

SMART PDLC FILM INTEGRATION INTO A CLASSICAL WINDOW SYSTEM

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Abstract. As prices for electrical and thermal energy continue to rise, special window films can help reduce a building's energy consumption in line with Nearly Zero Energy Building regulations. These films can provide automatic shading to maintain the desired level of light while blocking unwanted energy, including UV and IR radiation. This work investigates the real energy-consumption impact of integrating a Polymer Dispersed Liquid Crystal (PDLC) film into an experimental small-room model, highlighting energy savings for cooling and heating, even in an intermediate season with low solar energy. Based on the experimental results, the findings are extended and integrated into DesignBuilder, specialized building energy simulation software, showing an overall 2.71% energy savings with the PDLC system. Integrating the experiment into DesignBuilder will allow evaluation of the total energy impact of PDLC integration for any theoretical building.

Keywords: PDLC film; DesignBuilder; performance analysis; software integration.

1. INTRODUCTION

Given rising prices for electrical and thermal energy and international CO₂-reduction targets, reducing energy consumption in new and existing buildings, as well as during the rehabilitation of older buildings, is essential. In Romania, more than 42% [1] of total annual energy consumption is related to the building sector. New buildings are therefore bound by Nearly Zero-Energy Building (nZEB) rules [2,3] to have lower energy consumption, as up to 15% [4] of a building's energy is lost through glazed spaces. A smart glass system that regulates transparency can significantly affect a building's energy economy, especially in warm seasons. Increasing insulation in glazed spaces is also important because thermal energy losses are high at windows and other glazed areas.

Several technologies have been studied to reduce solar radiation on buildings, including older buildings [5], and to add extra insulation to glazed spaces; among the most promising are Suspended Particle Device (SPD) and Polymer Dispersed Liquid Crystal (PDLC) [6]. PDLC technology is gaining ground, according to other research [7], because it uses relatively inexpensive polymers [8] and is easier to produce and implement at large scale, with the possibility of extending to other areas, such as image and hologram projections [9].

This research monitors and highlights the energy variation effects of integrating PDLC film into classical systems with a double-glazed window system (2-GW). The 2-GW system

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is integrated into a Numerical Simulated Room (NSR) designed with DesignBuilder, using available manufacturer data coupled with data extracted from two experimental models: the first with normal glass windows and the second with PDLC film applied to the glass windows. The 2-GW system, defined by 4 mm glass and a 13 mm air gap, was chosen because it is the most commonly used window system in existing buildings in Romania.

This study aims to investigate the real impact of this new technology, since the PDLC film can be easily applied to traditional 2-GW systems [10]. After measuring the energy impact of the PDLC on the experimental room system, corroborated with the manufacturer's main data on PDLC behavior in the ON or OFF state, a custom-made PDLC 2-GW system model was created in DesignBuilder, a specialized building performance simulation software that provides a complex interface to declare new materials for use in simulated buildings. Existing studies suggest that PDLC technology has positive optical and visual impacts [11] and increases overall energy efficiency [12], with the potential to further improve building energy efficiency by double-filtering IR (infrared) light [13].

Therefore, the main purpose of this paper is to study: (i) energy consumption for air conditioning operation in the first room, without PDLC; (ii) energy consumption for air conditioning operation in the first room, with PDLC; (iii) analyze the energy differences recorded or any other notable system behavior differences; (iv) calculate and extrapolate all characteristics of the PDLC system, based on the gathered experimental data and definition of this new PDLC system in DesignBuilder. The main scope of the two experimental models is to highlight the energy difference by integrating PDLC technology into one model, while keeping the same components and envelope energy losses. The integration of a 5:1 simulated numerical room in DesignBuilder is dedicated to implementing the experimental and evaluated data of the PDLC window system in a format compatible with DesignBuilder. It is necessary to develop numerically controlled simulated rooms due to the difficulties in comparing real buildings or rooms (even if they are similar), such as (i) cardinal orientation of the room – it is unlikely to identify two identical orientated rooms; (ii) possible different shade shapes projected on the exterior walls (different nearby trees, vegetation, tall buildings, etc.); (iii) different numbers of people who occupy each room with different daily schedules and habits; (iv) probably different electrical equipment, with different exploitation behavior; (v) different nearby walls: difficult to identify 2 rooms with identical inside and outside walls. On the other hand, small-scale models allow exposure to identical conditions, including reorienting window spaces to various cardinal points. For this stage of the research, the study will analyze the window orientation [14] to the south in the Chiajna area, near Bucharest, Romania, with climatic conditions according to SR – EN 1907 / 2014 [15] (climatic zone II).

