

LONG-TERM ENERGY CONSUMPTION FORECASTS FOR HEATING AND COOLING OF A KINDERGARTEN CLASSROOM USING VARIOUS SHADING SYSTEMS – CASE STUDY

Veronika TALAŠOVÁ ^{1*}, Adela PALKOVÁ ¹

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Abstract

This study analyses the long-term impact of climate change on the energy consumption for heating and cooling of a standard nursery school and evaluates the energy efficiency of three different shading systems applied to a south-west facing classroom. Simulations were performed in DesignBuilder/EnergyPlus software using 225 future climate datasets for the years 2025–2100, which were derived from the Special Report on Emission Scenarios (SRES), using the A2, A1B and B1 scenarios with statistical downscaling. The results show a systematic decrease in energy consumption for heating and a simultaneous increase in energy consumption for cooling, with scenario A2 showing the highest dynamics of change. A comparison of the shading systems shows that exterior blinds are the most effective in reducing cooling energy consumption ($\approx 39\text{--}40\%$), followed by thermochromic glazing ($\approx 13\text{--}16\%$). Interior blinds do not have a significant effect in terms of cooling energy consumption. All the shading options cause a slight increase in heating energy consumption due to the reduction in winter solar gains, but this is minimal for exterior and interior blinds. The study emphasises the importance of passive measures in the long-term adaptation of buildings to changing climatic conditions and the optimisation of the energy efficiency of buildings.

Address

^{1*} Dept. of Building Construction, Faculty of Civil Engineering STU, Bratislava, Slovakia

* **Corresponding author:** veronika.talasova@stuba.sk

Key words

- Climate change,
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- Energy efficiency,
- Cooling energy consumption,
- Heating energy consumption,
- Shading,
- Thermochromic glazing,
- External blinds,
- Internal blinds.

1 INTRODUCTION

Global climate change represents one of the most significant factors affecting the energy performance of buildings. Rising average temperatures, along with changes in temperature extremes are causing a shift in the structure of energy consumption, particularly in terms of heating and cooling.

Energy consumption for heating is expected to decrease in many regions, while energy consumption for cooling is expected to increase, often at a faster rate than current energy systems are able to meet (IPCC, 2022). These changes are increasing the pressures and demands for buildings to adapt to new climatic conditions.

Regulating and optimising energy consumption in the context of energy efficiency in buildings is a key factor in achieving sustainable development goals and reducing greenhouse gas emissions. This includes, in particular, measures to improve the thermal insulation of buildings, increase the efficiency of technical equipment, digitise energy management, and promote renewable energy sources (IEA, 2023).

Climate change poses a challenge for building designers, primarily because the long-term goal of the global community is to reduce energy use in order to limit the extent of future climate change caused by human activity. Since people spend 80 to 90% of their time in buildings, it is necessary to prepare buildings for a changing climate in order to create conditions that will not negatively affect the comfort, health, and productivity of people in buildings (Herrera et al., 2017).

Children in kindergartens are a special group of users; a kindergarten school building must provide a comfortable indoor environment throughout the year (in both the cold and warmer months). The issue of thermal comfort in kindergartens was also addressed by Stiborová et al. (2025), who used dynamic simulation and CFD analysis to evaluate the indoor environment of a kindergarten classroom. Their results highlighted the importance of proper ventilation design and indoor environment control in ensuring children's thermal comfort. The type of shading and the quality of window glazing are among the key factors that affect a building's heat gains and indoor comfort throughout the year. These requirements make kindergartens an ideal case for analysing the impact of passive measures on energy consumption. Properly designed shading elements can significantly reduce demands on cooling and heating systems, which have a direct impact on a building's energy balance.

In a study by Pérez-Carramiñana et al. (2024), it was demonstrated that interior shading in a hot, dry Mediterranean climate reduced the need for cooling by only about 25%, while exterior movable shading achieved a cooling reduction of >60% under comparable conditions, while maintaining an appropriate level of daylight. Another study by Lee et al. (2025) evaluated automated interior motorized roller shutters and blinds in a real-world high-rise commercial building over 44 weeks, where the installation of roller shutters and blinds was an alternative to window replacement, which appeared to be cost-prohibitive and most likely unfeasible. The results showed that with the use of smart controls, total daily energy consumption could be reduced by up to 20.5%, while manually operated interior shading yielded savings of ~11.8% compared to the baseline condition without shading, with an average payback period for the initial investment of 15.1 years. Simulation studies also suggest that interior shading elements can be effective in reducing solar heat gains and glare, but their direct impact on energy consumption tends to be lower compared to exterior systems and depends on the method of control and integration with management strategies (Jongki et al., 2025). Research clearly shows that exterior shading (e.g., blinds, louvers, awnings) is more effective in terms of energy savings than interior shading, as it blocks or reflects solar radiation before it enters the building. In the

