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Energy Efficiency of Windows Integrating Electrophoretic Light Modulators

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Abstract

ELM (Electrophoretic Light Modulator) is a smart glass technology that modulate light transmission in the visible range from 0.1% up to 70% while also modulating the near Infrared spectra. ELM integrated windows demonstrate the ability to match ideal dynamic window thermal range and energy savings compared to standard glazing.

Keywords

Electrophoretic, Light Modulator, Dynamic Window, Smart Glass

Article Information

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1. Dynamic window with Electrophoretic Light Modulator (ELM)

A dynamic window integrating ELM benefits from a very broad transmittance range (typically from 0.1% to 70% - Figure 1). Current ELM windows absorb both visible and near infrared spectra. ELM technology is extremely versatile and can be adapted or modified to specific applications. It is based upon electrophoretic principles. An electrophoretic ink is placed between 2 transparent substrates (Figure 2). Metal electrodes are patterned on each of the substrates. By driving electric fields between the electrodes facing each other from bottom to top substates, the charged pigments (responsible for the dark state of the window) are displaced and grouped underneath the electrodes and therefore out of the field of view. The window becomes transparent. The technology enables efficient and affordable dynamic windows to better regulate visual and thermal comfort as described below. The study first establishes ideal dynamic window market performance for multiple locations, then detailed various dynamic window configurations and the impact on energy savings.

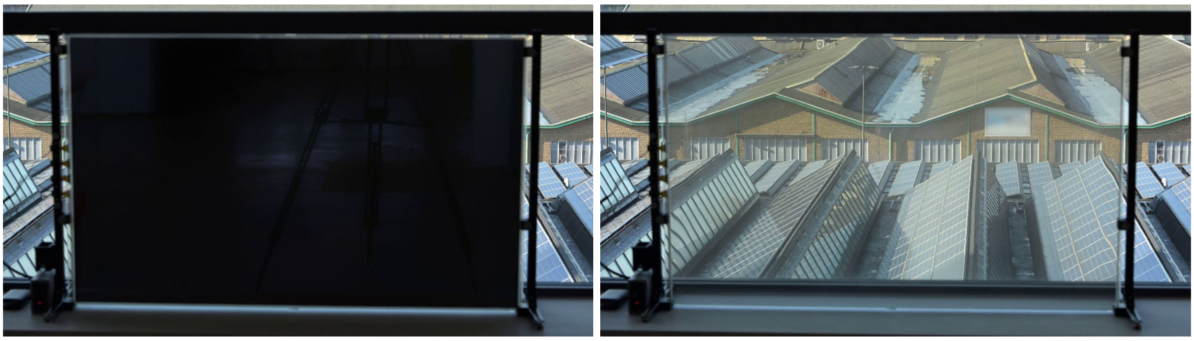

Fig. 1: ELM integrated laminated window (1x0.6m) – Left: Dark state, Right: Clear state.

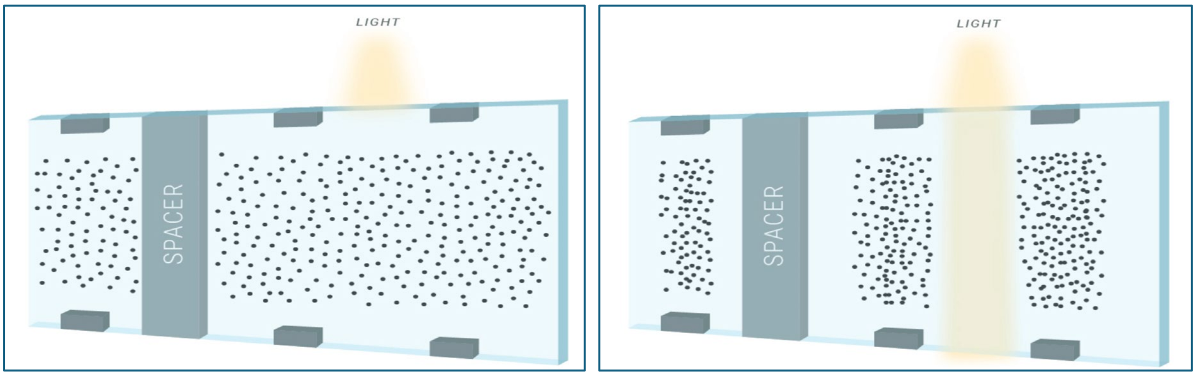

Fig. 2: ELM principle – Left: Dark state, Right: Clear state.