2. MATERIALS AND METHODS

The proposed software for numerical simulation (i.e., DesignBuilder) is a complex building energy simulation software, based on the Energy Plus simulation platform, which is the U.S. Department of Energy's flagship, open-source whole-building simulation engine, with the mention that the Energy Plus calculation procedure is in accordance with the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) definitions. Beyond this, DesignBuilder supports LEED (Leadership in Energy and Environmental Design) v4/v4.1 primarily through ASHRAE 90.1 Appendix G PRM (Performance Rating Method), which includes complex model setup, energy simulation, and comparisons between different models. Thus, DesignBuilder has proven reliable in producing accurate output data compared with measured data [16]. As a new technology and a new field of study for buildings in Romania, it is important that the PDLC 2-GW system in DesignBuilder matches the shape and

format of the two experimental models. The two simulated rooms designed in DesignBuilder are at a scale of 5:1, geometrically similar to the experimental models, and have the same window-to-total-wall-surface-area ratio (24.6%). The simulated rooms created in DesignBuilder have a length of 5 m, a width of 5 m, and a height of 3 m. The glazed space faces south and consists of 2 windows measuring 1.8 m × 1.025 m. The external insulation is mineral wool with a thickness of 15 cm, and the air conditioning system permanently maintains the temperature at 23°C.

2.1. MATERIALS

The experimental models are identical boxes measuring 1 m x 1 m x 0,6 m (L x W x H) and equipped with identical fully automated systems for climatization and light modulation (dimming), to highlight differences in energy consumption. Fig. 1 shows the two experimental models, which are identical in size and window ratio but differ in window technology: Model 1 has a standard 2-GW system without PDLC technology, and Model 2 has PDLC (film) integrated into the 2-GW system. Fig. 2 presents the functional diagram of experimental Model 1 (without PDLC technology), and Fig. 3 presents the functional diagram of experimental Model 2 (with PDLC technology (film)).



Figure 1. Photo of Model 1 – without PDLC (left) and Model 2 – with PDLC (right).

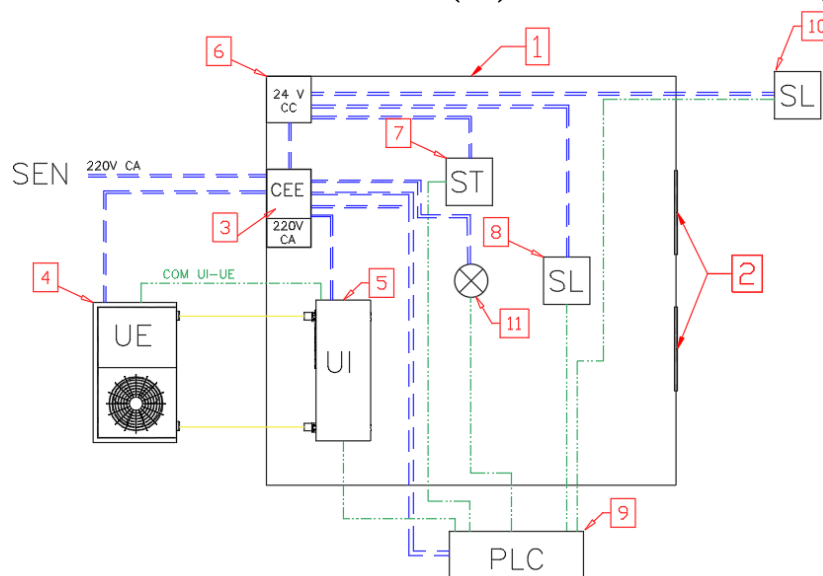


Figure 2. Functional diagram of Model 1, without PDLC film

Note: Yellow line – refrigerant pipework; interrupted blue lines – electrical feed wires; interrupted green lines – signal and control wires; 1 – wall, 2 – windows, 3- AC power junction box; 4 - outdoor unit, 5 - air conditioning indoor unit, 6 - power supply source - 24 V DC, 7 - temperature sensor 0 - 10 V, 8 - light sensor 0 - 10 V, 9 – PLC, 10 - pyranometer 0 - 10 V, 11 - modular LED lighting.

