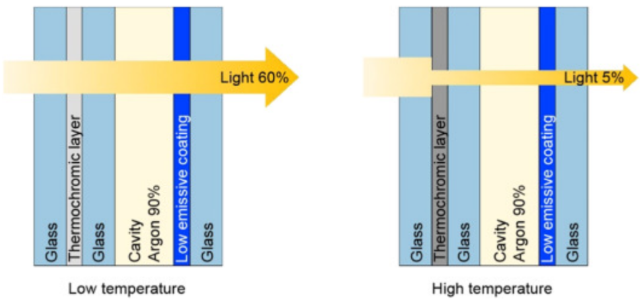



*Figure 10. Schematic of a thermochromic window [47].*

### 2.3.3 Photochromic

Photochromic (PC) materials are substances that change colour and optical properties when exposed to light. They have a special property where they can switch between two different states when exposed to light. This change can be reversible, meaning they can switch back and forth between two different states [48]. A visualisation of photochromic film on a window is shown in Figure 11. Photochromic materials can be both organic and inorganic, but the most studied are organic photochromic materials [49]. The mechanism behind photochromic materials typically involves the photoexcitation of the molecules from their ground state to an excited state upon absorption of light. One of the most used and investigated photochromic compounds is dithienylethene derivates. In this case, the mechanism involves a reversible photocyclisation reaction between an unconjugated open-ring isomer and a conjugated closed-ring isomer. This reaction is initiated by UV light and reversed by visible light [50].

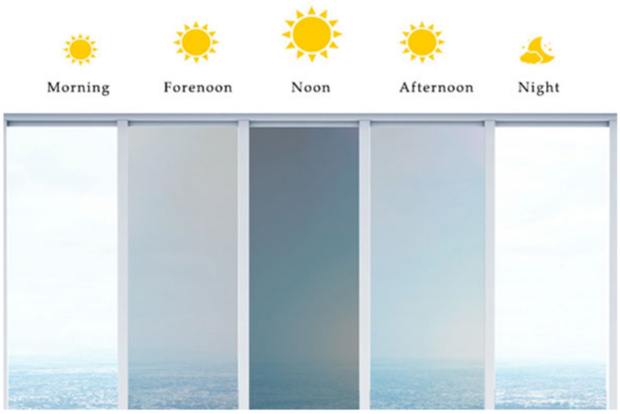



*Figure 11. Visualisation of window with photochromic film during a day [51].*

### 2.3.4 Gasochromic

In a gasochromic (GC) glazing, the GC material is usually placed between two glass panes with a cavity. Gasochromic glazing is made with a thin layer of GC material covered by a thin layer of catalyst on the inside of the external glass pane, a cavity filled with gas and an uncoated internal glass pane (Figure 12). The most used GC material is $WO_3$, but the gasochromic effect can also be seen from other materials such as $MoO_3$ and $V_2O_5$. The most used and investigated catalysts are platinum (Pt) or palladium (Pd). The gas used in GC glazing is usually hydrogen gas ($H_2$). The colour change to this film is achieved by pumping diluted $H_2$ into the window [31]. When $WO_3$ is exposed to the gas, the $WO_3$ will reduce, resulting in the colour turning blue. This process is reversed by exposing the film to diluted oxygen, then it will go back to a transparent state [52]. The switching speed from an opaque to transparent state depends on the concentration of the catalyst but is usually between 1-10 min [31].

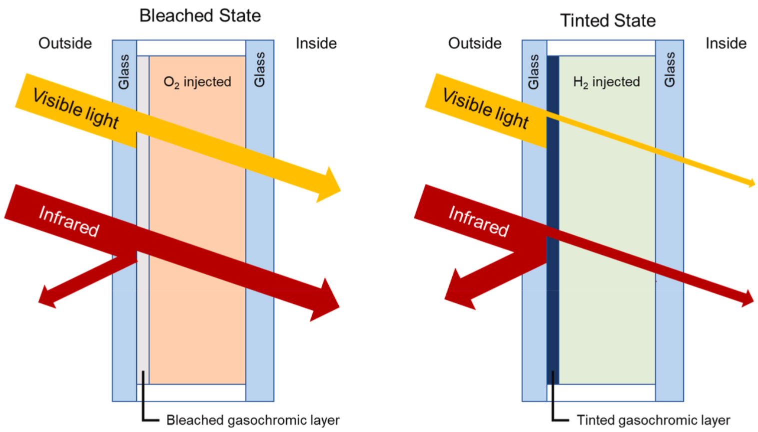



*Figure 12. Schematic of a Gasochromic double glazed window [53].*

## 2.4 Reversible metal electrodeposition devices

Reversible metal electrodeposition devices (RMED) enable a controlled deposition and dissolution of metal layers on electrode surfaces in a reversible manner. RMED is an electrochromic application that utilises the appearance and disappearance of a metal layer to control the spectrum of light passing through [54].

Unlike other electrochromic devices, RMEDs do not require an electrochromic layer to induce colour change. When a negative voltage is applied to the working electrode, metal ions in the electrolyte gain electrons on the electrode surface and are reduced to metal atoms. Simultaneously, reductive ions from the supporting redox couple lose electrons at the counter electrode, causing oxidation. This deposition process leads to the formation of metal nuclei that grow larger and connect with continuous voltage. This results in different colour states based on the composition of the deposited metal layer. The composition of an RMED is illustrated in Figure 13.

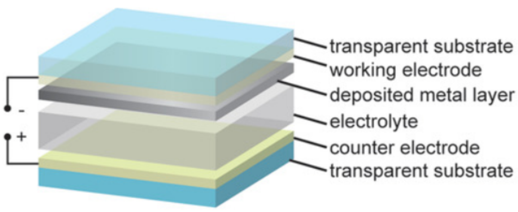



*Figure 13. Schematic of an RMED [54].*

To achieve reversible electrodeposition, the electrolyte must contain stable reductive substances that do not self-decompose upon oxidation. Suitable electrolytes can be fluoborite, thiosulphate, rhodanide and iodide complexes. These are often combined with host polymers to get a gel-like electrolyte. The switching speed for RMEDs is very dependent on the size of the RMED surface. In a study by Tao et al., the switching speed of a 1 $cm^2$ surface was 10 s, while for a 225 $cm^2$ surface the switching speed was 180 s [54].

The durability of the RMED is limited. When the solvent in RMEDs evaporates over time, solvent interferes with the flow of ions in the electrolytes, making it difficult for them to reach the electrodes. As a result, the necessary chemical reactions at the electrode surface cannot occur effectively. Additionally, issues like electrode failure, electrolyte decomposition, and unintended side reactions also play a role in limiting the device's lifespan [54].

## 2.5 Comparison of smart window technologies

Each smart window technology has unique advantages and limitations that cater to different application requirements. In Table 1, a comparison of each smart window technologies' properties are shown.

*Table 1. Comparison of properties of smart window technologies*

| | SPD | PDLC | RMED | EC | TC | PC | GC | Reference |
|---|---|---|---|---|---|---|---|---|
| **Adaptive or controllable** | Controllable | Controllable | Controllable | Controllable | Adaptive | Adaptive | Controllable | |
| **Activation type** | Electric field (10-150 V) | Electric field (10-80 V) | Electric field (0-2 V) | Electric field (1-5 V) | Temperature | Light | Gas exposure | |
| **Basis for the optical change** | Alignment of the suspended particles | Change in orientation of liquid crystal molecules | Deposition of suspended metal particles in the form of thin film on the transparent electrode | Oxidation and reduction | Structural phase change at a critical temperature depending on the substance. | Charge transfer between two electronic sites under the action of light | Metalinsualtor transition upon exposure to a gas | [49] |
| **Switching** | Fast* | Fast | Medium** | Slow*** | Slow | Slow | Slow | |

*: Fast, 0-10 s
**: Medium, 1-5 min
***: Slow, > 5 min

Smart windows are divided into adaptive or controllable windows based on if the user actively can control the transmittance by changing the tinting level of the window or not. Table 1 shows which windows are adaptive or controllable, and the activation type for the different smart window technologies. Activation type refers to the type of stimuli that activates the change in transmittance. Both SPD, PDLC, RMED and EC are activated by an electric field, while TC, PC and GC are activated by temperature, light and gas exposure. The switching speed is very variable for the different technologies and depends on the surface size for some materials.

Both SPD and PDLC have relatively fast switching speeds. RMED is categorised as having medium switching speed as this can take up to 3 minutes but is very dependent on the surface size. However, for smaller samples the switching speed can be as fast as 10 seconds [54]. Smart windows with slow switching speeds include EC, TC, PC and GC. For EC and GC the switching speed can take up to 10-12 minutes. TC and PC are adaptive smart window technologies. This means they are dependent on exposure to temperature and light to change their tinting level. The switching speed is therefore also dependent on how much temperature and light they are exposed to.

PDLC is a controllable smart window technology that can easily be controlled by an electric field and has the fastest switching speed among these smart window technologies. The PDLC have a high potential in contributing to increasing the energy efficiency and thermal and visual comfort of buildings. This thesis will dive further into the investigation of PDLC's properties, advantages, and disadvantages.