2. IGU thermal ideal performance values

Here are reported the ideal performance values (g-value, light transmittance) to be achieved in three climates considered (Amsterdam, Los Angeles, Dubai). Those values are interpreted from the local Building codes regulations and adapted to a dynamic window purpose. Please note that the dark state transmission is always set at 0.1% to provide privacy effect.

Table 1: Ideal g-value and light transmittance for Amsterdam, Los Angeles and Dubai.

City	Dark state Light transmittance	Dark state g-value	Clear state Light transmittance	Clear state g-value
Amsterdam	0.1%	0.05 - 0.15	55%-70%	0.30 – 0.50
Los Angeles	0.1%	0.01 – 0.10	55% - 65%	0.25 – 0.40
Dubai	0.1%	0.01 – 0.10	40% - 60%	0.28 – 0.35

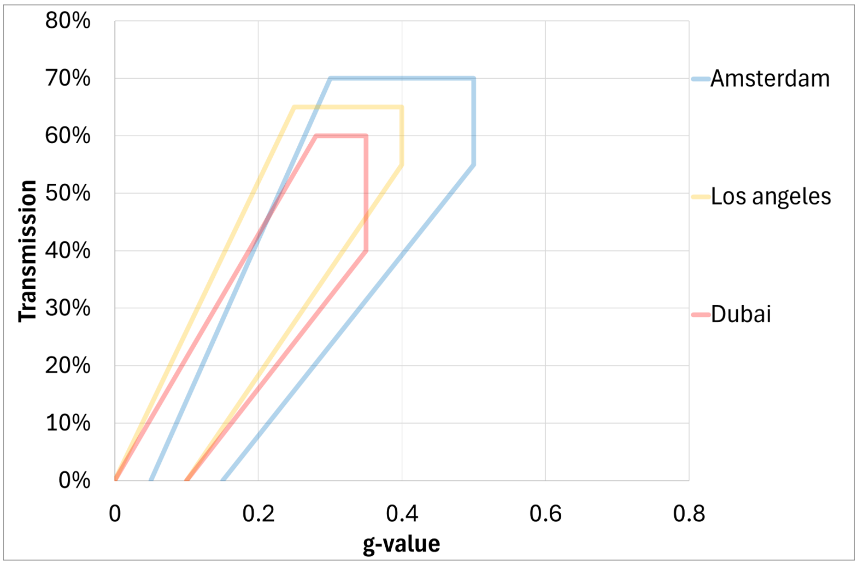

Fig. 3: Thermo-Optical ideal ranges for a dynamic window for Amsterdam, Los Angeles and Dubai.

3. ELM Integration into an IGU

ELM developed to date used an electrophoretic ink based on black pigments to create the light modulation. In the dark state, the ELM appears black and absorbs the visible and infra-red (IR) wavelengths (Figure 4).

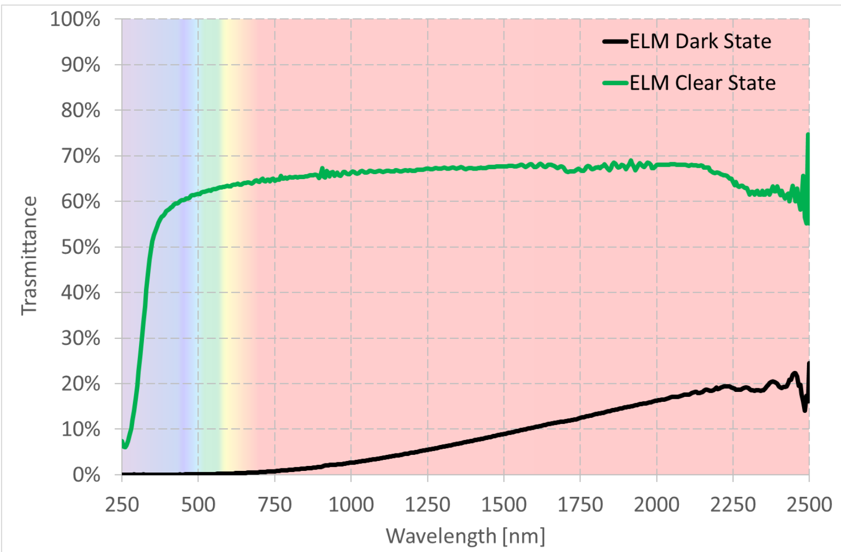

Fig. 4: Example of an ELM optical transmission in clear and dark states.