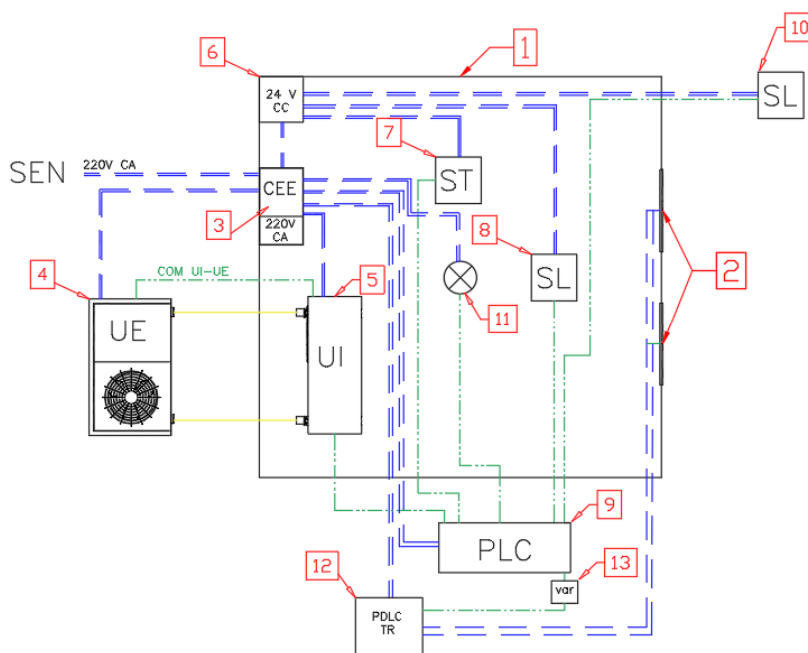


Figure 3. Functional diagram of Model 2, with PDLC film

Note: Yellow line – refrigerant pipework; interrupted blue lines – electrical feed wires; interrupted green lines – signal and control wires; 1 – wall, 2 – windows with PDLC, 3- AC power junction box; 4 - outdoor unit, 5 - air conditioning indoor unit, 6 - power supply source - 24 V DC, 7 - temperature sensor 0 - 10 V, 8 - light sensor 0 - 10 V, 9 - PLC, 10 - pyranometer 0 - 10 V, 11 - modular LED lighting, 12 - PDLC voltage modulation transformer, 13 - PDLC manual dimmer.

Table 1 presents the main equipment used in experimental work, the materials, and the functionality, highlighting the differences between Model 1 and Model 2.

Table 1. Materials and components for Model 1 and Model 2.

Component	Model 1	Model 2
1 - Exterior walls	18 mm melamine-coated chipboard, protected from the elements by varnishing and plastic foil solution.	
2 - Glazed space	2 panels of 3 mm plexiglass, with a 13 mm air gap between them, with sizes 360 x 205 mm. The system is simulated as general U; DesignBuilder results show 2 - GW, defining a 4 mm clear window with a 13 mm air gap.	The window system has an ultra-clear film, with copper conduction rods on both sides and with the possibility of 0 - 10 V modulation, applied with adhesive on the inner side of the glazed space.
3 - 220 V, AC power junction box	The junction box acts as a general electricity meter for the air conditioning system (4 + 5), an electricity meter for the PDLC system (12 +13), and an electricity meter for the lighting system (11)	
4 - Outdoor unit	The outdoor air conditioning unit has the role of evacuating excess heat in the summer and heating the refrigerant in a specific Carnot cycle in the winter. The outdoor unit was extracted from the European ADLER air conditioning unit, model AD 80084.	
5 - Air conditioning indoor unit	The indoor air conditioning unit air-conditions the premises to a set temperature of 23 °C, controlled by the PLC (9) according to the temperature sensor (7). The unit, Europe AD 80084 model, has dimensions (compact): 13.8 cm x 24.1cm. x 29.8 cm, with cooling power 42W and heating power of 38W. The power supply is 220 V - 50 Hz AC.	
6 - 24 V DC power supply	The source powers the light (8) and temperature (7) sensors by converting and transforming the voltage from the junction box (3) (220 V, 50 Hz AC) into 24 V DC.	
7 - Temperature sensor 0 - 10 V	The temperature sensor is powered by a 24 V DC source and monitors the indoor temperature reading on the 0 – 10 V range. The information is taken over by the PLC (9), which thus controls the operation of the air conditioning system.	

