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ENERGY EFFICIENCY IN SUSTAINABLE CONSTRUCTION IN SCHOOL BUILDINGS

Comparative Analysis Report: Lithuania – Poland – Greece

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This report is a collection of three national analyses (Poland, Greece and Lithuania), combining research, diagnosis and comparative analysis in the field of energy efficiency in sustainable construction resulting from climate change.

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The main elements of diagnosis and comparative analysis in the field of energy efficiency in sustainable construction resulting from climate change are as follows:

1. Energy efficiency in sustainable construction – introduction and basic definitions based on examples from Poland, Lithuania and Greece.

2. Renewable energy sources in school buildings – examples of solutions implemented in schools in Poland, Lithuania and Greece.

3. Culture of saving and managing energy in school buildings in Poland, Lithuania and Greece.

4. Latest trends in energy efficiency in sustainable construction resulting from climate change.

The report is intended for teachers, trainers, school management staff and decision-makers involved in the planning, renovation and management of school buildings.
The results of the report are intended to support the development of training activities, teaching materials and practical energy management solutions in schools.

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1. Introduction

Climate change has become one of the most significant global challenges of the 21st century, directly affecting environmental, economic and social systems across Europe. Rising temperatures, more frequent extreme weather events, increasing energy demand and the need to reduce greenhouse gas emissions require countries to rethink how buildings are designed, renovated and operated. The construction sector plays a crucial role in this transition, as buildings account for a substantial share of final energy consumption and carbon emissions.

School buildings are a particularly important part of this context. As public buildings with long life cycles and intensive daily use, schools represent both a challenge and an opportunity for improving energy efficiency. At the same time, schools serve as educational environments where sustainable practices, energy-saving behaviour and climate awareness can be demonstrated in practice and transferred to future generations. Therefore, improving energy efficiency in school buildings contributes not only to climate goals but also to educational and social objectives.

This comparative report has been prepared within the framework of the Energy@Schools (2024-2-PL01-KA210-VET-000290095) project and builds upon three national diagnosis reports developed by partners from Lithuania, Poland and Greece. While each national report focuses on country-specific conditions, policies and practices, this document aims to bring them together into a structured comparative analysis. The report identifies common trends, highlights national differences and presents good practices in the field of energy efficiency in sustainable construction, with a particular focus on school buildings.

The main objective of this comparative report is to analyse and compare how energy efficiency in sustainable construction is addressed in the three participating countries, taking into account differences in climate conditions, building stock, legal frameworks and technological development. By comparing national approaches, the report seeks to identify transferable solutions, innovative practices and key challenges that are relevant at the European level.

The analysis focuses on several interrelated thematic areas that together provide a comprehensive comparative perspective on energy efficiency in sustainable construction. First, the report examines the fundamental principles of energy efficiency in school buildings, including sustainable design approaches, material selection and the influence of different climate conditions. Second, it compares the integration of renewable energy sources in school buildings, such as solar energy systems, heat pumps, energy storage and monitoring solutions. Third, the analysis explores the culture of saving and managing energy in schools, addressing behavioural aspects, educational initiatives and the role of school management and municipalities. Finally, the report assesses the role of innovation, digitalisation, automation and climate change adaptation in improving the energy performance and long-term resilience of school buildings.

By presenting a structured comparison of Lithuania, Poland and Greece, this report provides a comprehensive overview of how different national contexts shape approaches to energy-efficient school buildings. The findings are intended to support policymakers, educational institutions and project stakeholders in developing more effective strategies for sustainable construction and energy management in schools across Europe.

2. Energy efficiency in sustainable construction

2.1 The main principles of energy efficiency in sustainable construction

Energy efficiency is a core pillar of sustainable construction across Lithuania, Poland and Greece, although it is implemented under significantly different climatic, regulatory and infrastructural conditions. In all three countries, energy efficiency is defined as the reduction of energy consumption required to deliver the same level of thermal comfort, lighting and ventilation, in line with the principles set out in EU Directive 2010/31/EU on the Energy Performance of Buildings (EPBD).