G-values of the ELM and of the window integrated ELMs were calculated from their respective spectral properties using the OPTICS 6.0 and WINDOW v7.8.74.0 software from Berkeley Lab. As the ELM in dark state will absorbs most solar energy from UV, visible and near IR wavelengths, it will behave thermally as a black body and remit heat in both directions. Consequently, as shown in Figure 5, the g-value range versus the transmission range is outside the ideal ranges for the chosen locations: Amsterdam, Los Angeles and Dubai. The thermal conduction is too high at clear state while the radiated black body behaviour of the dark state impacts the thermal insulation.

To prevent the thermal mismatch for those dedicated regions, integrating the ELM into an IGU is therefore beneficial. Various configurations were evaluated and summarized in Table 2 and Figure 5.

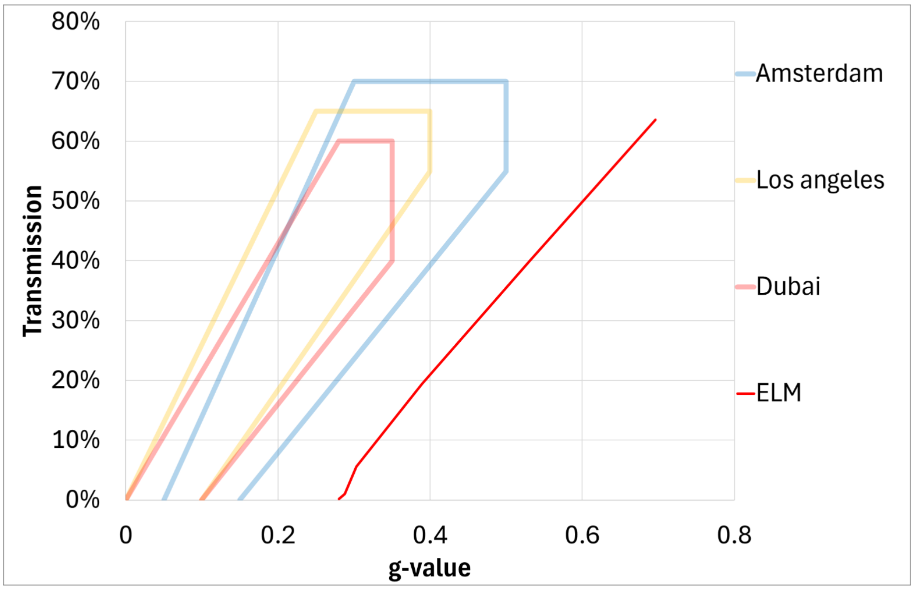

Fig. 5: ELM thermo-optical modulation.

Table 2: Double Glazing Unit build up including ELM and performance.

	Laminate 1	DGU 1 ELM + Low-E	DGU 2 ELM + HPC
#1	Float glass mid-iron 4mm	Float glass mid-iron 4mm	Float glass mid-iron 4mm
#2	PVB	PVB	PVB
#3	ELM	ELM	ELM
#4	PVB	PVB	PVB
#5	Float glass mid-iron 4mm	Float glass mid-iron 4mm	Float glass mid-iron 4mm
#6		Air/Argon 16mm	HPC
#7		Low-E	Air/Argon 16mm
#8		Float glass mid-iron 4mm	Float glass mid-iron 4mm
Transmission range	0.002 – 0.667	0.002 – 0.685	0.002 – 0.609
g-value range	0.322 – 0.679	0.161 – 0.538	0.155 – 0.345