Component	Model 1	Model 2
8 - Light sensor 0 - 10 V	The interior light sensor is powered by a 24 V DC source and monitors interior light intensity in the 0–10 V range. The PLC (9) integrates this information and modulates the PDLC voltage modulation transformer to maintain the light intensity at the desired setting.	
9 – PLC	The chosen model is SCN-LOG1.02, with the following main technical data - MDRC model, with 4 additional free LEDs for programming - 24 programmable functions - 5 integrable operating logics - 8 logic gate inputs and/or - Information storage in the logic loop	
10 - Pyranometer 0 - 10 V	This sensor is common to both models and analyzes the sensitivity/behavior of the PDLC film under different intensities of solar radiation, which can vary in Romania (Bucharest) at 14:00 from a maximum of 1200 W/m ² (summer) to 400 W/m ² in winter.	
11 - Modular LED lighting	Consists of an LED band placed perimetrically inside the box, with a maximum measured intensity of 340 lux / m ² .	
12 - PDLC voltage modulation transformer	N / A	- converts the 220 AC into a 0 – 65 V ± 5% AC voltage
13 - PDLC manual dimmer	N / A	- modulates the voltage of the PDLC power supply

The integrated PDLC (component 2 – model 2) is of the latest available technology, featuring ultra-clarity (95% in ON state), an AC power supply, and a lifespan of up to 20 years. The proposed PDLC is applied to the second layout and has general dimensions of 360 mm × 205 mm × 3 mm (L × W × D), is ultra-high-definition, has 95% visible light transmission in the ON state, and has solar radiation resistance to exposure over 1500 W/m². The power supply is 65 V AC ± 5%, and the film is modulable/ dimmable by voltage variation. The response time from ON to OFF is a maximum of 600 ms, and from OFF to ON is a maximum of 200 ms. The maximum power consumption is 3.7 W/ m². In addition to thermal insulation, UV blocking is a key feature: 45% in the ON state and 98% in the OFF state. IR blocking is 17% in the ON state and 80% in the OFF state. The visibility angle is up to 165°, and the operating temperature is between –20°C and 80°C. The PDLC manual dimmer directly modulates the PDLC power supply voltage; a lower voltage increases PDLC opacity. Additionally, the system also has a remote control that can turn the PDLC window ON/OFF or modulate it step by step, similar to the manual dimmer.

The PLC controller for Model 2 has the following extended functionality to control the PDLC modulation: (i) modulates the air conditioning unit to maintain the temperature at 23°C, using the temperature measured by the temperature sensor (7); (ii) modulates the PDLC in the 0-10 V range, based on the light intensity set by the light sensor (8), which is set to 50 lux, as the target is a residential one in accordance with Romanian Normative 57/ 2002 [17]; (iii) modulates the brightness to reach the threshold intensity, specific to the building's needs; (iv) integrates an operating program specific to a residential building, for example, to cut off the lighting power after 10:00 PM.

2.2. METHODS

The operation method of the two models has at its center the PLC, which has the following functions, with the possibility of data exports into the KNX data structures: 1. Modulates the air conditioning system to maintain the temperature of 23°C (with the possibility of changing this set value), using the temperature read via the temperature sensor (7); 2. Modulates the PDLC system depending on the light intensity set and permanently monitored by the brightness sensor (8); 3. To modulate the brightness to reach the set

intensity of at least 50 lx, in the program specific to the building served. The PLC has the possibility of setting the minimum targeted light intensity value, for possible reconversion of the experiment (e.g., from residential to office spaces); 4. To integrate an operating program specific to a residential building, for example, to cut off the lighting power after 10:00 PM; 5. To integrate the data recorded by each electricity meter as follows: (a) general electricity meter; (b) electricity meter for air conditioning system (4 + 5); (c) electricity meter for PDLC system (12 + 13); (d) electricity meter for lighting system (11).