aforementioned study by Pérez-Carramiñana et al. (2024), exterior movable shading reduced the need for cooling by more than 60%, which significantly exceeds the effect of interior shading (25%). Similarly, a comprehensive evaluation of shading systems and their control strategies (Kurwan and Bhandari, 2020) confirms that integrated exterior shading and control systems can reduce total energy consumption by up to ~28% compared to a situation without shading. Furthermore, experimental studies and parametric simulations indicate that well-designed and controlled exterior shading can reduce the thermal load and the need for active cooling by 25–40% in building models under various climatic conditions, with differences depending on the orientation of the facade and local solar conditions (Dudzińska, 2021). Other studies emphasize that the method of controlling shading elements significantly affects their energy efficiency. Automated and dynamic control based on outdoor conditions, time of day, and indoor target temperatures can maximize energy savings and user comfort (Jongki et al., 2025). The importance of shading in regulating the indoor environment was also confirmed by the simulation study of Ponechal and Chabada (2021), which indicates that properly controlled blinds, in combination with natural ventilation, can significantly affect indoor temperatures during the summer period. These results are particularly relevant in the context of climate change, where an increase in average summer temperatures and significantly higher solar radiation are expected. This brings exterior shading to the forefront as a measure to minimize the need for cooling and the risk of overheating the indoor environment. At the same time, the need for intelligent or at least rule-based control of blinds is highlighted in order to maximize solar gains in winter and minimize overheating in summer.

In contrast, thermochromic glazing automatically adjusts its solar transmittance, depending on the glazing temperature. Mann et al. (2020) conducted an extensive simulation study of energy consumption, comparing traditional static energy-efficient glazing with new thermochromic glazing in various climatic regions. According to the simulation results, thermochromic glazing can reduce annual energy consumption by up to 22% compared to clear glass, which was significantly higher than for other types of glazing, particularly in transitional climates with combined heating and cooling needs. In a simulation of thermochromic glazing, Teixeira et al. (2022) found that thermochromic glass can improve a building's energy performance by up to approximately 50% under conditions with significant solar gains during the summer months. Thermochromic glazing also increases the number of hours during which indoor thermal comfort is maintained without mechanical cooling or heating, by up to approximately 48% in some climate zones. The results of these studies suggest that thermochromic glazing has the potential to reduce energy consumption for cooling, particularly in climate zones where summer heat loads are combined with cooler periods. Therefore, thermochromic glazing is considered a promising level of adaptive systems for buildings exposed to climate change.

The above overview confirms that the literature contains numerous studies focused on the energy optimization of office and residential buildings; however, more detailed analyses of

kindergartens (considering their specific operational schedules and the type of spaces used), which consider different types of shading systems and their effect in different climate scenarios, are still limited. In the context of ongoing climate change, it is therefore essential to examine how passive measures can contribute to the energy efficiency of buildings over a period of decades. Taking long-term climate scenarios into account makes it possible to design buildings that will be resilient to future conditions and energy efficient at the same time.

This study evaluates the development of annual energy consumption for cooling and heating a standard kindergarten and the annual energy consumption for heating and cooling a specific kindergarten classroom using three fundamentally different shading strategies. The first strategy uses dynamic self-regulating shading with thermochromic glazing, while the second and third options involve manually operated interior and exterior blinds, with user-dependent control. The energy impacts of all three approaches are analysed over the long term until 2100 based on climate scenarios for the future climate.

2 METHODOLOGY

For the purposes of the simulation, 225 future weather files in the epw format were required for the period from 2025 to 2100 (75 files for each of the three climate scenarios). The kindergarten building was modelled using DesignBuilder software, which serves as a graphic interface for the EnergyPlus calculation programme.

2.1 Creation of the climate files for the period 2025–2100 – data processing methodology

Within this study, it was necessary to work with a long-term time series of climate data, which represents not only historical but also projected future climate conditions in Slovakia. The datasets used were processed and provided by Ing. Ján Hollý, who has long been engaged in the construction of future test climate years based on climate scenarios for individual years up to 2100. These scenarios are based on methodologies commonly used in climatology to create locally adapted (downscaled) projections based on global and regional climate models.

The primary measured climate data for the period 1951–2014 were provided by the Slovak Hydrometeorological Institute (SHMÚ). These included daily measurements of air temperature, precipitation, relative humidity, and wind speed, which served as the basis for statistical processing and the subsequent creation of climate scenarios.

IPCC SRES emission scenarios were used to create future climate time series, specifically:

- A1B – processed from the KNMI regional model,
- A2 and B1 – processed from the CGCM3.1 global model.

These scenarios represent different possibilities for future

socio-economic and emission developments, thereby leading to different climate predictions. More significant differences between the individual scenarios begin to emerge after approximately 2040, which is also consistent with the results of other European climate projections.

Scenarios of daily averages and extremes of climatic elements were constructed using the methodology described in the available literature. A key step was statistical downscaling, which allows the outputs of climate models with a coarser spatial resolution to be converted into the local station conditions (e.g., Lapin et al., 2012).

For the CGCM3.1 model, the spatial variability was defined by nine grid points around Slovakia. The KNMI regional model worked with a denser network of 190 grid points. For the downscaling, the four nearest grid points were always used for each station and were supplemented by the data measured from the reference period 1961–1990 at that station. This approach ensures that for time series longer than 25 years, both the characteristic variability and the distribution curve of each climate variable are preserved.

It is important to emphasise that these time series do not represent an accurate forecast for a specific day or month, but rather climate scenarios – i.e., the likely climate in the coming decades.