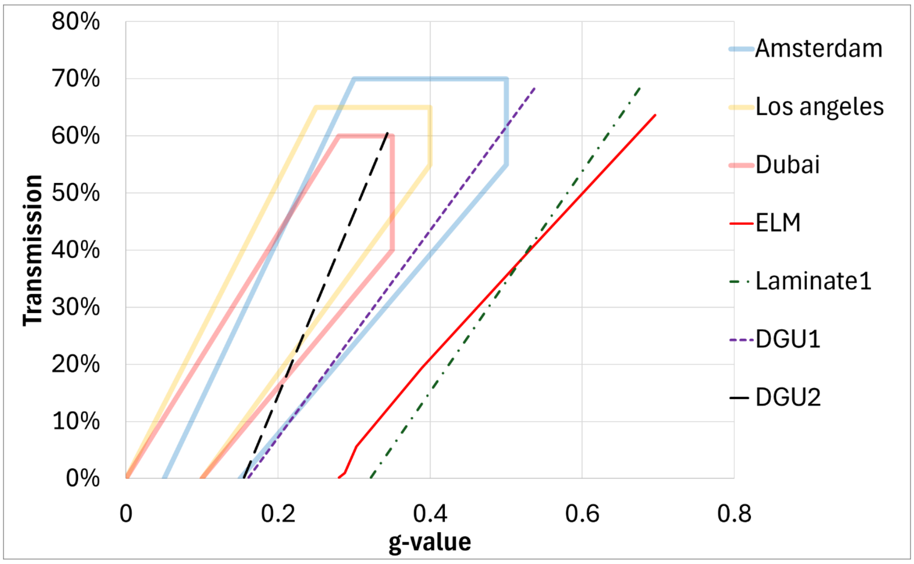

Fig. 5: Thermo-Optical of ELM windows Laminate 1, DGU1 and DGU2.

The addition of the air/argon insulated layer clearly diminish as expected the thermal conduction through the window. The additional coatings (low-E or HPC) acts on the steepness of the curve and the ability to better fit specific climates. It has to be noted that despite the use of the HPC, the dark state g-value is still too high for Los Angeles or Dubai climates. Considering this, only the Amsterdam climate (tempered climate) was studied for energy savings.

4. Shoebox Model description

The energy modelling was undertaken for a 'shoebox' geometry consisting of a rectangular volume representing the perimeter zone of a typical commercial building. These types of models are often used to establish the impact of facade design changes on energy performance as they're less complex to create and faster to run than whole building energy models. The shoebox geometry was based on the BESTEST Case 600 Low Mass Building, which considers a rectangular single zone (8m wide x 6m long x 2.7m high) with no interior partitions and 12m2 of windows on the external elevation. (EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001 (BESTEST) (lbl.gov)). This geometry corresponds to a glazing ratio of 55%, representing a high glazing ratio for commercial buildings in London and typical of Northern Europe generally. This was not changed depending on the location.

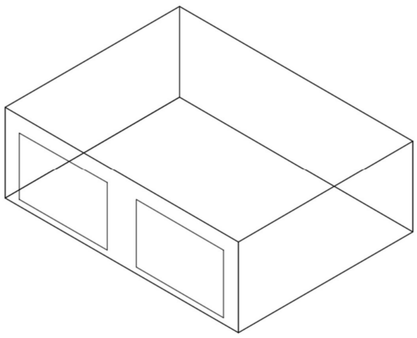

Fig. 6: BESTTEST Case 600 shoebox geometry.

The following assumptions were made in the energy model:

- Occupied hours were assumed to be 8am-6pm on weekdays (LETI – Operational Energy Modelling Guide – Mid Range). No occupancy on weekends or holidays.
- Occupant density was 0.1 Ppl/m2
- The ventilation rate was 12l/s/person. This is equivalent to 58l/s.
- The heating setpoint was 21ºC
- The heating setback temperature when unoccupied was 12ºC
- The cooling setpoint was 24ºC
- The cooling setback temperature when unoccupied was 50ºC
- Heating and cooling loads were scheduled to be on during occupied hours and off at other times.
- The energy loads are calculated as ideal air loads with a Coefficient of Performance applied to adjust the results considering the efficiency of the mechanical systems. The COP shall be taken as 2.5 for winter and 3.5 for summer, representing all electric heat pump-based systems.

A key element of the energy modelling is how the dynamic glazing is controlled as this determines what the performance of the glazing is at each timestep in the model. The objective of the control strategy was to reduce energy consumption while maintaining acceptable internal daylight levels. To achieve energy savings, a different approach is required if there is heating or cooling demand at each timestep. Therefore, one of the three states below was selected based on whether the zone temperature was within the setpoint range, above it or below it:

- If the zone temperature exceeds the setpoint temperature (cooling demand), the glazing is placed in the darkest possible state while maintaining a minimum internal daylight level in order to reduce solar gain.
- If within the setpoint range, the glazing is placed in the lightest possible state while not exceeding a daylight threshold.
- If the zone temperature is less than the setpoint temperature (heating demand), the glazing is placed in the lightest possible state while not exceeding a direct daylight threshold in order to increase solar heat gain.