Energy performance certification and building standards

All three countries apply mandatory Energy Performance Certificates (EPCs) for new and renovated public buildings, including schools. Buildings are classified on a scale from A+ (or A++) to G, based on calculated energy demand for heating, cooling, ventilation, domestic hot water and lighting.

- In Lithuania, most newly renovated public buildings are required to reach at least Class B, with a growing number of schools achieving A or A+ standards under national renovation programmes.
- In Poland, EPC requirements are similarly aligned with EU regulations, but the pace of upgrading is uneven, with strong progress in urban areas and slower improvement in older school buildings in smaller municipalities.
- In Greece, EPC classification places strong emphasis on cooling demand, as high summer temperatures significantly affect overall energy performance; many school buildings remain in lower EPC classes (C–E), particularly those constructed before modern insulation standards.

Building envelope and thermal insulation

Improvement of the building envelope is identified as the most cost-effective energy efficiency measure in all three countries. National technical regulations define minimum U-values for walls, roofs, floors and windows:

- Lithuania and Poland focus primarily on reducing heat losses during long heating seasons, where heating accounts for the largest share of school energy consumption.
- Greece, while also improving insulation, places additional emphasis on preventing overheating, using reflective materials, shading systems and bioclimatic design to reduce cooling demand.

Heating, cooling and ventilation systems

Across all three countries, energy-efficient HVAC systems are a central component of sustainable school infrastructure.

- Heat recovery ventilation (HRV) systems are increasingly implemented in Lithuania and Poland, reducing heating demand by recovering waste heat from exhaust air.
- In Greece, natural ventilation, passive cooling strategies and hybrid systems play a more prominent role due to climatic conditions.
- The replacement of outdated boiler systems with heat pumps, biomass boilers or district heating solutions is common in Lithuania and Poland, while Greece prioritises efficient cooling technologies.

Integration of renewable energy sources

The integration of renewable energy sources (RES) is a shared objective across all three countries, though implementation levels differ.

- Lithuania has rapidly expanded the installation of photovoltaic (PV) systems in public buildings, supported by national climate programmes and EU funding.
- Poland also deploys PV systems, often combined with energy efficiency retrofits, though financial and administrative barriers still limit broader adoption.
- Greece benefits from high solar irradiation, making solar PV and solar thermal systems particularly effective and economically attractive for school buildings.

Life-cycle approach and long-term sustainability

All three national strategies increasingly adopt a life-cycle perspective, recognising that energy efficiency must be addressed from design and construction through operation and renovation. Tools such as Life Cycle Assessment (LCA) and Environmental Product Declarations (EPDs) are gaining importance, particularly in Poland and Greece, while Lithuania is gradually integrating these concepts into public procurement practices.

Overall, while Lithuania, Poland and Greece share a common regulatory framework and strategic objectives driven by EU policy, their approaches to energy efficiency in sustainable construction reflect distinct climatic challenges, technological priorities and implementation capacities, which form the basis for further comparative analysis in subsequent chapters.

2.2 Sustainable design principles

Sustainable design principles in school buildings across Lithuania, Poland and Greece are shaped by a shared European regulatory framework, yet they differ significantly in practical implementation due to contrasting climate conditions, building traditions and renovation priorities. While all three countries aim to reduce energy demand and improve indoor comfort, their design strategies reflect distinct emphases: insulation-driven solutions in Lithuania and Poland versus bioclimatic and cooling-oriented design in Greece.

In Lithuania, sustainable design in school buildings is primarily driven by the need to minimise heat losses during long and cold heating seasons. Design strategies focus on compact building forms, improved thermal insulation of building envelopes and airtightness. National technical regulations, aligned with EU Directive 2010/31/EU, define strict requirements for thermal transmittance (U-values), particularly for walls, roofs and windows. As a result, renovated or newly constructed school buildings increasingly achieve high Energy Performance Certificate (EPC) classes, typically A or A+, with significantly reduced heating demand compared to the pre-renovation building stock, which often falls within D–G classes. Passive solar gains are utilised mainly through window orientation and glazing, but the overall design approach remains strongly insulation-centred rather than climate-adaptive.