# 3 Experimental

## 3.1 Materials

The investigation measured transmittance and reflectance PDLC films provided by Fågg AS. Glass was also used as a reference to compare the results to. These materials will be discussed further.

### 3.1.1 PDLC films from Fågg AS

Fågg AS has supplied PDLC films for this study. Currently, these products are mostly being used as privacy screening in office environments, to either seclude workspaces or prevent insight to meeting rooms, by attaching the PDLC films to existing glass surfaces. The PDLC films can also be used as displays on store windows or as whiteboards [55]. Their most notable application that will be tested in this investigation is their ability to be used for shading from solar radiation. Fågg AS currently uses 48 V and 60 V for optimal transparency control. When a voltage of 48 V or 60 V is applied to the PDLC films, their optical properties change from a translucent to a transparent state. This will be investigated further in this experiment.

A larger PDLC film sample (about an A4 size, 21 cm x 30 cm) from Fågg AS was cut into smaller samples of about 5 cm x 5 cm. Connection was made by attaching metal strips to the ITO layers, as shown in Figure 14. The wires were then attached to the AC-supply to measure the transmittance and reflectance. Thus, the PDLC's optical and solar radiation properties could then be studied at different applied voltages.

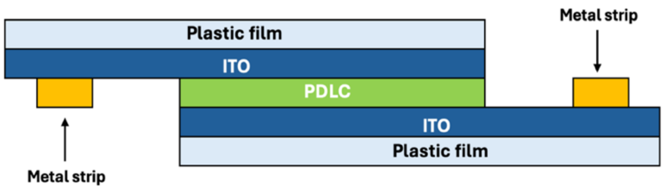



*Figure 14. An illustration of how the PDLC sample is attached to the metal strips.*

### 3.1.2 Glass

Clear glass substrate (75 mm x 25 mm x 1.0 mm) was used as a reference in this study. Glass will provide a reference value to compare to, particularly when measuring total transmittance and reflectance. Transmittance and reflectance measurements were conducted on glass alone and as glass attached to the PDLC samples.

## 3.2 Characterisation

### 3.2.1 General

This chapter will first discuss the apparatuses and equipment used in the experiments then present the method and intended measurements.

### 3.2.2 Apparatuses

The following apparatuses were used in the laboratory investigations:

- Perkin Elmer® Lambda 1050 UV/VIS/NIR spectrophotometer
- 10 V AC-supply (Hewlett-Packard 3310A function generator)
- 20 V AC-supply (Mascot power supply, type 8930)
- 48 V and 60 V AC-supply (H30, provided by Fågg AS)
- 150 mm integrated sphere (IS) accessory
- Three-detector model (3D) accessory
- Universal reflectance accessory (URA)
- Multimetre

Measurements of transmittance and reflectance of PDLC and PDLC on glass were carried out using a Perkin Elmer® Lambda 1050 UV/VIS/NIR spectrophotometer. Data from the instrument was collected and stored using the PerkinElmer UV WinLab software. The measuring chamber of the spectrophotometer was swapped out with various accessories to measure total, diffuse and specular (direct) transmittance and reflectance. A 150 mm integrating sphere accessory was used to measure total and diffuse transmittance and reflectance between 280-2500 nm. A three-detector model (standard detector system) was used to measure specular transmittance between 280-3300 nm. A universal reflectance accessory (URA) was applied to measure specular reflectance between 280-2500 nm.

Total, diffuse and specular transmittance and reflectance were measured to study the solar radiation properties of the PDLC samples. The samples' solar radiation properties were tested at 0, 10, 20, 48 and 60 V. As an AC-supply that could measure voltages from 0 to 60 V was not available, three separate AC-supplies were used (see list of apparatuses). The 48 V and 60 V were chosen as these are the voltages the company currently operates with for the transparent state. In addition to 0 V, by also testing 10 and 20 V, one can determine an approximate range within which the PDLC becomes translucent and transparent. In this experiment, total and diffuse transmittance and reflectance were measured with wavelengths from 280 nm to 2500 nm. Specular transmittance and reflectance were measured from wavelengths of 280 nm to 3300 nm. Figure 15 illustrates the translucent state of the PDLC sample at 0 V (left) and the transparent state at 60 V (right).

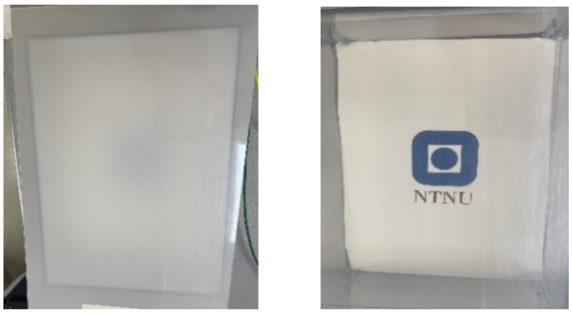



*Figure 15. Comparison of PDLC sample at 0 V (left) and 60 V (right).*

### 3.2.3 Measurements

**Electrical power performance of PDLC**

Using an AC supply, the voltage and current of each sample size was measured. Using this, the average power was then calculated. The sizes, power and average energy consumption is shown in Table 2. Although the sample sizes vary, they have similar energy requirements and an average energy consumption of about 0.076 mW/cm$^2$ can be obtained for the PDLC films from Fågg AS.

*Table 2. Energy requirement for different sizes of PDLC*

| Sample no. | Area (cm$^2$) | Power (mW) | Energy consumption (mW/cm$^2$) |
|---|---|---|---|
| 1 | 613.2 | 54.4 | 0.089 |
| 2 | 386.0 | 26.9 | 0.070 |
| 3 | 27.5 | 1.9 | 0.070 |
| Average energy consumption (mW/cm$^2$) | | | 0.076 |

**Switching speed**

The switching speed of PDLC at 60 V was measured in 30 second intervals using a multimetre to provide insight into how rapidly the PDLC can change from a translucent to transparent state (Figure 16). It is worth mentioning that the switching was conducted manually which is why the intervals are not exactly 30 s. However, it can be observed that when switching the PDLC on with 60 V, there is a sudden increase in transmittance from about 58% to 81%. When the PDLC is switched off, it takes about 2 seconds longer for the transmittance to decrease before the transmittance remains at 58%.

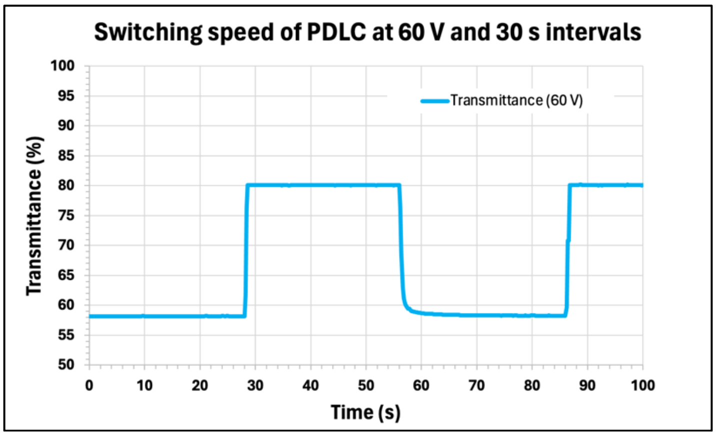



*Figure 16. Switching speed of PDLC at 60 V and 30 s intervals.*

## Overview of measurements

In tables 3 – 5, an overview of all the measurements that were conducted in this investigation is shown. Abbreviations in the table are as follows: total transmittance (TT), diffuse transmittance (DT), total reflectance (TR), diffuse reflectance (DR), specular transmittance (ST) and specular reflectance (SR).

*Table 3. Overview of all measurements conducted with the integrated sphere (IS).*

| | **Integrated sphere** | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0 V** | | | | **10 V** | | | | **20 V** | | | | **48 V** | | | | **60 V** | | | |
| | TT | DT | TR | DR | TT | DT | TR | DR | TT | DT | TR | DR | TT | DT | TR | DR | TT | DT | TR | DR |
| **PDLC** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **PDLC/glass** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Glass** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

*Table 4. Overview of all measurements conducted with the 3D (three-detector model) instrument.*

| | **3D** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0 V** | | | **10 V** | | | **20 V** | | | **48 V** | | | **60 V** | | |
| | TT | DT | ST | TT | DT | ST | TT | DT | ST | TT | DT | ST | TT | DT | ST |
| **PDLC** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |
| **PDLC/glass** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |
| **Glass** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |

*Table 5. Overview of all the measurements conducted with the (URA) universal reflectance accessory.*

| | **URA** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0 V** | | | **10 V** | | | **20 V** | | | **48 V** | | | **60 V** | | |
| | TR | DR | SR | TR | DR | SR | TR | DR | SR | TR | DR | SR | TR | DR | SR |
| **PDLC** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |
| **PDLC/glass** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |
| **Glass** | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ | × | × | ✓ |

# 4 Results and discussion

This chapter will first present the results of transmittance and reflectance of the PDLC sample. Results will be followed with a discussion of voltages with highest total and diffuse transmittance or reflectance, comparisons with total transmittance and reflectance, and any anomalies.