The acceptable range of daylight was assessed using the Annual Solar Exposure (ASE) and Spatial Daylight Autonomy (sDA) metrics. ASE refers to the percentage of space that receives too much direct sunlight (1000 Lux or more for at least 250 occupied hours per year) at the work plane height, which can indicate increased risk of glare and visual discomfort. The sDA describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours (8am-6pm) on the horizontal work plane. The ASE represents the upper bound of the acceptable daylight level, while sDA represents the lower bound. The daylight level was assessed by measuring the daylight levels at each timestep on an evenly distributed grid of control points across the internal space at 850mm above FFL, representing design horizontal work plane height. The glazing state at each timestep was selected from a series of pre-defined coefficients (scaling between dark and light states) based on the measured daylight levels on the work plane. This required an iterative process to set the coefficients, run the analysis, post-process the results to calculate the daylight metrics and then adjust the coefficients if the daylight metric thresholds were not met. This was undertaken for the South elevation of each location to optimise the control for the elevation which has the greatest solar exposure and therefore largest potential for energy benefits.

The annual numerical simulations to assess the energy and daylight performance were carried out by means of the software IDA ICE (https://www.equa.se/en/ida-ice).

5. Energy Savings with ELM included windows

For comparison, the baseline window was assuming a double glazing unit with a g-value of 0.35 and a transmittance of 65%.

5.1. Energy

The eLstar + HPC (DGU2) configuration shows an improvement both compared to the baseline (-18.1% to -40.2%) and to the eLstar + Low-E (DGU1) (-7.7% to -15.2%). With DGU2, the most significant improvement is obtained for the South orientation, for which both heating and cooling needs are reduced, while for the other orientations the cooling need is reduced while the heating need is increased.

5.2. Daylight control (ASE)

A significant improvement in terms of daylight control is observed for all the orientations, with a reduction between - 77.0% and -100.0% compared to the baseline and from -18.6% to -100.0% compared to the eLstar + Low-E (DGU1). The higher reduction compared to the baseline was obtained for the South orientation, while if the eLstar + Low-E is considered, the highest ASE decrease is observed for the West orientation.

5.3. Daylight availability (sDA)

A performance decrease is observed, even if less significant than the improvement observed for the daylight control assessment. In more detail, the sDA shows a percent reduction between -28.0% and -69.8% compared to the baseline and from -9.4% to -33.6% compared to the eLstar + Low-E (DGU1). The higher reduction compared to the baseline was obtained for the North orientation, while if the eLstar + Low-E is considered, the highest sDA decrease is observed for the South orientation.

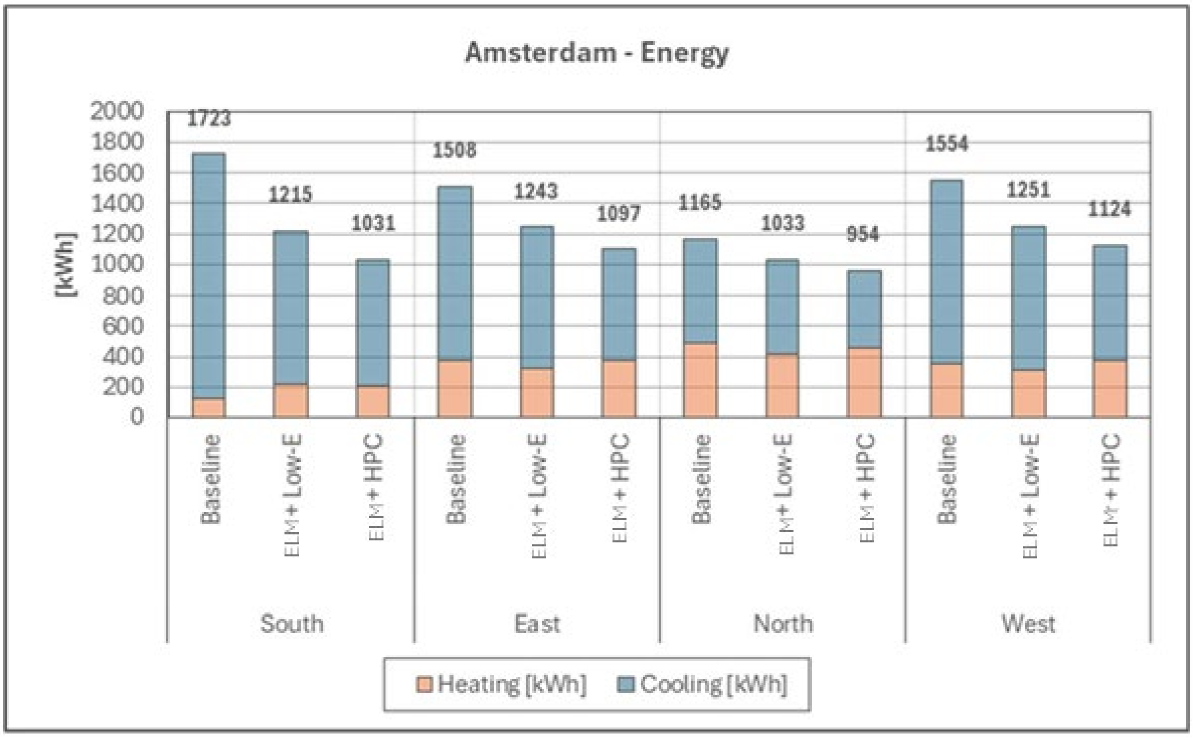

Fig. 7: Energy results for the climate of Amsterdam.