To export data to a PC, the system supports querying and automatic recording at 15-minute intervals. During the experimental tests, the following parameters are measured: consumed energy, temperature, PDLC modulation value (0–100%), and light intensity. The temperature is set from the PC interface and controlled by the PLC, with 2°C hysteresis between heating and cooling. For example, if the set temperature is 23°C, the system will automatically switch to heating when the temperature drops below 21°C and to cooling when the temperature rises to 25°C. To protect the air conditioning system, a timer controls the switch from cold to hot, with a minimum of 1 hour between mode changes. The heating or cooling logic also follows the temperature curve/temperature trend. For example, if the system is set to cooling, the temperature drops quickly from 25 to 21°C. When the temperature reaches 21°C, the system switches to heating with a one-hour hysteresis, and only if the interior temperature trend is negative. The switch back to cooling follows the same logic in reverse. The models were placed next to each other at a distance of 1 m, in an area that was neither naturally nor artificially shaded. A PLC collected the received data and communicated it to a PC via the KNX protocol. The data were acquired every 15 minutes for 3 days, and the daily mean values were used for analysis. Table 2 presents the data integrated and stored during the measuring campaign.

Table 2. Measured experimental data.

Symbol	Parameter
E - CG	Electric energy general electrical energy meter - [Wh]
E - Climate	Electricity meter for the air conditioning system - [Wh]
E-PDLC	Electricity meter for PDLC system - [Wh]
E - Light	Electricity meter for lighting system - [Wh]
SL1	Interior light sensor - [lux]
SL2	Sensor for measuring light intensity and solar variation intensity [W / m ²]
T1	Temperature transducer for monitoring indoor temperature [°C]
PDLC - line	PDLC system variation value, to maintain the set brightness value

3. RESULTS AND DISCUSSION

3.1. RESULTS

The results from the first three days of continuous measurements (16-19 September 2025) are presented in Table 3 for Model 1 and Table 4 for Model 2. Table 5 presents the energy consumption analysis for the two models.

The second objective of this study is to characterize the behavior of the studied PDLC technology for any building using DesignBuilder software. This objective will be addressed by calculating or importing the characteristics of a 2-GW PDLC system from the manufacturer and defining them in DesignBuilder. The calculations and definitions will use the data currently presented, either in a transparent state of the PDLC film or in an opaque state.

Table 3. Consumption and values collected for Model 1 – without PDLC.

Day	Total E - CG [Wh]	Total E - Climate [Wh]	Total E - PDLC [Wh]	Total E [Wh]	Average SL1 [lux]	Average SL2 [W/m ²]	Average T1 [°C]	PDLC – average variation [%]	Heating / Cooling / Neutral
1.	350.65	C: 146.95 H: 32.23	0	9.12	52.51	451.86	22.94	N/A	C: 11 - 18 H: 18 - 23
2.	343.94	C: 137.41 H: 36.42	0	9.87	51.32	422.31	22.89	N/A	C: 11 - 18 H: 18 - 23
3.	339.06	C: 131.62 H: 39.31	0	10.54	52.28	411.63	22.84	N/A	A: 11 - 18 H: 18 - 23

Note: C is cooling, H – heating, defined per working hours (e.g., cooling between 11 – 18 is expressed as C: 11 – 18).

Table 4. Consumption and values collected for Model 2 – with PDLC.