A similar insulation-driven design logic dominates in Poland, where sustainable school design prioritises reducing transmission heat losses and improving energy efficiency through building envelope modernisation. Extensive national renovation programmes have resulted in widespread upgrades of façades, roofs and windows, often combined with improved ventilation systems. Polish school buildings increasingly integrate energy-efficient lighting and controlled ventilation, yet the architectural form remains relatively conservative. While bioclimatic principles are acknowledged, they are secondary to insulation performance and energy demand reduction. EPC improvements in renovated schools typically aim to move buildings from E–F classes to B or A levels, reflecting a strong focus on compliance with energy performance standards rather than climate-responsive design.

In contrast, Greece applies sustainable design principles that are strongly rooted in bioclimatic architecture, reflecting the country's Mediterranean climate and the dominant challenge of overheating rather than heat loss. Greek school buildings increasingly incorporate passive cooling strategies such as building orientation, shading devices, ventilated façades, reflective materials and natural cross-ventilation. External shading systems, atriums and light-coloured surfaces are widely used to reduce solar heat gains and limit reliance on mechanical cooling. While insulation remains important, particularly for roofs and external walls, the design priority is to stabilise indoor temperatures during hot periods and reduce electricity consumption for air conditioning. As a result, sustainable design in Greece emphasises cooling efficiency, daylight optimisation and thermal comfort rather than maximum airtightness.

Across all three countries, sustainable design principles are increasingly linked to life-cycle thinking, including material durability, maintenance costs and long-term energy performance. However, the balance between bioclimatic design and insulation-based solutions varies significantly. Lithuania and Poland demonstrate a predominantly energy-demand reduction approach, focused on heating efficiency and compliance with EPC standards, whereas Greece illustrates a climate-adaptive design model, where passive cooling and solar control play a central role.

These differences highlight that sustainable design in school buildings cannot follow a single universal model. Instead, effective energy-efficient design must respond to local climate conditions, energy consumption patterns and user behaviour, while remaining aligned with shared European sustainability objectives.

2.3 Sustainable building materials

The selection of sustainable building materials is a critical factor influencing the overall environmental performance of school buildings. Beyond operational energy efficiency, increasing attention is paid to embodied carbon, life-cycle impacts and the use of locally sourced materials. In Lithuania, Poland and Greece, material strategies differ significantly, reflecting national construction traditions, climate conditions and renovation priorities.

Embodied carbon and life-cycle perspective

Embodied carbon refers to greenhouse gas emissions associated with the production, transport, construction, maintenance and end-of-life stages of building materials. Across all three countries, the reduction of embodied carbon is becoming increasingly relevant, particularly in the context of European climate targets and the transition towards life-cycle-based assessment.

In Lithuania, embodied carbon considerations are emerging mainly in pilot projects and new public buildings. National discussions increasingly reference Life Cycle Assessment (LCA) and Environmental Product Declarations (EPD) as tools for comparing material impacts. Engineered wood products, particularly cross-laminated timber (CLT), are recognised as low-carbon alternatives to traditional reinforced concrete. CLT structures typically store biogenic carbon and may reduce embodied CO_2 emissions by approximately 30–50% compared to conventional concrete structures, depending on design and sourcing.

In Poland, sustainable material strategies focus primarily on reducing operational emissions through renovation rather than replacing structural materials. As a result, embodied carbon reduction is achieved indirectly by extending the lifespan of existing reinforced concrete buildings. While reinforced concrete has a high embodied carbon footprint (approximately 250–350 kg CO_2e per m^3), large-scale renovation avoids demolition and new material production, which significantly lowers total life-cycle emissions. The application of LCA and EPD methodologies is growing, particularly in public procurement, but remains uneven across school projects.