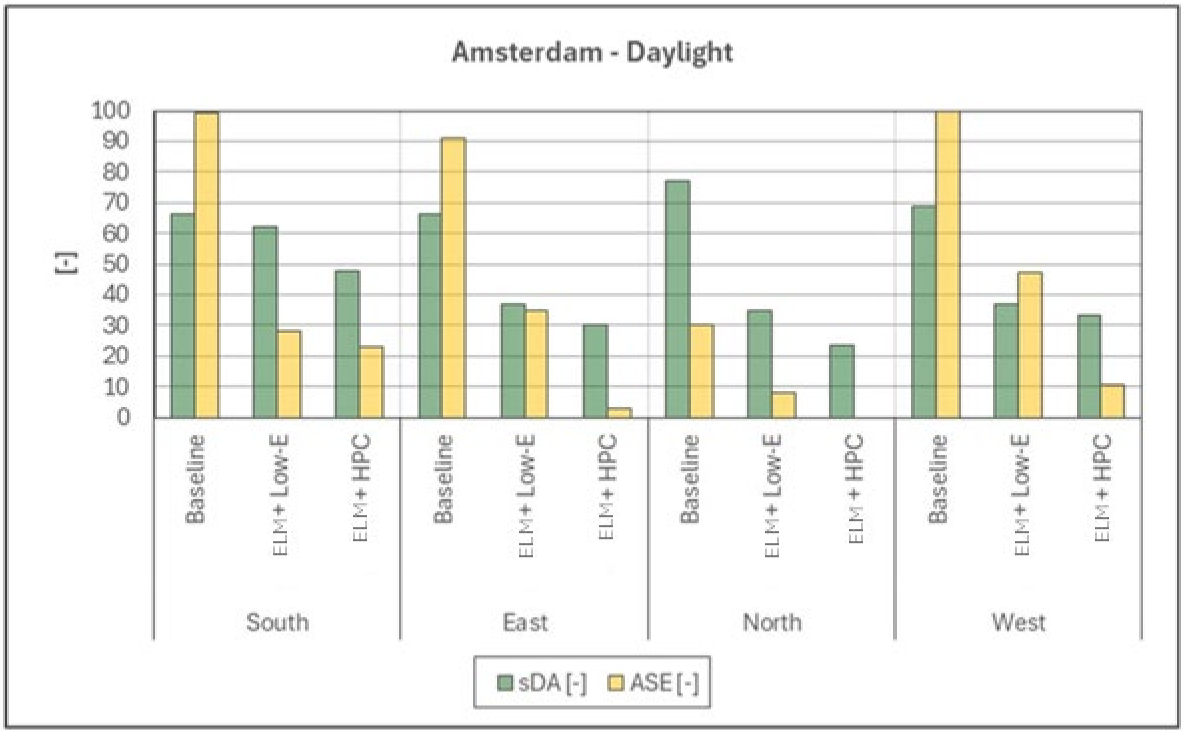

Fig. 8: Energy results for the climate of Amsterdam.

6. Conclusions

For temperate countries, ELM integrated windows show significant energy savings for both cooling and heating conditions while maintaining sufficient natural daylight in the room. South facades show more significant reduction and should be used as the guideline as the model was optimized for such orientation. For hotter climates as Los Angles or Dubai, the current configuration of the ELM irradiates back too much energy into the room as behaving as a black body. The dark state g-value of the simulated ELM integrated windows is still too high to enable sufficient energy savings. For such regions, the ELM integrated windows can be modified to repulse infra-red further. A first option is to modify the electrode coverage to enhance the light reflection and by default limiting the transmission. A second option would be to modify the ink as for example using a white ink to operate from white opaque to clear transparent or modify the optical characteristic of the current black ink. Current ELM performance is based on a broadband black ink, targeting visible light control, as well as energy management. An independent control of visible light and energy modulation will be achieved in the future by manipulating multiple pigments.