The EnergyPlus simulation software requires hourly meteorological data as the input for the energy consumption calculations. Therefore, it was necessary to convert the daily temperature values provided to hourly values. This conversion was performed using an algorithm based on trigonometric functions. The daily minimum, maximum and average air temperature values were used as the basis for adjusting the input data. The conversion assumed that the daily minimum temperature occurs approximately one hour before sunrise, while the maximum temperature is reached approximately two hours after the sun's zenith (i.e., around 2 p.m.). This time lag corresponds to the delayed response of the atmosphere to the intensity of the solar radiation that affects daily warming. The temperature profile during the day between these extremes was modelled using sinusoidal functions, which were then adjusted so that the daily average temperature remained unchanged (Hollý and Palková, 2018). The hourly temperature profiles processed in this way made it possible to create comprehensive climate files compatible with EnergyPlus, which served as the input for the energy simulations of the individual locations.

The climate years used in this study were derived from the EnergyPlus Weather file (EPW) reference file for Ivanka pri Dunaji and Bratislava, which is part of the official DesignBuilder software database. This file represents a standardised Typical Meteorological Year (TMY), which was created by selecting representative months from long-term climate series. For the purposes of this study, the individual future years were then recalculated from the existing EPW file using scenario-based corrections of the climate variables that reflected projections derived from the SRES emission scenarios. This procedure allows for the physical coherence of climate variables on an hourly scale to be maintained, which

is essential for energy simulations of buildings and modelling the thermal behaviour of the structures to be analysed.

2.2 SRES scenarios and the justification for their use

In 2000, the Intergovernmental Panel on Climate Change (IPCC) published Special Report on Emissions Scenarios (SRES) scenarios that represented different visions of future socio-economic developments. Each SRES scenario contains a precisely defined trajectory of the population, economic growth and technological development. The emissions are calculated from these socio-economic assumptions (IPCC, 2000). The most commonly used scenarios in regional modelling are:

- A1B – rapid economic growth, homogenisation of the global market, technological progress, balanced energy mix,
- A2 – a regionally oriented world with a high population growth and slow technological development,
- B1 – a globalised, environmentally oriented world with population stabilisation and efficient technologies (IPCC, 2000).

Unlike older SRES scenarios, Representative Concentration Pathway (RCP) scenarios are not derived from socio-economic assumptions, but are defined according to the target level of radiative forcing caused by human activities by 2100. Four basic trajectories i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5, represent 2.6, 4.5, 6.0 and 8.5 W/m² of additional radiative forcing (Moss et al., 2010). Shared Socioeconomic Pathways (SSPs) are a new generation of detailed socio-economic pathways, which can be paired with RCPs into SSP–RCP combinations, thereby enabling the creation of consistent climate-society projections (van Ruijven, 2014).

Tab. 1 Link between SRES, RCP and SSP

SRES	Approximate emission equivalence RCP	Closest SSP framework	SSP-RCP combination
A2	RCP8.5	SSP3	SSP3-6.0
A1B	RCP6.0	SSP2	SSP2-4.5
B1	RCP4.5	SSP1	SSP1-2.6

Although the SRES scenarios no longer represent the latest generation of emission projections, their use in this work is methodologically and practically justified. Regional climate data based on SRES scenarios provide the most comprehensive source of information available for analysis.

Newer datasets based on SSP-RCP are not available in an adequate temporal resolution, spatial resolution, or in the complete set of climate variables needed for this analysis.

Table 1 provides a clear mapping of SRES scenarios to

RCPs and SSPs, which allows the results to be interpreted in the context of the latest literature. Therefore, the results obtained from SRES scenarios can be compared with modern trajectories by enhancing their interpretability and relevance in the context of current scientific knowledge.

At the same time, it is important to emphasise that the primary objective of the energy simulations in this study is not to provide precise quantitative predictions of future climate conditions, but rather to capture trends in the energy consumption of buildings in the context of a changing climate. The simulations of future climate years are mainly used to identify the direction and relative intensity of changes that climate change may cause in the energy performance of buildings. The aim is to understand how sensitive the building analysed is to changing climatic conditions and how the effectiveness of individual measures changes in different emission scenarios. In this context, even older SRES scenarios allow for a reliable assessment of the relative differences between future states and provide a sufficient framework for identifying trend shifts, which are crucial for strategic building renovation planning and investment decision-making.

3 MODEL

3.1 Model description – the building

The kindergarten in the village of Miloslavov (Slovak Republic) was selected as the reference building for energy simulation purposes. It represents a building stock constructed in the 1970s using cinder concrete blocks. This construction system is characterized by the poor thermal performance of the building envelope and high operational energy demands.

The kindergarten building was approved in 1974 and began operating in 1975. The original function of the building remains unchanged to this day. The site is located on flat terrain.

The building is a detached structure with a rectangular floor plan measuring approximately 32.610 m x 23.910 m (Fig. 2). It is a single-storey building with a flat roof. The roof was renovated in 2009; in 2011, the infill structures of the perimeter shell were replaced; and in 2012, the facade was renovated. This consisted of insulating the facade with 80 mm thick polystyrene and installing a 200 mm thick insulated ceiling in the interior. The building model was based on actual measurements carried out by the authors of the project "Thermal insulation of the Miloslavov kindergarten".