Day	Total E - CG [Wh]	Total E - Climate [Wh]	Total E - PDLC [Wh]	Total E [Wh]	Average SL1 [lux]	Average SL2 [W/m ²]	Average T1 [°C]	PDLC – average variation [%]	Heating / Cooling / Neutral
1.	354.36	C: 125.71 H: 29.88	3.71	9.12	52.37	451.86	22.89	13.61%	C: 11 - 18 H: 18 - 23
2.	347.33	C: 117.55 H: 33.76	3.68	10.64	51.44	422.31	22.89	12.84%	C: 11 - 18 H: 18 - 23
3.	342.09	C: 112.60 H: 36.44	3.63	11.36	51.39	411.63	22.84	11.57%	C: 11 - 18 H: 18 - 23

Note: C is cooling, H – heating, defined per working hours (e.g., cooling between 11 – 18 is expressed as C: 11 – 18).

Table 5. Energy consumption analysis Model 1 (E_{M1}) and Model 2 (E_{M2}).

Measured parameter	Model 1	Model 2	E _{M1} - E _{M2}	(E _{M1} - E _{M2}) / E _{M1}	(E _{M1} - E _{M2}) / Total E _{M1}
Total Cooling [Wh]	415.98	355.85	60.13	14.45%	5.76%
Total Heating [Wh]	107.96	100.09	7.87	7.29%	0.75%
Total Lighting [Wh]	29.53	31.83	-2.30	-7.79%	-0.22%
Total energy consumption (including PDLC) [Wh]	1033.65	1043.78	-10.13	-0.98%	-0.98%

The goal and challenge of this work is to implement data collected from two experimental models, combine it with specific manufacturer specifications, and define the behavior of the systems that will use a 2-GW system in DesignBuilder. For this purpose, an NSR is designed with similar geometry, window-to-surface ratio, and orientation. Thus, in DesignBuilder, various PDLC build impacts can be studied by implementing the PDLC film with continuous modulation and a full system programmed to maintain the set brightness level, depending on a light sensor. The specific characteristics resulting from implementing an ultra-clear PDLC film are determined for a double insulating glass unit characterized by 2 rows of glass and a 13 mm air space, based on data obtained in the manufacturer's laboratory using an engineering approach [18]. Apply the self-adhesive PDLC film, 0.1 mm thick, to the 4 mm outer glass. The total conductivity [U] value of the assembly must be determined in advance and entered in DesignBuilder. For the 2-GW system with PDLC, calculate the total resistance ($R = 1/U$) of the entire system using the structure shown in Fig. 4. The surfaces with their associated temperatures are defined in Table 6.

Table 6. Characteristic surfaces for 2-GW system with PDLC film

Surfaces	Characteristics
S1 with T1	Ambient air, considered in the worst case, summer at 35°C
S2 with T2	Classic insulating glass, 4 mm
S3 with T3	0.1 mm self-adhesive foil-type PDLC ultra-clear film
S4 with T4	Air 13 mm
S5 with T5	4 mm insulating glass
S6 with T6	Building ambient air, set in summer at 24°C

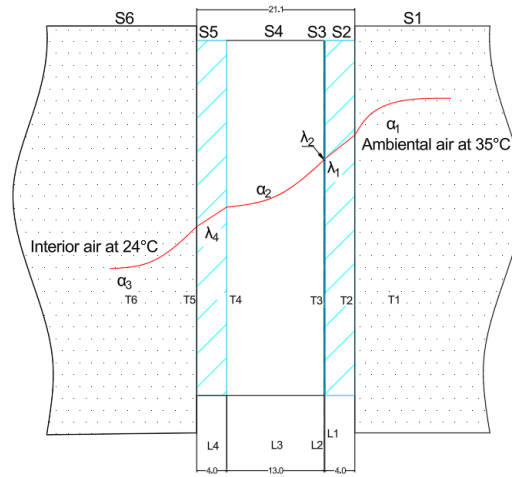


Figure 4. The conductive and convective elements specific to a 2-GW system with PDLC film.

Note: AutoCAD composition of the specific resistance levels of photovoltaic double glazing

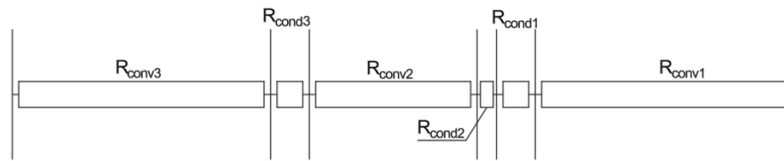


Figure 5. Composition of the specific resistance levels of a 2-GW with a PDLC film.