## 4.1 Transmittance

Total, diffuse and direct transmittance of PDLC and PDLC on glass was measured at 0 V, 10 V, 20 V, 48 V and 60 V. Total, diffuse and direct transmittance of glass on its own was also measured to use as a reference.

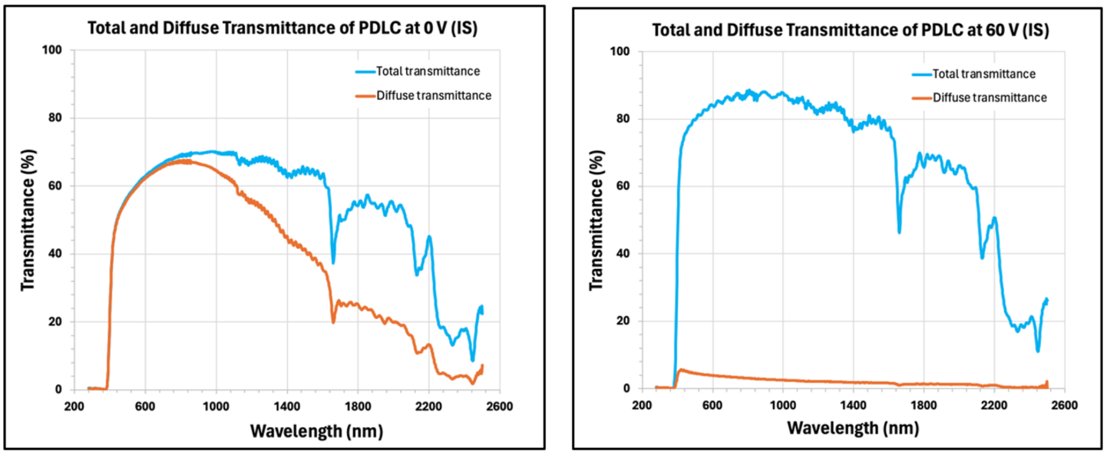



*Figure 17. Comparison of total and diffuse transmittance of PDLC at 0 V (left) and 60 V (right).*

Results show that the total transmittance of PDLC at 0 V reached highest total transmittance of approximately 70% total transmittance at about 900 nm (Figure 17 left). Diffuse transmittance at 0 V was highest at about 67% at 800 nm (Figure 17 left). At 60 V, the highest total transmittance was approximately 88% transmittance at about 900 nm (Figure 17 right). Diffuse transmittance at 60 V was highest at about 5% at 430 nm (Figure 17 right).

At 0 V, the PDLC sample is translucent, and the liquid crystals are arranged such that less light transmits directly through the sample (see, for example, Figure 8). Therefore, both total and diffuse transmittance have similar trends from 280-2500 nm. However, there is still absorption of light which causes a lower transmittance compared to more transparent materials such as glass, as seen in Figure 18.

At 60 V, there is a significant difference in total and diffuse transmittance (Figure 17 right). At this voltage, the PDLC is in a transparent state whereby the LC molecules are aligned to allow the light to transmit through the sample. Due to this transparent state, diffuse transmittance is naturally much lower as there is less scattering of light.

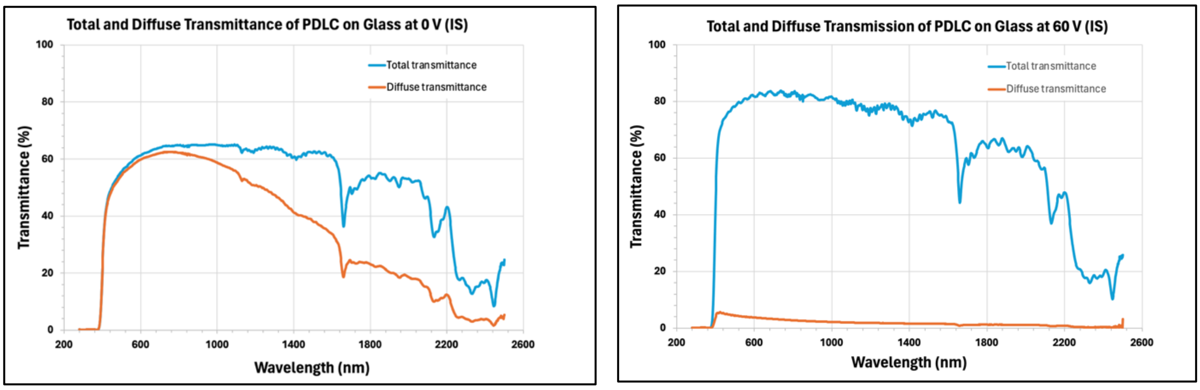



*Figure 18. Comparison of total and diffuse transmittance of PDLC on glass at 0 V (left) and 60 V (right).*

The addition of glass to the PDLC sample should reduce the transmittance to some degree. This is shown in Figure 18, where the highest total transmittance reached for PDLC on glass was approximately 65% at about 900 nm. This constitutes a difference of 5% from just PDLC at 0 V (as shown in Figure 17). The similar results of diffuse and total transmittance of PDLC with and without glass indicate that the addition of glass affects only the intensity of the transmittance. The addition of an extra layer to the PDLC will affect how much light reaches the PDLC layer without being absorbed or reflected by the glass layer. This effect is seen across all measurements of transmittance.

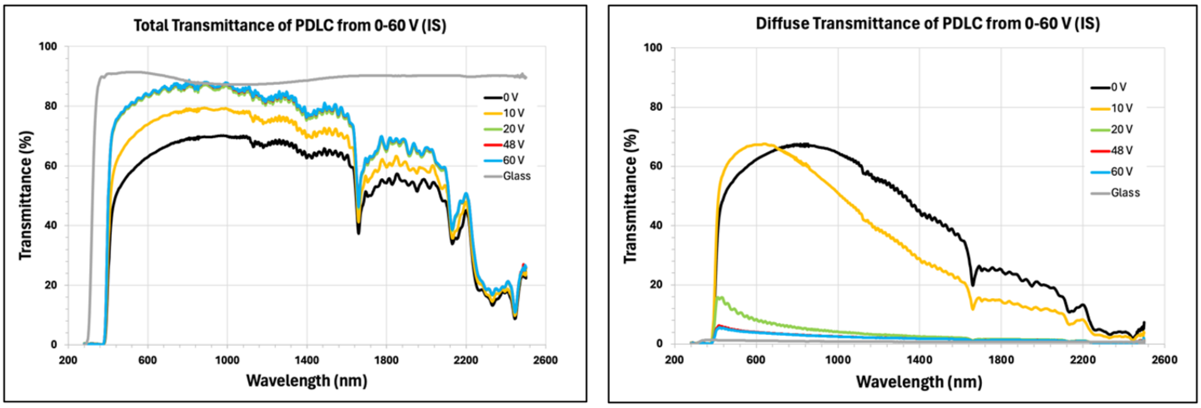



*Figure 19. Comparison of total transmittance (a) and diffuse transmittance of (b) of PDLC from 0 – 60 V.*

Results of total transmittance of PDLC from 0-60 V show uniform trends across all voltages (Figure 19). There is an increase in total transmittance as the voltage increases from 0 to 60 V (Figure 19 left). This is due to the LCs aligning more as the voltage increases. This is also seen for diffuse transmittance of PDLC whereby the diffuse transmittance decreases as the voltage increases (Figure 19 right). Between 1600 and 2500 nm, there is a lot of absorption in transmittance. Around 1650 nm, there is a strong absorption in transmittance from approximately 52% to 37%. Measurements of the plastic layer of the PDLC film show that these absorptions are likely caused by the plastic in the NIR spectrum (see Figure 22).

Another significant change in total transmittance appears around 400 nm, when the transmittance increases from 0% to over 50% transmittance across all voltages. This change occurs between 280-400 nm. Results for diffuse transmittance show a general decrease in transmittance from about 865-2500 nm. Lastly, although PDLC achieves a high transmittance of 88% at 60 V, it is not able to become as transparent as glass which has a transmittance of about 92%.