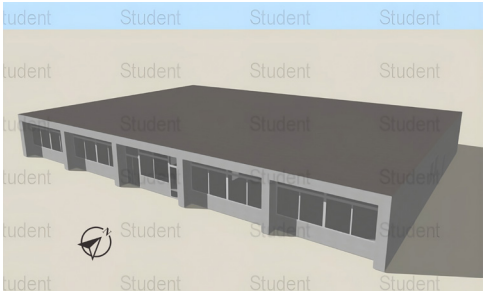


Fig. 1 3D geometry of the building created in DesignBuilder



Fig. 2 Floor plan of the kindergarten building in Miloslavov with the location and basic dimensions of the corner classroom analysed

Tab. 2 Overview of input data – structures

Construction	Layers	Conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m³)	U (W/m².K)
External wall	Lime-cement plaster, 20 mm	0.9900	790.00	2000.00	0.323
	Cinder concrete blocks, 400 mm	0.5200	830.00	900.00	
	Lime-cement plaster, 20 mm	0.9900	790.00	2000.00	
	Adhesive render, 3 mm	0.800	1000.00	1350.00	
	EPS-F polystyrene, 80 mm	0.040	1270.00	18.00	
	Adhesive render, 3 mm	0.800	1000.00	1350.00	
	Silicate plaster, 3 mm	0.7000	1000.00	1800.00	
Flat roof	IPA 3 layers, 1.53 mm	0.2100	1470.00	1280.00	0.143
	ARMAPORIT insulation, 200 mm	0.1700	840.00	580.00	
	Closed air layer, 100 mm	0.6250	1010.00	1.20	
	Vapour barrier A330ASH, 0.2 mm	0.2100	1470.00	900.00	
	Reinforced concrete, 250 mm	1.4300	1020.00	2300.00	
	Lime-cement plaster, 20 mm	0.9900	790.00	2000.00	
	Closed air layer, 25 mm	0.6250	1010.00	1.20	
	Mineral thermal insulation, 200 mm	0.0390	840.00	100.00	
	Vapour barrier, 0.2 mm	0.3000	1470.00	900.00	
	Plasterboard ceiling, 12.5 mm	0.2200	1060.00	750.00	
Ground floor	PVC, 3 mm	0.1600	1100.00	1400.00	0.816
	Dense concrete, 40 mm	1.0500	1020.00	2100.00	
	HERAKLIT boards, 25 mm	0.1300	1580.00	400.00	
	Expanded perlite, 45 mm	0.0600	1090.00	150.00	
	Waterproofing layer, 3.5 mm	0.2100	1470.00	1114.00	
Windows	Plastic windows with double glazing (6+12+6 mm) and exterior entrance doors with thermal insulation filling.				$U_g = 1.357$ $U_i = 1.3$

3.2 Model description – the classroom

The classroom model represents a kindergarten classroom, which was designed in DesignBuilder as a separate zone in order to quantify the impact of different shading systems on the heating and cooling energy consumption under multiple climate scenarios. The input data are presented in Tabs. 2 and 3. The room is a rectangular unit with dimensions of an actual classroom in the Miloslavov kindergarten and a window configuration corresponding thereto. It is a south-west facing corner classroom; i.e., two walls are exterior, and the remaining two walls are defined with an adiabatic boundary condition. This setting assumes that the room is adjacent to interior spaces and that these have similar temperature conditions. Therefore, the heat flow between zones is not considered. This approach minimises the computational complexity of the model and allows for a clear interpretation of the changes resulting solely from the exposure of the south-west facade to the climatic conditions.

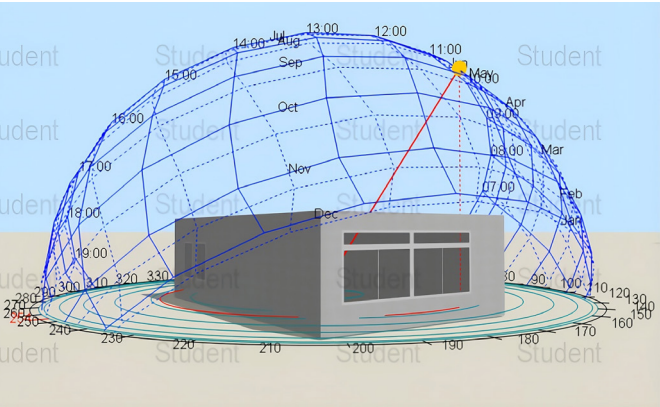


Fig. 3 3D geometry of the classroom created in DesignBuilder with a diagram of the sun's path

Tab. 3 Overview of input data – the classroom

People density (people/m ²)	0.1100	Cooling setback (°C)	28
Metabolic activity	standing/walking	Fresh air (l/s.person)	8
DHW consumption rate (l/m ² .day)	0.253	Target illuminance (lux)	30
Heating setpoint (°C)	22	Normalised power density (W/m ² .100lux)	1.5
Heating setback (°C)	18	Infiltration rate at 50 Pa (ac/h at 50 Pa)	2.5
Cooling setpoint (°C)	26	Ventilation type	natural

3.3 Operating modes

The simulations work with a weekly schedule that corresponds to a standard school regime:

- active operation and occupancy during working days, active heating, cooling and ventilation from 6:00 to

18:00.

- Minimal internal gains, reduced ventilation, heating and cooling during weekends, holidays, vacations and night hours.

This schedule allows the model to capture typical fluctuations between peak loads during school hours and reduced demand during nights, weekends, holidays, and vacations. It was assumed that the systems used for cooling and heating are ideally sized to meet the required energy demand.