The resistance of the entire system, R_{total} , is calculated considering the components from Fig. 5:

$$R_{total} = R_{conv1} + R_{cond1} + R_{cond2} + R_{conv2} + R_{cond3} + R_{conv3} \quad (1)$$

where:

$$R_{conv1} = \frac{1}{\alpha_1} \quad (2)$$

$$R_{cond1} = \frac{L1}{\lambda_1} \quad (3)$$

$$R_{cond2} = \frac{L2}{\lambda_2} \quad (4)$$

$$R_{conv2} = \frac{1}{\alpha_2} \quad (5)$$

$$R_{cond3} = \frac{L4}{\lambda_4} \quad (6)$$

$$R_{conv3} = \frac{1}{\alpha_3} \quad (7)$$

For the evaluated system, the total resistance was $R = 0.458 \text{ m}^2\text{K/W}$ and the conductivity was $U = 1/R = 2.184 \text{ W/m}^2\text{K}$, close to the initial reference assembly value of $U = 2.547 \text{ W/m}^2\text{K}$. This results in better insulation in the 2-GW system with PDLC, as the PDLC film is a good thermal insulator. As a next step, the calculated values, as well as the specific values from the manufacturer's specifications (e.g., reflection, refraction, transparency, and UV and IR refractivity), are defined in DesignBuilder. After all calculations, including the new PDLC window calculation and design, DesignBuilder creates a 5:1 simulated room similar to Models 1 and 2. To maintain the similarity of the geometry and window-to-wall ratio, the two

simulated rooms with general dimensions of 5 m × 5 m × 3 m (L×W×H), with a 2-GW system having dimensions (each) of 1.8 m × 1.025 m (H×L), were created in DesignBuilder (Fig. 6).

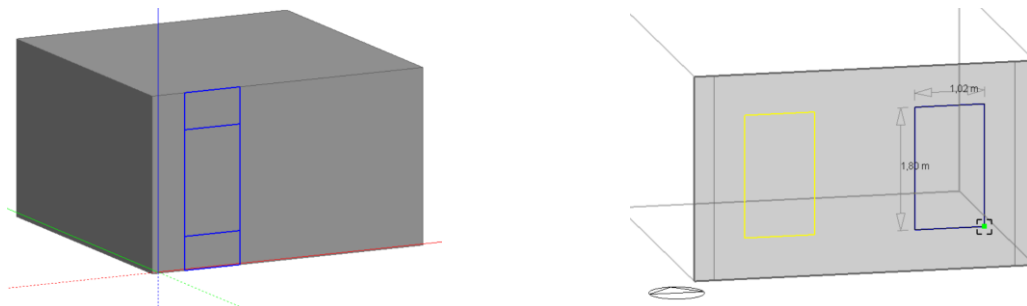


Figure 6. Simulated room and window design and definition in DesignBuilder.

The theoretical energy consumption was generated in DesignBuilder for two NSRs, one without PDLC (NSR 1) and one with PDLC (NSR 2), with the results presented in Table 7.

Table 7. The energy consumption for NSR 1 – without PDLC and NSR 2– with PDLC

Energy consumption with:	NSR 1 [kWh]	NSR 2 [kWh]	Energy variations [%]
Miscellaneous (including PDLC) [kWh]	452.31	453.46	-0.25%
Lighting [kWh]	653.35	710.85	-8.80%
Heating [kWh]	1,817.79	1,688.36	7.12%
Cooling [kWh]	74.61	63.13	15.39%
Hot water [kWh]	40.91	40.91	0.00%
Total	3,038.97	2,956.71	2.71%