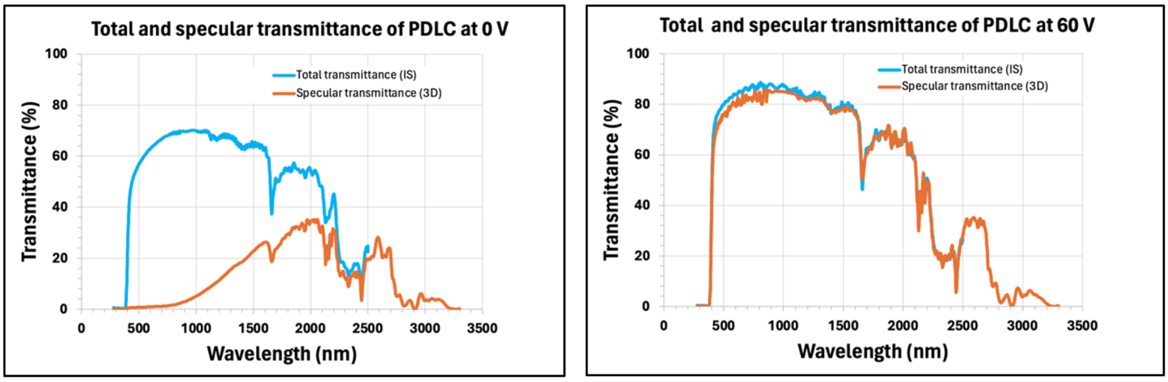



*Figure 20. Total transmittance of PDLC using the integrated sphere (IS) and the three-detector model (3D) at 0 V (left) and 60 V (right).*

Figure 20 shows a comparison of total transmittance (IS) and specular transmittance (3D) of PDLC at 0 V (left) and 60 V (right). The results for total and specular transmittance of PDLC at 0 V show that specular transmittance makes up a smaller portion of the total transmittance (Figure 20 left). However, at 60 V, the results show that specular transmittance accounts for most of the total transmittance (Figure 20 right).

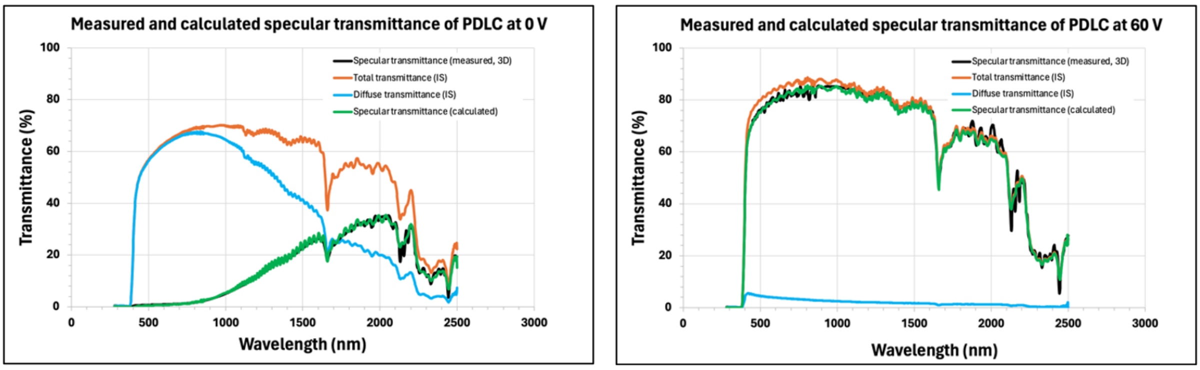



*Figure 21. Measured and calculated specular transmittance of PDLC at 0 V (left) and 60 V (right).*

To find the specular transmittance of PDLC and PDLC on glass, the diffuse transmittance was subtracted from the total transmittance as shown in equation 1. This was then compared to the measurements of specular transmittance from the URA accessory.

$$Specular\ transmission = total\ transmission - diffuse\ transmission \qquad (1)$$

Results show that specular transmittance measured at 0 V with the 3D instrument is very similar to the calculated specular transmittance from 280-2500 nm (Figure 21 left).

Specular transmittance at 60 V was also very similar between the measured and calculated specular transmittance (Figure 21 right).

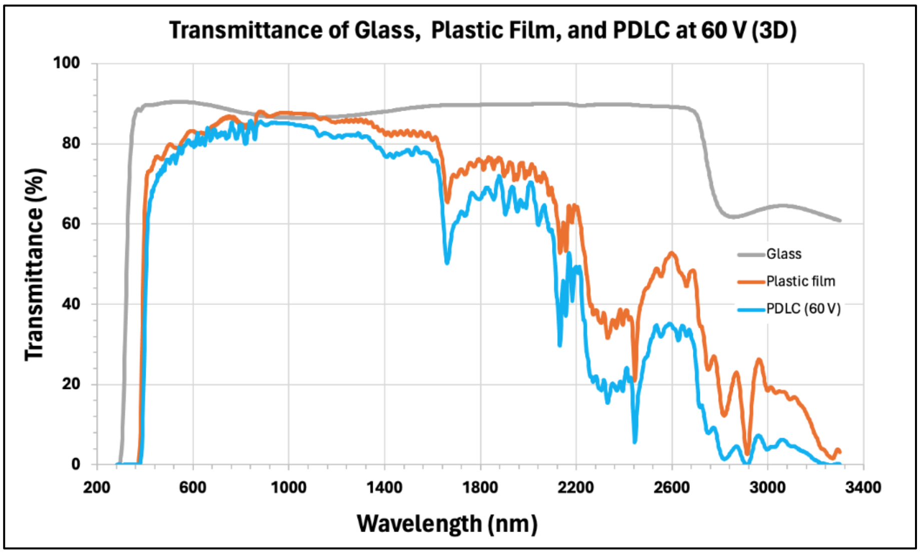
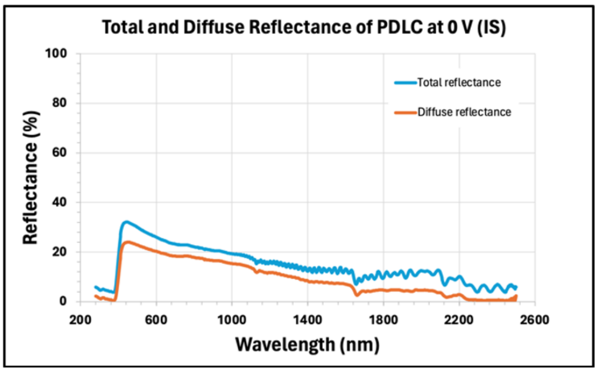



*Figure 22. Comparison of transmittance from glass, plastic film and PDLC at 0 V.*

Measurements of transmittance of only the plastic film indicates that the fluctuations in transmittance between 3300 or 2500 nm to 280 nm for PDLC are due to the plastic substrate (Figure 22).

## 4.2 Reflectance

Total, diffuse and specular (direct) reflectance of PDLC was measured at 0 V, 10 V, 20 V, 48 V and 60 V. A 150mm integrated sphere (IS) was used to measure total and diffuse transmittance whilst a universal reflectance accessory (URA) was used to measure specular reflectance. Total, diffuse and specular reflectance of glass on its own was also measured to use as a reference.



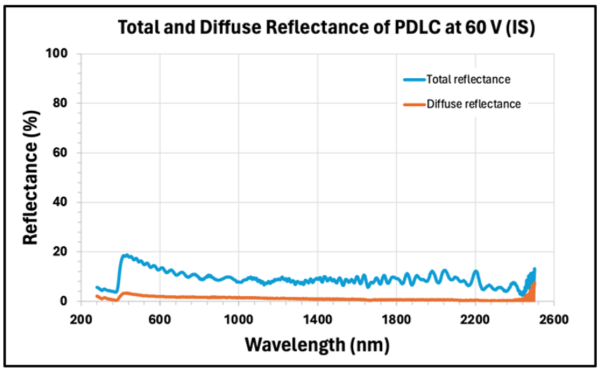




*Figure 23. Comparison of total and diffuse reflectance of PDLC at 0 V (left) and 60 V (right).*

Results show that total reflectance of PDLC reached highest total reflectance of about 32% at approximately 450 nm and at 0 V (Figure 23 left). Diffuse reflectance at 0 V was highest around 450 nm with a reflectance of 24% (Figure 23 left). At 60 V, both total and diffuse reflectance decreased. Total reflectance at 60 V reached a reflectance of about 18% at approximately 450 nm (Figure 23 right). Diffuse reflectance at 60 V reached peak reflectance at 3% at 450 nm.

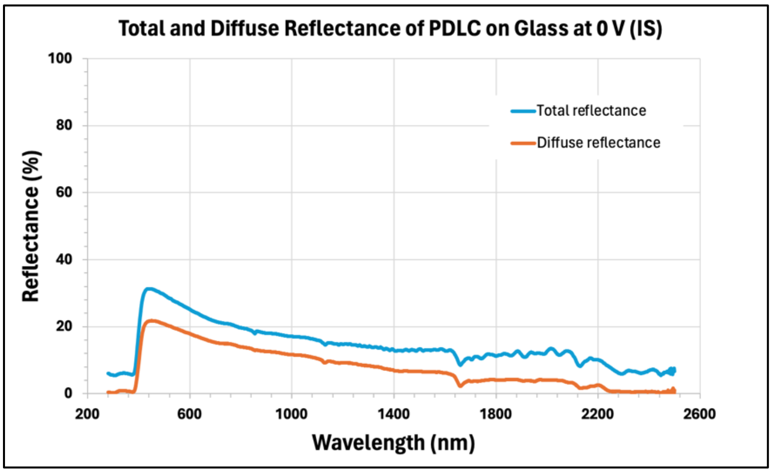



*Figure 24. Comparison of total and diffuse reflectance of PDLC on glass at 0 V (left) and 60 V (right).*

Figure 24 shows results for total and diffuse reflectance of PDLC on glass at 0 V. Total reflectance was highest at about 450 nm with a reflectance value of approximately 31%. Diffuse reflectance was highest at about 450 nm with a reflectance of around 22%. The values of diffuse reflectance show a significant portion of scattered light across the visible spectrum. Compared to only PDLC at 0 V (Figure 23), there is an approximately 1% difference in reflectance. This could be due to the additional layer of glass between the spectral beam and PDLC that will reflect some rays before they reach the PDLC layer. However, such a low difference in reflectance is likely due to an experimental error or uncertainty of the instruments.