3.4 Shading options

For purposes of comparison, three separate shading systems were modelled, each of which was applied to both exposed facades of the classroom. In order to objectively evaluate the differences between the shading methods analysed, the basic window configuration (plastic frame with double-glazed insulated glazing) was kept unchanged. The exception was the thermochromic glazing variant, in which the outer glazing pane was replaced with dynamic thermochromic glazing.

1. **Interior blinds** - Manually operated interior blinds reduce solar gains mainly by reflecting part of the incident radiation back to the exterior; however, a significant part of the thermal energy still penetrates the interior with this type of shading. Therefore, their effectiveness is expected to be lower compared to dynamic thermochromic glazing and exterior blinds, especially during periods of high solar radiation intensity. However, the advantages of interior blinds are lower investment costs, simple installation and low maintenance requirements. An overview of the input parameters used in the model is provided in Tab. 4.
2. **Exterior blinds** - Exterior blinds are a highly effective passive shading system, with the main advantage being their ability to limit solar heat gains before the radiation reaches the glazing. This significantly reduces heat transfer into the interior and lowers the risk of overheating in summer. Unlike interior blinds, exterior shading reflects and absorbs a significant portion of solar radiation outside the thermal envelope of the building, which increases the overall efficiency of the system in terms of energy consumption for cooling. An overview of the input parameters used in the model is provided in Tab. 4.

The control of the blinds in the simulations was implemented using fixed operational rules. During the winter period, the blinds were assumed to be fully raised to maximize solar gains. In the summer period, the blinds were operated based on the cooling system's activity and the intensity of the incident solar radiation, i.e., the blinds were activated at the same time as the interior cooling was activated, with the tilt of the blinds set to block direct sunlight when the solar radiation intensity exceeded 250 W/m².

Tab. 4 Overview of the input data – interior and exterior blinds

Slat properties	Interior blinds	Exterior blinds	Scheme*
Blind-to-glass distance (m)	0.015	0.10	
Slat width (m)	0.0250	0.080	
Slat separation (m)	0.0190	0.070	
Slat thickness (m)	0.0010	0.002	
Slat conductivity (W/m.K)	0.9	200	
Slat solar transmittance	0	0	
Slat solar reflectance	0	0	
Slat visible transmittance	0	0	
Visible reflectance	0	0	
Slat hemispherical transmittance	0	0	
Slat hemispheric emissivity	0.9	0.9	
			*Source: DesignBuilder Software Ltd.

3. **Thermochromic glazing** – this is an adaptive type of glazing whose optical properties change depending on the surface temperature of the glazing without the need for an external power supply. When the surface temperature increases, the glazing darkens, thereby significantly reducing the solar heat gains entering into the interior. Thermochromic glazing systems are among the most important concepts of facade adaptability, which allow for optimizing solar gains and losses without the need for mechanical shading control. They improve the energy efficiency of buildings in different climatic conditions (Mann, 2020). The specifications of the thermochromic glazing used in the simulations are provided in Table 5.

reaches approximately $0.0497\text{ }^{\circ}\text{C}/\text{year}$ and indicates the most significant temperature increase by 2100. This scenario also shows the highest R^2 value of ≈ 0.69 , which means that the warming trend is relatively consistent and the year-on-year variability is lower. The second scenario (A1B) shows a more moderate increase in temperature, with a gradient of approximately $0.0376\text{ }^{\circ}\text{C}/\text{year}$. The value of the coefficient of determination $R^2 \approx 0.61$ confirms that the trend is also relatively stable, although the year-on-year fluctuations are slightly more pronounced than in the first scenario. The lowest increase in temperature was observed in the third scenario (B1), where the gradient is approximately $0.0134\text{ }^{\circ}\text{C}/\text{year}$. This scenario also has the lowest R^2 value ≈ 0.16 , which indicates significant year-on-year variability and a less distinct long-term trend. Warming is occurring, but the time course is less clear and shows significant deviations from the linear trend.

Tab. 5 Overview of input data – thermochromic glazing

Layer definition		Solar transmittance
Outermost pane	Thermochromic 8 mm	0.684
	-thermochromic 24	0.632
	-thermochromic 34	0.533
	-thermochromic 48	0.410
	-thermochromic 62	0.331
	-thermochromic 75	
Air	Argon 12 mm	
Innermost pane	Coated 6 mm	0.575

4 RESULT

4.1 Weather trends and variability

Figure 4 shows the development of the average annual temperature for the three scenarios analysed along with their linear trend lines. The highest rate of warming is achieved by the scenario with the steepest trend line (A2), where the gradient, which represents the rate of change per year,

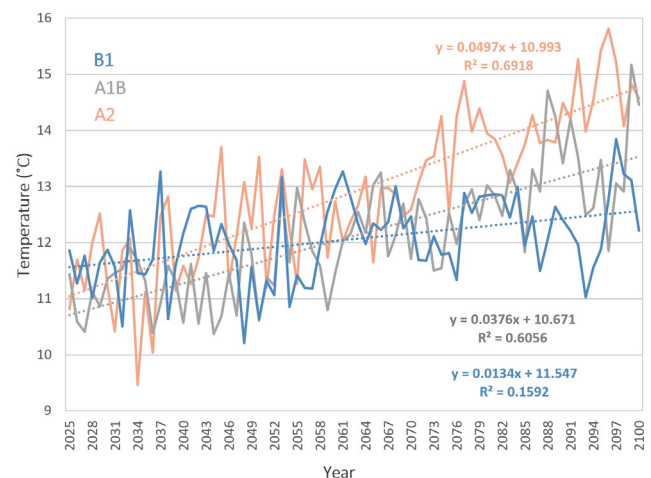


Fig. 4 Development of the average annual temperature in the years 2025 to 2100 according to the SRES scenarios with the linear regression trendline and coefficient of determination R^2

4.2 Future energy consumption trends of the simulated building

The analysis of the annual heating and cooling energy consumption for the simulated kindergarten building shows differences in the long-term energy consumption trends, depending on the climate scenario.