3.2. DISCUSSION

Although Model 2 (with PDLC) consumes more total energy than Model 1, the absolute consumption is small (due to the model size), and any idle consumption from additional systems, such as the PDLC, becomes significant. Generally, at larger windows in large buildings (like NSR), the PDLC system electrical consumption becomes insignificant, as shown in Table 7, where, as a percentage of total energy consumption (including miscellaneous, with PDLC), a total energy economy of 2.71% is registered even in a period without high sun intensity. Therefore, for the studied experimental models, the main focus should be strictly on heating, cooling, and lighting savings, where the PDLC system achieves a total saving of 65.7 Wh relative to total consumption, representing an overall energy saving of 6,29% for these three categories. Because this is an early-stage calculation, it is limited to an NSR (5 times larger than the experimental models, but with the same geometry and window-to-wall ratio) to facilitate validation of the initial results. After collecting a more complex dataset and refining the calculations, we will define the new parameters in DesignBuilder and simulate their behavior under real conditions, allowing simulation of any building type. Therefore, for the moment, a theoretical saving of 2.71% is recorded for NSR 2 (with PDLC), related to the analyzed period (cold period), which can be explained mainly by the additional insulation and small UV and IR reflection of the PDLC system (data being gathered in an inter-season). The importance of glazed windows is increasing because of pollution and ozone depletion, along with rising UV and IR radiation levels. Therefore, window shading plays an increasingly important role; from this perspective, this study proposes to analyze a modern shading system for a studied building [19] using PDLC film that can be applied to any existing window. According to other studies [20], PDLC technology does not negatively affect human visual perception and maintains stable visual intensity, even with considerable variations in outside light intensity. Although

manufacturers provide data on PDLC film behavior in the ON or OFF state, additional research is still needed on the behavior of the latest ultra-transparent technology under continuous modulation.

This study also proposes, under the title of innovation, the control of an ultra-clear PDLC film based on a light sensor that will aim to maintain an optimal light intensity in such a way that when the PDLC film closes/becomes opaque, the building's insulation characteristics increase and implicitly reduce energy consumption for air conditioning (especially in summer). However, it must not fall below the visual comfort zone, as regulated by EU and Romanian norms and legislation. Preliminary data, according to Table 3 for the registered period (3 days in September), shows no meaningful difference between proposed models. Still, it is again of great importance to highlight that much better results are expected on warm/sunny days, when the PDLC system will actively block the solar radiation, including UV and IR light, and thus reduce the energy consumption impact needed for cooling, corroborated by greater-scale applications, where the miscellaneous consumption with the PDLC system becomes insignificant. After obtaining the results and observing the models' behavior, the next stage of the study was to calculate the properties of the proposed 2-GW system with PDLC film assembly to implement a modulating PDLC system in DesignBuilder.

If the collected final data demonstrate the energy and economic efficiency of the proposed system, implementing PDLC film in a smart home can be achieved quite easily, as PDLC film is compatible with a series of management systems, including IoT [21]. Moreover, according to the latest studies and developments of PDLC technology, the power consumption of this technology will have better results by means of lowering the voltage feed modulation [22], complemented by the integration of a specific micro-modulation driver [23] or even interconnected with a photovoltaic hybrid window [24] to even produce energy by means of using smart glazing spaces. The simulated period in DesignBuilder can be extended to the warm and sunny period (May to September), but more experimental data are needed. So even if the values are very close for the cold period, the preliminary results are promising. Better results could be expected on sunny days, when the PDLC system will play an essential role in blocking solar rays (including UV and IR) rather than acting only as a supplementary insulator integrated into the 2-GW system. As a further study, the cardinal orientation of the experimental models can be investigated to determine the real energy impact of PDLC window positioning and, eventually, the color change of the films with dual-responsive fluorescence and phosphorescence for multicolor pattern display [25].

4. CONCLUSIONS

This study demonstrates the effectiveness of integrating smart Polymer Dispersed Liquid Crystal (PDLC) film into classical double-glazed window (2-GW) systems to reduce building energy consumption. By scaling the experimental results through numerical simulations in DesignBuilder, the analysis indicates an overall energy reduction of 2.71% for climate control, even during an intermediate season with moderate solar radiation. These findings validate the system's ability to block unwanted UV and IR gains while providing adaptive shading, suggesting that higher savings can be expected under increased solar exposure. PDLC technology proves to be a practical and easily deployable solution for existing window systems, directly supporting Nearly Zero-Energy Building (nZEB) requirements by reducing cooling and heating loads. Furthermore, the calibrated PDLC model developed in this study and integrated into DesignBuilder offers a robust framework for accurately extrapolating and evaluating the full energy impact of PDLC systems for any building configuration.

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