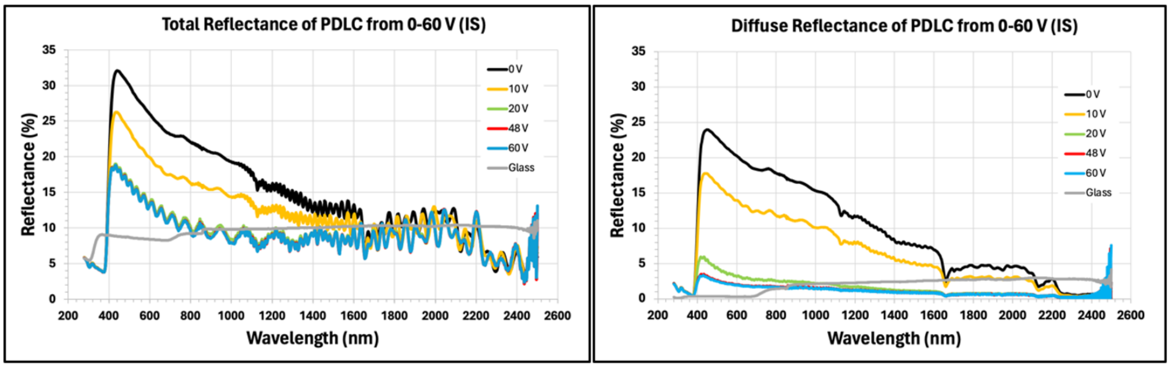



*Figure 25. Total reflectance (left) and diffuse reflectance (right) of PDLC from 0 to 60 V.*

In Figure 25, total and diffuse reflectance of PDLC from 0-60 V is shown with glass as a reference. Both total and diffuse graphs show a decrease in reflectance as the voltage increases. The reflectance varies much more between 0 V and 20 V whilst reflectance from 20-60 V is very similar. The decrease in reflectance with increased voltage can be attributed to the change in the refractive properties of LCs and polymer matrix. At lower voltages (0-20 V), the LC molecules are in a disordered state resulting in light scattering and leading to higher reflectance. Increasing the voltage beyond 20 V causes the molecules to realign. As a result, the reflectance decreases as the LC molecules align more uniformly. The similarity in reflectance values between 20 V and

60 V indicates that the realignment of the LC crystals reaches a stable state beyond 20 V.

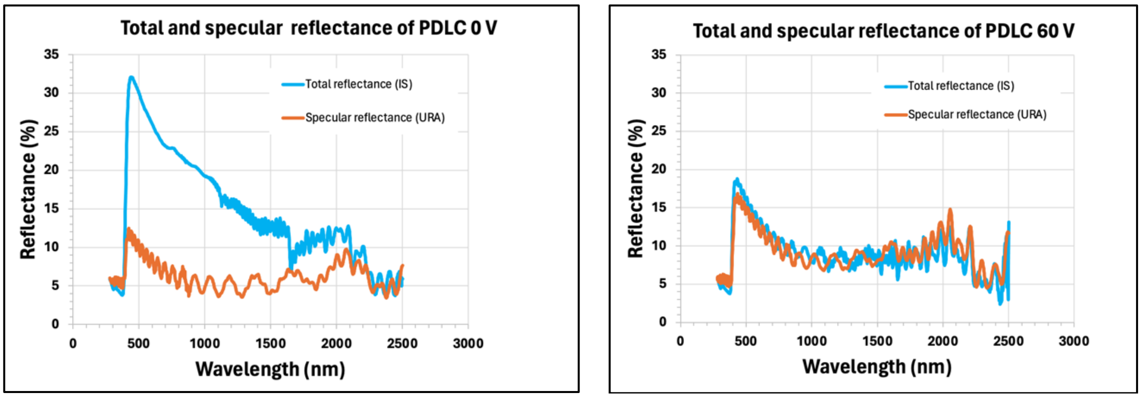



*Figure 26. Total and specular reflectance of PDLC at 0 V (left) and 60 V (right) measured with the integrated sphere (IS) and universal reflectance accessory (URA) respectively.*

In Figure 26, a comparison of total reflectance (IS) and specular reflectance (URA) of PDLC at 0 V (left) and 60 V (right) is presented. Results for total and specular reflectance of PDLC at 0 V show that specular reflectance accounts for a smaller portion of the total reflectance, particularly between about 400 to 1600 nm (Figure 26 left). At 60 V, the specular reflectance of PDLC accounts for a majority of the total reflectance (Figure 26 right).

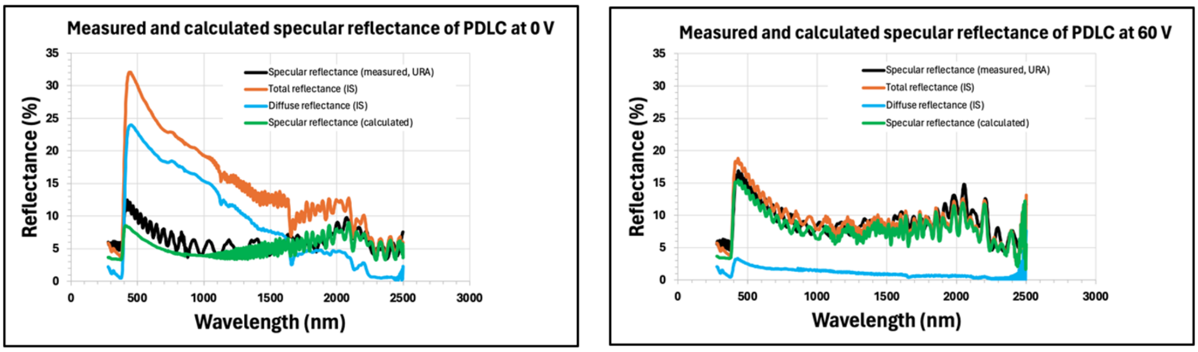



*Figure 27. Comparison of measured and calculated specular reflectance of PDLC at 0 V (left) and 60 V (right).*

Specular reflectance was calculated by subtracting diffuse reflectance from total reflectance (equation 2).

$$Specular\ reflectance = total\ reflectance - diffuse\ reflectance \qquad (2)$$

Figure 27 (left) shows that at 0 V, both measured and calculated specular reflectance are similar between 280 and 2500 nm. Likewise, at 60 V, the measured and calculated specular reflectance also remains similar between 280 and 2500 nm (Figure 27 right).

Overall, the observed trends in total, diffuse and specular transmittance and reflectance highlight the influence of applied voltage on the PDLC's solar radiation properties. Controlling the dynamic lighting effects of PDLC offers the opportunity for applications in smart windows that can contribute to energy efficiency of buildings. Although the sample currently operates with 48 V and 60 V, it is also possible to achieve the same level of transparency with 20 V based on the measurements. However, the measurements were only conducted on one relatively small sample size. It needs to be investigated further whether these same lower voltages can also cause the same degree of transparency in the larger samples and full-size windows.

## 4.3 Building practices

Considering the findings presented in the study, it is evident that advancements in smart windows, such as PDLC films, may have significant potential for improving energy efficiency and thermal and visual comfort.

One key factor of this study was to evaluate the importance of smart windows as components of building envelopes. The ability of the PDLC sample to achieve transparency at lower voltages than 60 V shows potential in reducing energy consumption of buildings. Ideally, voltages between 20 and 48 V should also be measured to determine the lowest possible operating voltage for maintaining transparency. However, it is possible to investigate the PDLC's solar radiation properties at a later stage with these new parameters; this is discussed further in Chapter 5.

Another potential benefit of PDLCs was the enhanced user comfort from dynamic light control. The results of this study showed that the PDLC sample is able to operate at an opaque state which allows for natural daylight to transmit and reduces the need for artificial lighting. This also indicates that the PDLC can maintain privacy and reduce glare from the sun without the need for an applied voltage. Here there is also potential for further testing such as studying the effects of thermal and visual comfort of PDLC on the user when PDLC is applied to glass in homes and offices (Chapter 5).

## 4.4 Advantages and disadvantages

The PDLC smart film has properties that present advantages and disadvantages when integrated into the building envelope depending on its applications. A summary of these strengths and limitations is presented in Table 6 but will also be discussed further.