The results of the annual heating energy consumption trends in Figure 5 for the monitored climate scenarios confirm the expected impact of gradual warming. In all three cases, there is a clear decreasing trend in the heating consumption, but its intensity and stability vary significantly between the scenarios. Scenario B1 shows the smallest decrease in energy consumption for heating (–44.869 kWh/year). This decrease is accompanied by a very low $R^2 \approx 0.0753$ value, which indicates a high interannual variability and weak statistical reliability of the linear trend. This scenario represents slower and less predictable winter warming. Scenario A1B shows a moderately significant decrease in heating consumption (–128.99 kWh/year). The value $R^2 \approx 0.4788$ indicates that the trend is relatively stable and accurately reflects the long-term behaviour. It represents a mild-to-moderate climate scenario in which the winter temperatures increase faster than in B1. Scenario A2 shows the sharpest decrease in heating consumption (–194.84 kWh/year) and also shows the most stable trend. It reflects the rapid warming of the winter season in this scenario. The rate of reduction in heating consumption under A2 is approximately four times faster than in B1. The higher consistency of the decrease in scenario A2 may be due to more balanced climatic conditions, while scenario B1 shows greater instability in the winter temperatures. For the design of technical systems, this means that in scenario A2, a more significant reduction in heat demand can be expected from year to year, while scenario B1 brings a higher degree of uncertainty, which complicates the load prediction.

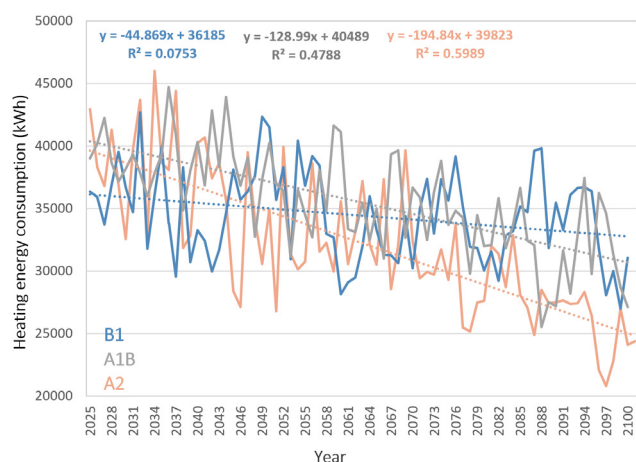


Fig. 5 Development of the energy consumption for heating in a simulated building between 2025 and 2100 according to the SRES scenarios with a linear regression trendline and coefficient of determination R^2

Fig. 6 shows the development of energy consumption for cooling the entire building from 2025 to 2100 for all three climate scenarios analyzed. The trends in energy consumption for cooling show an opposing trend: in all the scenarios,

consumption increases as rising the temperatures increase the need to ensure thermal comfort in the summer. While scenario A2 shows a strong and stable increase in cooling consumption, scenario B1 does not show a clear upward trend despite higher projected temperatures ($R^2 \approx 0.0318$). The energy consumption for cooling in scenario B1 increases only minimally (~7.4 kWh/year) and the trend is almost entirely non-linear. This may be related to the increased weather extremes in this scenario; i.e., high summer temperatures do not occur every year; heat waves alternate with milder periods. For practical applications, this indicates that the design of cooling systems under the B1 climate scenario must account for significant year-to-year variability, which complicates the estimation of peak cooling loads. Scenario A1B shows moderately rapid growth with a stable and well-defined trend ($R^2 \approx 0.519$).

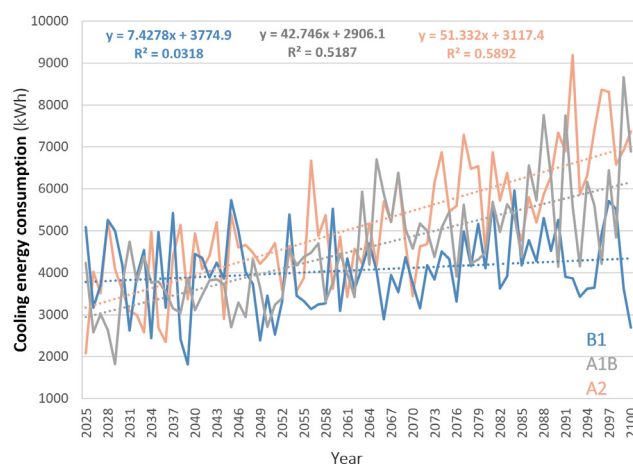


Fig. 6 Development of the energy consumption for cooling in a simulated building between 2025 and 2100 according to the SRES scenarios with a linear regression trendline and coefficient of determination R^2

4.3 Effectiveness of shading systems for the kindergarten classroom

This section analyses the energy consumption for the cooling and heating of the selected kindergarten classroom in three different climate change scenarios using three shading variants. The results were compared with a reference situation without any shading. Since the overall trends were very similar across all three scenarios, the interpretation and conclusions from scenario A1B are largely generally applicable to all future climatic conditions.