In Greece, embodied carbon considerations are closely linked to the use of local and traditional materials. Stone, ceramics and mineral-based finishes have lower processing requirements and reduced transport emissions compared to imported industrial materials. Although reinforced concrete remains common in school construction, the use of local materials contributes to lower embodied emissions and improved thermal performance in hot climates. Formal LCA application is less widespread; however, material choices implicitly support embodied carbon reduction through climate-adapted design.

CLT versus reinforced concrete

Cross-laminated timber and reinforced concrete represent two fundamentally different construction paradigms in sustainable school buildings.

CLT offers significant advantages in terms of embodied carbon reduction, construction speed and precision. Its renewable nature and carbon storage capacity make it particularly attractive for new public buildings in Lithuania and, to a lesser extent, Poland. However, CLT adoption is limited by cost considerations, regulatory familiarity and fire safety perceptions.

Reinforced concrete remains the dominant material in all three countries due to its structural reliability, fire resistance and established construction practices. Its high embodied carbon footprint is a challenge, but renovation-based strategies in Poland and Lithuania reduce overall environmental impact by avoiding new concrete production. In Greece, concrete is often combined with passive design elements and surface treatments that mitigate its thermal disadvantages.

Local materials and climate-adapted construction

The use of local materials is a key sustainability strategy, particularly in Greece, where climate-adapted construction traditions support passive cooling and long-term durability. Locally sourced stone and ceramics reduce transport emissions and perform well in high-temperature environments. In Lithuania, local material use is expanding gradually, especially in insulation products and timber-based solutions. Poland applies local sourcing primarily through renovation supply chains, ensuring material availability and cost efficiency.

Across all three countries, local materials support circular economy principles by reducing transport emissions, supporting regional economies and facilitating maintenance and replacement over the building life cycle.

Comparative overview of sustainable building materials in school buildings (LT–PL–GR)

Criteria	Lithuania	Poland	Greece
Dominant structural material	Reinforced concrete; emerging CLT in new buildings	Reinforced concrete (existing stock)	Reinforced concrete with local finishes
Use of CLT (Cross-Laminated Timber)	Pilot projects in public buildings; increasing interest due to CO_2 reduction goals	Limited use; mainly conceptual or small-scale pilots	Rare; limited by climate and construction tradition
Embodied carbon reduction approach	Growing focus on LCA (Life Cycle Assessment) and EPD (Environmental Product Declarations)	Indirect reduction via reuse, refurbishment, and extended building life	Implicit reduction through local sourcing and durable materials
Typical embodied CO_2 emissions (kg CO_2e/m^2 GFA)	Concrete schools: ~450–550 kg CO_2e/m^2**;** CLT	Reduced mainly through renovation instead of demolition	Lower transport-related emissions; materials typically

	schools: ~250–350 kg CO_2e/m^2	(savings ~30–40% vs new build)	~400–500 kg CO_2e/m^2
Local material use	Timber, mineral insulation, locally produced prefabricated elements	Renovation materials sourced from regional supply chains	Stone, ceramics, mineral plasters, locally produced finishes
Circular economy relevance	Emerging (design-for-disassembly, material reuse discussed)	High – renovation-driven circularity, reuse of structures	Medium – durability-oriented rather than reuse-oriented
Climate suitability	Cold climate → insulation-driven design (U-values, airtightness)	Cold/transitional climate → renovation- and insulation-driven	Hot climate → bioclimatic and thermal-mass-driven design

2.4 Climate context relevant to sustainable construction

Climatic conditions are a decisive factor shaping sustainable construction strategies and energy efficiency priorities in school buildings. Lithuania, Poland and Greece represent three clearly differentiated climate contexts within Europe, which directly affect energy demand profiles, building design logic and technology choices. As a result, sustainable construction solutions in schools are strongly climate-driven rather than uniform.

Cold-climate context: Lithuania and Poland

Lithuania and Poland are characterised by a cold temperate climate with long heating seasons and relatively high Heating Degree Days (HDD). Average annual HDD values exceed 4,000 in Lithuania and range between approximately 3,000–4,000 in Poland, which translates into high demand for space heating in school buildings.