*Table 6. Advantages and disadvantages of PDLC integration into the building envelope.*

| Advantages | Disadvantages |
|---|---|
| Dynamic daylight control | Requires voltage to be transparent |
| Works for large surfaces | Aesthetics (dependent on what is desired) |
| Fast switching speed | Energy consumption from applied voltage |
| Privacy control | |
| Simple design and integration | |
| Glare reduction | |
| UV-protection | |

### 4.4.1 Advantages

PDLC films offer many advantages for enhancing the efficiency of buildings and user comfort. Firstly, as evidenced by the results, PDLC films exhibit low transmittance in the UV range. This confirms that PDLC is capable of blocking a significant portion of UV radiation. Results of reflectance also show the PDLC exhibits high reflectance in the UV spectrum meaning most UV radiation is reflected away from the building's interior. As a result, material degradation will be limited, and skin will be protected from harmful UV-radiation. This property makes for a notable advantage of PDLC films.

PDLC films can also enhance buildings' energy efficiency by reducing the need for artificial lighting and heating and cooling systems. They allow natural daylight to enter while also minimizing solar heat gain. This decreases the reliance on artificial lighting and cooling, leading to potential energy savings. Due to the high absorption in transmittance when the PDLC is in an off state, less solar energy is transmitted through the window. The results show that PDLC provides high transparency in the visible solar radiation spectrum when switched on, allowing natural daylight to transmit and consequently reducing the need for artificial lighting. Conversely, in the off state, the PDLC film exhibits lower transmittance which reduces the solar heat gain and the need for cooling, which may save energy.

Another advantage of PDLC films is the ability to dynamically control light transmittance, allowing users to adjust the ratio of natural light to artificial light. The dynamic light control is evidenced by the significant differences in transmittance and reflectance between 0 V and 60 V. This ability to control both transmittance and reflectance enhances user comfort by reducing glare and reliance on artificial lighting. The dynamic control of light transmittance may also lead to energy saving because of the reduced need for artificial lightning.

The ability of PDLC to switch between transparent and translucent states enables privacy within various spaces. This property is especially useful in spaces where occasional privacy is required such as meeting rooms or residential buildings.

In terms of practical applications, PDLC films can cover large areas, making them ideal for installations on building facades. This streamlines the installation processes and reduces material waste. The PDLC films can also be seamlessly integrated into the building envelope and does not require replacement of existing windows in the building.

In summary, PDLC films have a range of factors that make them advantageous additions to the building envelope. Their versatility, user-friendly features and logistical advantages make them a promising technology for sustainable building design.

### 4.4.2 Disadvantages

PDLC films present many opportunities for enhancing energy efficiency, user comfort and functionality in buildings. However, challenges related to voltage, energy consumption costs, aesthetics and durability must be considered.

The requirement of a voltage to maintain a transparent state for the PDLC may be a disadvantage. As evidenced by the results, optimal transparency of the PDLC film is achieved between 20 V and 60 V. However, this can be a drawback in scenarios where constant transparency is essential for operation or service. However, in applications such as ceiling windows where diffused daylight with reduced glare is preferred most of the time, this characteristic can be advantageous.

For PDLC to switch between a transparent and translucent state, a voltage is required. This increases installation costs in terms of wiring to an electrical source. Moreover, while PDLC films may improve energy efficiency by reducing the need for HVAC systems, the energy consumption associated with maintaining a transparent state cannot be overlooked. This factor will be reviewed further in Chapter 5. Lastly, the reliance on an electrical supply leaves the film prone to failures in the electrical system.

Although a cheaper alternative to many other smart window technologies, PDLC can be more expensive than traditional windows. Furthermore, the PDLC's durability and longevity can be impacted by exposure to UV radiation, mechanical stress, and moisture. Over time, a loss of alignment of the liquid crystals may occur. This would diminish the PDLC's performance as a smart window application.

# 5 Further work

## 5.1 Energy Simulations

To gain a deeper understanding of the energy-saving potential of PDLC windows, it is necessary to conduct energy simulations. Energy simulations should be conducted to evaluate the impact of PDLC on heating, cooling and lighting consumption within a realistic building environment. An example of one such energy simulation software is the BIM Energy software. This software is able to calculate and analyse energy performance in buildings [56]. By comparing the energy consumption with traditional windows and other smart windows technologies, the effectiveness of PDLC windows can be estimated.

## 5.2 Accelerated climate ageing

An essential element of evaluating the durability and effectiveness of PDLC films involves conducting accelerated climate ageing tests. Accelerated climate ageing involves exposing the material to extreme (accelerated) climate conditions in laboratory to simulate the effects of long-term exposure over shorter periods of time. This may include exposure to high temperatures, cold, driving rain, UV radiation and other stresses the material may be exposed to. These tests on the PDLC film could be conducted using the different accelerated climate ageing apparatus in the SINTEF and NTNU laboratories to evaluate the durability, performance, and stability under such conditions to predict how the PDLC films will behave over time. By closely monitoring alterations in solar radiation (e.g. optical) properties, durability, and functionality, we can gain valuable insight into the long-term performance of PDLC windows.

For example, a climate simulator exposes the sample to climate parameters such as sun, rain, heat, cold, wind pressure and suction. The instrument provides solar radiation up to 1000 W/m$^2$ and can control the season and temperature with both rain and sun simultaneously. By utilising such a simulator, insight into the durability of the PDLC window under different climate parameters will be provided [57].

Another notable apparatus that can be utilised is the hotbox. The hotbox measures the heat loss and U-value for building components such as floors, walls, roofs, and windows with large and full-scale samples (up to 9 m$^2$) at all inclination angles from the vertical to the horizontal position. This will be very useful for measuring the heat loss of the PDLC window and how it will change over time [57].

The Atlas SunTest XXL+, sunsimulator can also be a good option. Atlas SunTest consists of a large xenon lamp in a weathering and lightfastness test chamber. The simulator is used for checking the degradation of materials and products due to solar radiation, temperature, and humidity in a short period of time. The ageing of a material which naturally happens outdoors or indoors over months or years, such as fading, yellowing or reduced strength, can be simulated within weeks with the Atlas SunTest. This will provide information about the durability of the PDLC in terms of sun, humidity, and temperature [58].

## 5.3 Testing of PDLC properties in real-world scenarios

Testing of PDLC properties in real-world scenarios involves field testing and monitoring of PDLC installations in building environments. This approach will provide data on factors such as degradation, energy consumption, maintenance requirements and overall performance. Real-world testing could also validate laboratory findings of the PDLCs solar radiation properties.

One possibility for testing would be to apply PDLC films onto windows at the ZEB Living Lab constructed by NTNU and SINTEF. This laboratory functions as a habitable house with instruments to analyse how humans interact with climate and energy systems [59]. This is especially of interest in terms of reviewing user comfort but also provides insightful data on the energy consumption of the PDLC films.

## 5.4 Enhancement of PDLC properties

With its many advantageous properties, it could be ideal to focus research efforts on improving key elements of PDLCs. These include optical clarity, switching speed, durability, and power efficiency. Optical clarity of PDLCs is important in ensuring optimal daylighting, user comfort and aesthetics. Investigating how to reduce light scattering and maximizing light transmittance will address these issues.

Energy consumption is a defining factor in the usefulness of PDLC films. Reducing energy consumption while maintaining optimal performance will maximise the PDLCs efficiency and lower costs. Possibilities here include optimising the voltage threshold or altering the composition of the liquid crystals amongst other things. For example, a silver coating inside the glass along with PDLC has shown to further decrease the energy consumption [60]. This demonstrates the potential for enhancing the technology of PDLCs.

## 5.5 Testing of other LC technologies

By testing other LC technologies in further research, we can compare their performance up against PDLC. This helps identifying the strengths and weaknesses of each technology and allows researchers to make informed decisions about which technology is most suitable for specific applications. This also allows researchers to optimise the performance of smart window technologies. Each technology may offer unique advantages, some of them have lower driving voltage, faster switching speeds, or improved solar radiation properties. By testing alternative technologies, the user can determine which technology is most suitable for their application.

A polymer stabilised liquid crystal (PSLC) window represents a reverse mode haze improved window device. The PSLC window is transparent in an off state, unlike PDLC windows that require voltage to maintain transparency. The switching time is less than 3.5 ms and can be operated hundreds of times without any degeneration in the switching speed and haze. The PSLC requires lower driving voltage than the PDLC, 10-25 V depending on the cell gap [61]. The lower voltage makes this PSLC an attractive alternative to PDLC in terms of energy consumption in buildings. However, currently we do not have access to PSLC samples for laboratory tests.

The field of LC technologies is evolving rapidly with new advancements and innovations constantly emerging. Testing other technologies is essential in identifying promising solutions that may offer improved performance or better functionalities compared to the existing technologies.

# 6 Conclusions

The aim of this laboratory investigation was to explore the transmittive and reflective solar radiation properties of polymer-dispersed liquid crystal (PDLC) films for applications in smart windows, including the determination of the optimal threshold voltage of the PDLC films. These findings will contribute to the advancement of smart window technologies for energy efficiency in buildings.

Results showed that the PDLC samples used in the laboratory investigations are able to operate at 48 V and even down to 20 V while maintaining a transparent state. However, further research is needed to see if the same applies for larger samples and full-scale window sizes.