All four curves (no shading, interior blinds, thermochromic glazing, exterior blinds) show an increasing trend in cooling consumption, which corresponds to the expected increase in outdoor temperatures due to climate change (Fig. 7). However, a comparison of the average energy consumption values reveals significant differences in the efficiency of the individual shading systems. The lowest long-term cooling energy consumption is achieved by external blinds, which eliminate a significant portion of the solar radiation before it reaches the glazing. The external blinds provide a significant effect. They reduce consumption by approximately 38.6–40.3% compared to the reference condition. Thermochromic

glazing is the second most effective solution, as it can dynamically limit solar gains on hot days without any user intervention. The reduction in cooling energy consumption is approximately 13.3–15.8%, depending on the climate scenario. In contrast, interior blinds have virtually no reduction effect on cooling energy consumption. In all the scenarios, their impact is negligible (-0.1 to $+0.7\%$), which confirms that this type of shading is not a suitable measure for limiting summer overheating in terms of long-term energy efficiency. These results are consistent in scenarios B1, A1B, and A2. Thermochromic glazing has a greater effect, mainly because it reacts to high surface temperatures by automatically darkening and reducing solar gains during hot periods without the need for any user intervention. Exterior blinds are even more effective as they eliminate incident solar radiation before it interacts with the glazing, thus preventing heat transfer through the glazing into the interior. In contrast, interior blinds capture solar radiation only in the interior environment, where heat accumulation has already occurred, which significantly limits their ability to reduce heat flow through the glazing and explains their negligible impact on energy consumption for cooling.

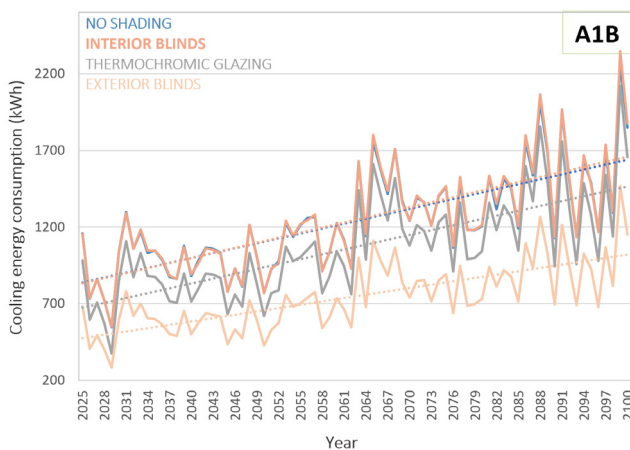


Fig. 7 Cooling energy consumption in a simulated classroom for the A1B scenario from 2025 to 2100 using different shading systems

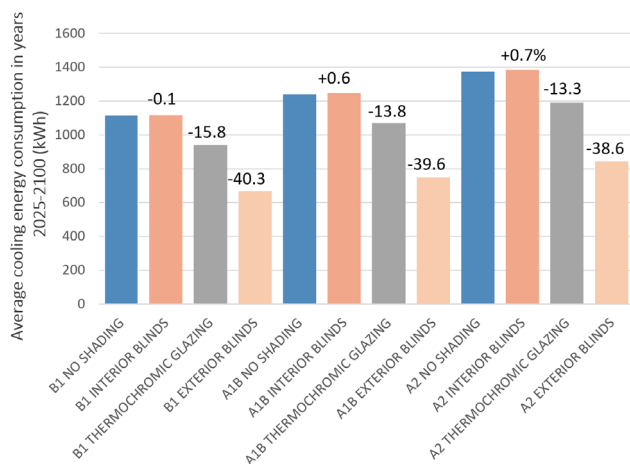


Fig. 8 Average cooling energy consumption in a simulated classroom for all three SRES scenarios from 2025 to 2100 using different shading systems

Fig. 9 clearly shows that all the shading variants analysed exhibit a decreasing trend in heating energy consumption. The regression curves in the three variants confirm a slight decrease in the heating requirements (-20.5 to -20.8 kWh/year), with the impact of the type of shading on the trend itself being negligible. In terms of the average heating energy consumption, the differences between the variants are significantly smaller than for cooling: the interior and exterior blinds cause only a slight increase in consumption of $\approx +0.3$ in all three scenarios. The thermochromic glazing increases consumption by approximately $+2.4\%$ (Fig. 10). The reason for the slightly higher energy consumption is the limitation of solar heat gains during winter; both the blinds and thermochromic glass prevent the penetration of solar radiation, which would otherwise contribute to the passive heating of the room. In the case of blinds, rational control by users was assumed (i.e. raising the blinds in cold months to maximise solar gains), which explains the relatively low increase in heating consumption. However, thermochromic glazing does not allow for such regulation, as its control mechanism is based solely on the surface temperature of the glass and does not allow for a targeted increase in solar gains in winter; it therefore shows a higher increase in energy consumption for heating.

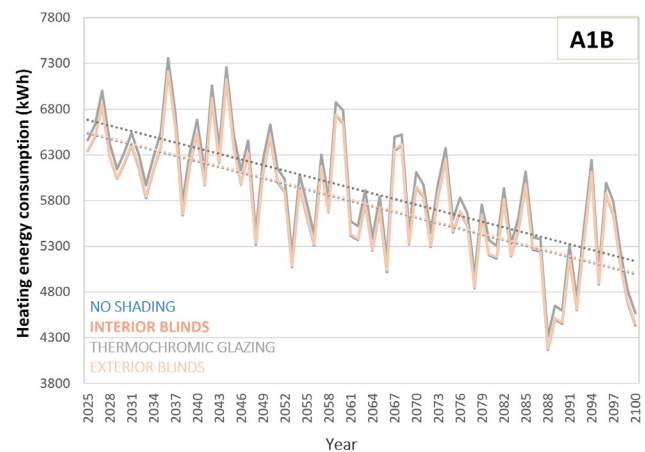


Fig. 9 Heating energy consumption in a simulated classroom for the A1B scenario from 2025 to 2100 using different shading systems

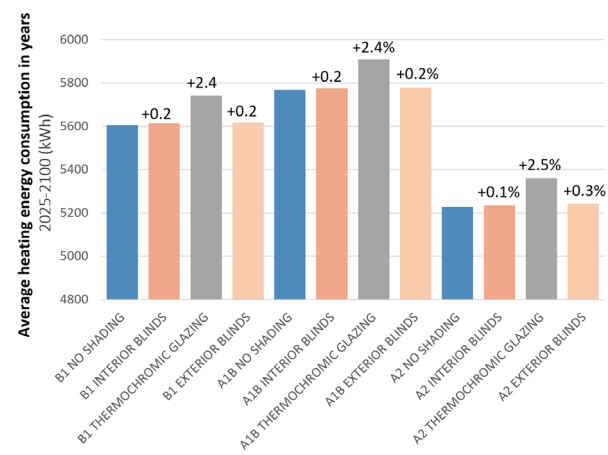


Fig. 10 Average heating energy consumption in a simulated classroom for all three SRES scenarios from 2025 to 2100 using different shading systems

5 DISCUSSION

An analysis of the long-term development of energy consumption in the kindergarten building over the period 2025–2100 shows a clear shift in the building's energy balance across all the climate scenarios. Regardless of the climate model used, a systematic decrease in the heating energy requirements can be observed, which is accompanied by a gradual increase in cooling consumption. This trend is a consequence of global warming and the increased frequency of hot periods, with its dynamics varying depending on the scenario.

Scenario A2 shows the most consistent and statistically reliable development of both energy demands. Scenario A1B shows a similar character, with a more stable trend of $R^2 \approx 0.5187$ for cooling and $R^2 \approx 0.4788$ for heating. In scenario B1, there is also a decrease in energy consumption for heating, but its trend is very weak ($R^2 = 0.0753$), which indicates significant interannual variability. Even higher instability is evident in cooling energy consumption, with an increase of only 7.4 kWh/year; the coefficient of determination $R^2 = 0.0318$ practically rules out the existence of a reliable long-term trend. This scenario is characterised by the highest climate variability, which indicates frequent alternations between extremely hot and mild periods. As a result, the predictability of the energy demands is also lower. Although the intensity and stability of the trends vary between the scenarios, all three show the same transformation, which will need to be taken into account in the design of the energy, certification, and long-term planning of buildings.

Further results show that the appropriate choice of shading measures can significantly affect the future energy balance of a building: shading is of crucial importance for maintaining energy efficiency with increased cooling consumption. For buildings such as kindergartens, it is particularly important to reduce overheating during the summer months and ensure thermal comfort for children without excessive use of cooling systems.

The analysis shows that not all types of shading used can significantly contribute to reducing the energy load of a building. Exterior blinds show the highest benefit in all three climate scenarios, which provide the most significant reduction in cooling energy consumption by eliminating solar heat gains before the radiation hits the glazing. Thermochromic glazing is the second most effective solution; although it causes a slight increase in heating energy consumption, this effect is compensated for over the long term by savings in the cooling energy. Interior blinds prove to be the least energy-efficient solution in the conditions analysed, as their impact on reducing energy consumption for cooling is negligible and highly dependent on the user's behaviour. Their main benefit lies in the possibility of maintaining passive solar gains in the winter when operated rationally; but in terms of adapting buildings to future climatic conditions, they do not provide sufficient cooling effect. The above results show that exterior blinds and thermochromic glazing represent a more effective choice if the priority is to minimise summer consumption and ensure long-term thermal comfort in buildings with an exposed orientation.

An important practical aspect influencing the real energy performance of shading systems is the method of control and the behaviour of the building occupants. In the present study, the interior and exterior blinds were modelled using predefined control strategies; however, in real operation, user behaviour may significantly affect the actual energy savings achieved. The manual operation of blinds is often irregular and depends on individual preferences, visual comfort requirements, occupancy patterns, and user awareness, all of which may reduce the effectiveness of shading systems compared to idealized simulation conditions.

In contrast, thermochromic glazing operates passively and automatically responds to solar and thermal conditions without requiring occupant interaction or additional control systems. This characteristic may represent an advantage in educational buildings such as kindergartens, where the operation of shading devices is not always consistent throughout the day. Nevertheless, practical implementation of thermochromic glazing is currently associated with higher investment costs and potential constraints related to optical properties and long-term durability. Therefore, further experimental and economic studies under real operating conditions are needed to evaluate the long-term applicability and cost-effectiveness of this technology.

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