*What is the relationship between applied voltage and solar radiation properties (transmittance and reflectance) of PDLC films?*

The investigation revealed a significant relationship between applied voltage and solar radiation properties of PDLC films. The results showed that, at 60 V, the PDLC exhibited high total transmittance at 900 nm with 88% transmittance. At 0 V, the PDLC exhibited higher diffuse transmittance and reflectance, with the highest diffuse transmittance at 67% at 800 nm and highest total and diffuse reflectance of 32% and 24%, respectively, at 450 nm. The results also showed that as the voltage increased from 0 V to 60 V, the transmittance of the PDLC increased. Likewise, as the voltage increased, the reflectance decreased. However, as previously mentioned, between 20 V and 60 V, the transmittance only increased slightly. The relationship between applied voltage and solar radiation properties confirms that PDLC films are able to effectively control the amount of solar radiation that is transmitted or reflected. Therefore, PDLC films can enhance the energy efficiency of buildings by reducing the need for artificial lighting and HVAC systems.

*Is it possible to operate PDLC films effectively at lower voltages, and what impact would this have on a building's energy consumption?*

The investigation also explored the possibility of operating the PDLC films at lower voltages. Since Fågg AS currently applies 48 V and 60 V to their PDLC films and this thesis aims to contribute to increasing energy efficiency in buildings, it was necessary to investigate the possibility of a lower threshold voltage for optimal transparency. The results indicated that PDLC films were still able to achieve high transparency at a voltage of as low as 20 V. Operating the PDLC films at lower voltages could therefore potentially reduce the energy consumption associated with maintaining a transparent state. Despite this, the requirement of an electrical supply to switch to and maintain a transparent state remains a challenge. As previously mentioned, these results are from smaller PDLC samples but it remains to be investigated further whether or not larger PDLC samples can operate effectively at 20 V. Further research such as energy simulations is therefore required to determine if 20 V is enough to reduce the overall energy consumption of buildings.

Overall, the laboratory investigations have highlighted the potential of PDLC films as a possible solution for smart window applications. Their dynamic solar radiation properties make them well-suited for saving energy, regulating daylight, enhancing building sustainability and increasing user comfort. However, further research is needed to optimise the product, as well as to gain insight into the energy-saving potential of the PDLC films and the durability over time. This can be achieved using energy simulations, climate ageing tests, performance under real-life laboratory conditions and enhancement of the PDLC properties.

In conclusion, the laboratory investigations conducted on the PDLC films have provided valuable insight into their solar radiation properties, particularly in the context of their application in smart windows. PDLC smart window technology shows significant promise in improving the energy efficiency and comfort of buildings. By addressing the identified challenges and optimising the technology further, PDLC smart windows have the potential to become integral components of sustainable building design. As a result, PDLC smart windows can contribute to efforts in reducing energy consumption globally and mitigating the effects climate change from the building sector. The findings from this study contributes to improved understanding of PDLC films and lays the foundation for future advancements in smart window technologies aimed at improving energy efficiency and indoor comfort in buildings.

# References

[1] “Energy performance of buildings directive,” Directorate-General for Energy. Accessed: Apr. 21, 2024. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en
[2] “Census Bureau Projects U.S. and world populations on new year’s day,” U.S. Department of Commerce. Accessed: May 02, 2024. [Online]. Available: https://www.commerce.gov/news/blog/2024/01/census-bureau-projects-us-and-world-populations-new-years-day
[3] R. Davey, “Aerogel windows for green building,” AZoM. Accessed: May 01, 2024. [Online]. Available: https://www.azom.com/news.aspx?newsID=58419
[4] T. Roberts, “We spend 90% of our time indoors. Says who?,” BuildingGreen. Accessed: May 08, 2024. [Online]. Available: https://www.buildinggreen.com/blog/we-spend-90-our-time-indoors-says-who
[5] Y. Al horr, M. Arif, M. Katafygiotou, A. Mazroei, A. Kaushik, and E. Elsarrag, “Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature,” *International Journal of Sustainable Built Environment*, vol. 5, no. 1, pp. 1–11, Jun. 2016, doi: 10.1016/j.ijsbe.2016.03.006.
[6] P. Lotfabadi, “High-rise buildings and environmental factors,” *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 285–295, Oct. 2014, doi: 10.1016/j.rser.2014.05.024.
[7] cbeecher, “Understanding the importance of your building envelope | GCI,” GCI Consultants^SM. Accessed: May 08, 2024. [Online]. Available: https://www.gciconsultants.com/blog/understanding-the-importance-of-your-buildings-envelope/
[8] R. F. Haines, “Windows: Their importance and functions in confining environments,” in *From Antarctica to Outer Space*, Springer, New York, NY, 1991, pp. 349–358. doi: 10.1007/978-1-4612-3012-0_32.
[9] J. H. Pu, X. Yu, Y. Zhao, G. H. Tang, X. Ren, and M. Du, “Dynamic aerogel window with switchable solar transmittance and low haze,” *Energy*, vol. 285, p. 129437, Dec. 2023, doi: 10.1016/j.energy.2023.129437.
[10] J. Aguilar-Santana, M. Velasco-Carrasco, and S. Riffat, “Thermal transmittance (U-value) evaluation of innovative window technologies,” *Future Cities and Environment*, vol. 6, Dec. 2020, doi: 10.5334/fce.99.
[11] “2050 long-term strategy - European Commission.” Accessed: May 02, 2024. [Online]. Available: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
[12] B. P. Jelle, “Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings—Measurement and calculation,” *Solar Energy Materials and Solar Cells*, vol. 116, pp. 291–323, Sep. 2013, doi: 10.1016/j.solmat.2013.04.032.
[13] B. P. Jelle, A. Gustavsen, T. N. Nilsen, and T. Jacobsen, “Solar material protection factor (SMPF) and solar skin protection factor (SSPF) for window panes and other glass structures in buildings,” *Solar Energy Materials and Solar Cells*, vol. 91, no. 4, pp. 342–354, Feb. 2007, doi: 10.1016/j.solmat.2006.10.017.
[14] O. M. Victoria and Albert Museum, “UV-VIS-NIR Spectrocopy: what is it and what does it do?” Accessed: May 06, 2024. [Online]. Available:

http://www.vam.ac.uk/content/journals/conservation-journal/issue-01/uv-vis-nir-spectrocopy-what-is-it-and-what-does-it-do/
[15] L. Wang and J. Yu, “Chapter 1 - Principles of photocatalysis,” in *Interface Science and Technology*, vol. 35, J. Yu, L. Zhang, L. Wang, and B. Zhu, Eds., in S-scheme Heterojunction Photocatalysts, vol. 35. , Elsevier, 2023, pp. 1–52. doi: 10.1016/B978-0-443-18786-5.00002-0.
[16] P. Sadooghi and N. P. Kherani, “Influence of slat angle and low-emissive partitioning radiant energy veils on the thermal performance of multilayered windows for dynamic facades,” *Renewable Energy*, vol. 143, pp. 142–148, Dec. 2019, doi: 10.1016/j.renene.2019.04.121.
[17] “Triple-pane windows cost | 2024 buying guide,” Modernize. Accessed: May 06, 2024. [Online]. Available: https://modernize.com/windows/energy-efficient/triple-pane-windows
[18] H. Zhang, C. Zhang, W. Ji, X. Wang, Y. Li, and W. Tao, “Experimental characterization of the thermal conductivity and microstructure of opacifier-fiber-aerogel composite,” *Molecules*, vol. 23, no. 9, p. 2198, Aug. 2018, doi: 10.3390/molecules23092198.
[19] M. Koebel, A. Rigacci, and P. Achard, “Aerogel-based thermal superinsulation: an overview,” *J Sol-Gel Sci Technol*, vol. 63, no. 3, pp. 315–339, Sep. 2012, doi: 10.1007/s10971-012-2792-9.
[20] B. P. Jelle, “Innovative and new materials and products for the building envelope”.
[21] “How aerogels work,” HowStuffWorks. Accessed: May 02, 2024. [Online]. Available: https://science.howstuffworks.com/aerogel.htm
[22] T. Gao, B. P. Jelle, T. Ihara, and A. Gustavsen, “Insulating glazing units with silica aerogel granules: The impact of particle size,” *Applied Energy*, vol. 128, pp. 27–34, Sep. 2014, doi: 10.1016/j.apenergy.2014.04.037.
[23] C. Buratti, E. Moretti, and M. Zinzi, “High energy-efficient windows with silica aerogel for building refurbishment: Experimental characterization and preliminary simulations in different climate conditions,” *Buildings*, vol. 7, no. 1, Art. no. 1, Mar. 2017, doi: 10.3390/buildings7010008.
[24] T. Gao, B. P. Jelle, and A. Gustavsen, “Building integration of aerogel glazings,” *Procedia Engineering*, vol. 145, pp. 723–728, Jan. 2016, doi: 10.1016/j.proeng.2016.04.090.
[25] E. Abraham,V. Cherpak, B. Senyuk, J. Hove, T. Lee, Q. Liu, I. Smalyukh, “Transparent aerogels reduce energy loss through building windows,” *Nat Energy*, vol. 8, no. 4, pp. 327–328, Apr. 2023, doi: 10.1038/s41560-023-01229-4.
[26] E. Cuce and P. M. Cuce, “Vacuum glazing for highly insulating windows: Recent developments and future prospects,” *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1345–1357, Feb. 2016, doi: 10.1016/j.rser.2015.10.134.
[27] “Vacuum glazing vs triple glazing - Which is best? - George Barnsdale.” Accessed: May 14, 2024. [Online]. Available: https://www.georgebarnsdale.co.uk/blog/vacuum-glazing-vs-triple-glazing-which-is-best/
[28] jason, “Glazing retrofit solution for existing building,” ReThink HK. Accessed: May 06, 2024. [Online]. Available: https://rethink-event.com/insight/glazing-retrofit-solution-for-existing-building/

[29] M. Casini, “Smart windows for energy efficiency of buildings,” *International Journal of Civil and Structural Engineering – IJCSE Volume 2 : Issue 1 [ISSN : 2372-3971]*, vol. 2, pp. 2372–3971, May 2015.
[30] S.-J. Lee and S.-Y. Song, “Energy efficiency, visual comfort, and thermal comfort of suspended particle device smart windows in a residential building: A full-scale experimental study,” *Energy and Buildings*, vol. 298, p. 113514, Nov. 2023, doi: 10.1016/j.enbuild.2023.113514.
[31] A. Ghosh *et al.*, “Active smart switchable glazing for smart city: A review,” *Journal of Building Engineering*, vol. 84, p. 108644, May 2024, doi: 10.1016/j.jobe.2024.108644.
[32] K. V. Wong and R. Chan, “Smart glass and its potential in energy savings,” *Journal of Energy Resources Technology*, vol. 136, no. 012002, Aug. 2013, doi: 10.1115/1.4024768.
[33] D. Barrios, R. Vergaz, J. M. Sanchez-Pena, C. G. Granqvist, and G. A. Niklasson, “Toward a quantitative model for suspended particle devices: optical scattering and absorption coefficients,” *Solar Energy Materials and Solar Cells*, vol. 111, pp. 115–122, Apr. 2013, doi: 10.1016/j.solmat.2012.12.012.
[34] L. Niklaus, M. Schott, and U. Posset, “Electrochemical devices | Electrochromic windows,” in *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, Elsevier, 2023. doi: 10.1016/B978-0-323-96022-9.00017-7.
[35] I.-C. Khoo, *Liquid crystals*. John Wiley & Sons, 2022.
[36] P. Kumar Choudhury and A.-B. M. A. Ibrahim, Eds., *Liquid crystals*. IntechOpen, 2022. doi: 10.5772/intechopen.95648.
[37] “Liquid crystals,” Chemistry LibreTexts. Accessed: Apr. 21, 2024. [Online]. Available: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Physical_Properties_of_Matter/States_of_Matter/Liquid_Crystals
[38] V. Shibaev, “Liquid crystalline polymers,” in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2016. doi: 10.1016/B978-0-12-803581-8.01301-1.
[39] A. Hemaida, A. Ghosh, S. Sundaram, and T. K. Mallick, “Evaluation of thermal performance for a smart switchable adaptive polymer dispersed liquid crystal (PDLC) glazing,” *Solar Energy*, vol. 195, pp. 185–193, Jan. 2020, doi: 10.1016/j.solener.2019.11.024.
[40] D. Lötzsch, V. Eberhardt, C. Rabe, “Chromogenic polymers,” Fraunhofer Institute for Applied Polymer Research. Accessed: Apr. 06, 2024. [Online]. Available: https://www.chromogene-polymere.de/en/chromogenic-polymers.html
[41] M. Pittaluga, “17 - Electrochromic glazing and walls for reducing building cooling needs,” in *Eco-Efficient Materials for Mitigating Building Cooling Needs*, F. Pacheco-Torgal, J. A. Labrincha, L. F. Cabeza, and C.-G. Granqvist, Eds., Oxford: Woodhead Publishing, 2015, pp. 473–497. doi: 10.1016/B978-1-78242-380-5.00017-0.
[42] C. Meng, M. C. Tseng, S. Tang, and H. Kwok, “77-3: High-performance smart window with haze enhancement via micro-domains manipulation on alignment surface,” *SID Symposium Digest of Technical Papers*, vol. 50, pp. 1106–1109, Jun. 2019, doi: 10.1002/sdtp.13122.
[43] P. M. Martin, “Optical materials | Smart optical materials,” in *Encyclopedia of Modern Optics*, R. D. Guenther, Ed., Oxford: Elsevier, 2005, pp. 9–16. doi: 10.1016/B0-12-369395-0/00869-1.

[44] J. Tarver, J. E. Yoo, and Y.-L. Loo, “4.14 - Organic electronic devices with water-dispersible conducting polymers,” in *Comprehensive Nanoscience and Technology*, D. L. Andrews, G. D. Scholes, and G. P. Wiederrecht, Eds., Amsterdam: Academic Press, 2011, pp. 413–446. doi: 10.1016/B978-0-12-374396-1.00136-7.
[45] F. Asdrubali and U. Desideri, Eds., “Chapter 6 - Building envelope,” in *Handbook of Energy Efficiency in Buildings*, Butterworth-Heinemann, 2019, pp. 295–439. doi: 10.1016/B978-0-12-812817-6.00039-5.
[46] G. Leftheriotis and P. Yianoulis, “3.10 - Glazings and coatings,” in *Comprehensive Renewable Energy (Second Edition)*, T. M. Letcher, Ed., Oxford: Elsevier, 2022, pp. 360–401. doi: 10.1016/B978-0-12-819727-1.00022-4.
[47] M. Casini, “Chapter 7 - Advanced construction materials,” in *Construction 4.0*, M. Casini, Ed., in Woodhead Publishing Series in Civil and Structural Engineering. , Woodhead Publishing, 2022, pp. 337–404. doi: 10.1016/B978-0-12-821797-9.00005-2.
[48] H. Tian and S. Yang, “Recent progresses on diarylethene based photochromic switches,” *Chem. Soc. Rev.*, vol. 33, no. 2, pp. 85–97, Feb. 2004, doi: 10.1039/B302356G.
[49] P. Talvenmaa, “11 - Introduction to chromic materials,” in *Intelligent Textiles and Clothing*, H. R. Mattila, Ed., in Woodhead Publishing Series in Textiles. , Woodhead Publishing, 2006, pp. 193–205. doi: 10.1533/9781845691622.3.193.
[50] J. Zhang, Q. Zou, and H. Tian, “Photochromic materials: More than meets the eye,” *Advanced Materials*, vol. 25, no. 3, pp. 378–399, 2013, doi: 10.1002/adma.201201521.
[51] “Photochromic film for windows | Sunlight responsive technology.” Accessed: May 05, 2024. [Online]. Available: https://generalsolar.net/photochromic-film-2/
[52] V. Wittwer, M. Datz, J. Ell, A. Georg, W. Graf, and G. Walze, “Gasochromic windows,” *Solar Energy Materials and Solar Cells*, vol. 84, no. 1, pp. 305–314, Oct. 2004, doi: 10.1016/j.solmat.2004.01.040.
[53] H. S. K. Morrey and A. Ghosh, “Energy assessment of gasochromic smart windows for a high-rise apartment block in a temperate climate,” *Journal of Building Engineering*, vol. 84, p. 108625, May 2024, doi: 10.1016/j.jobe.2024.108625.
[54] X. Tao, D. Liu, J. Yu, and H. Cheng, “Reversible metal electrodeposition devices: An emerging approach to effective light modulation and thermal management,” *Advanced Optical Materials*, vol. 9, no. 8, p. 2001847, 2021, doi: 10.1002/adom.202001847.
[55] “Fågg - Fågg smartfilm,” Fågg. Accessed: May 01, 2024. [Online]. Available: https://www.faagg.no/smartfilm-demonstasjon
[56] “BIM Energy - About us,” BIM Energy. Accessed: May 20, 2024. [Online]. Available: https://bimenergy.com/about-us/
[57] “Laboratoriet for avanserte materialer og komponenter.” Accessed: May 09, 2024. [Online]. Available: http://www.zeb.no/index.php/no/laboratorier/280-advanced-materials-and-component-laboratories-pa-norsk
[58] “Suntest xxl+ – Cromocol.” Accessed: May 09, 2024. [Online]. Available: https://cromocol.se/produkter/suntest-xxl/
[59] “ZEB Living Lab,” SINTEF. Accessed: May 08, 2024. [Online]. Available: https://www.sintef.no/laboratorier/living-lab/

[60] D. Chidubem Iluyemi, S. Nundy, S. Shaik, A. Tahir, and A. Ghosh, “Building energy analysis using EC and PDLC based smart switchable window in Oman,” *Solar Energy*, vol. 237, pp. 301–312, May 2022, doi: 10.1016/j.solener.2022.04.009.
[61] “(PDF) 77-3: High-performance smart window with haze enhancement via micro-domains manipulation on alignment surface,” *ResearchGate*, doi: 10.1002/sdtp.13122.