In both countries, heating accounts for the dominant share of final energy consumption in educational buildings, often exceeding 60–70% of total energy use in older school facilities. Many school buildings were constructed before modern energy performance requirements were introduced, resulting in poor thermal envelopes, low airtightness and inefficient heating systems. Consequently, sustainable construction strategies prioritise:

- reduction of transmission losses through walls, roofs and windows,
- improved airtightness and controlled ventilation,
- high-efficiency heating systems and heat recovery.

From a regulatory perspective, both Lithuania and Poland increasingly require school buildings to reach EPC classes B or higher after renovation, reinforcing insulation-driven design approaches. Climate change further intensifies these challenges, as colder winter extremes and increased precipitation raise the risk of moisture damage and thermal instability in poorly renovated buildings.

Hot-climate context: Greece

Greece represents a fundamentally different climate context, characterised by high Cooling Degree Days (CDD), extended summer seasons and increasing frequency of heatwaves. In many regions, CDD values exceed 1,000–1,500 annually, and summer temperatures frequently surpass 35°C. As a result, cooling demand plays a central role in school energy consumption.

In Greek school buildings, cooling and indoor comfort are often more critical than heating efficiency. Energy demand peaks during hot periods, placing stress on electricity systems and increasing operational costs. Sustainable construction in this context prioritises:

- limiting solar heat gains through shading and orientation,
- passive cooling strategies and natural ventilation,
- reflective materials and light-coloured façades,
- reducing dependence on mechanical air conditioning.

Unlike Lithuania and Poland, where insulation thickness is the primary performance driver, Greek school buildings rely more heavily on bioclimatic design principles, where architectural form, shading and ventilation determine energy performance. Climate change further amplifies these challenges by increasing heat stress and extending periods of thermal discomfort during the academic year.

Climate-driven divergence in design priorities

The comparative analysis clearly shows that climate context fundamentally shapes sustainable construction logic. In Lithuania and Poland, energy efficiency is largely insulation-driven and heating-oriented, while in Greece it is bioclimatic and cooling-oriented. This divergence explains differences in material selection, renewable energy integration and technology deployment observed in later chapters of this report.

At the same time, climate change is gradually narrowing the gap between these contexts. Lithuania and Poland face more frequent summer heat events, while Greece must also address increasing energy security concerns. As a result, climate-responsive design is no longer optional but a prerequisite for long-term resilience of school buildings.

In conclusion, climate context is a key explanatory factor in comparative energy efficiency analysis. Understanding cold- and hot-climate constraints allows for more accurate assessment of why certain solutions are effective in one country but less suitable in another. This climate-driven perspective provides a necessary foundation for the analysis of renewable energy systems, digitalisation and adaptive technologies in subsequent sections of this report.

2.5 Legal framework regulating energy efficiency

The legal framework regulating energy efficiency in sustainable construction across Lithuania, Poland and Greece is largely shaped by a common European Union policy framework, while national legislation determines the pace, scope and practical implementation of school building renovation and modernisation.

At EU level, all three countries operate under the same core legislative instruments, most notably Directive 2010/31/EU on the Energy Performance of Buildings (EPBD) and Directive (EU) 2018/844, which strengthened requirements related to nearly zero-energy buildings (nZEB), renovation strategies and energy performance certification. These directives establish mandatory energy performance standards, introduce building energy performance certificates (EPCs), and require Member States to develop long-term renovation strategies for public buildings, including schools.

Lithuania

In Lithuania, the legal basis for energy efficiency in buildings is primarily defined by the Law on Construction and the Law on Energy, which transpose EU directives into national regulations. Public buildings, including educational institutions, are subject to mandatory energy performance certification, with EPC classes ranging from A++ to G. New public buildings are required to meet A++ or A+ standards, while renovated school buildings must significantly improve their energy class.

Lithuania has also adopted national technical regulations such as STR 2.01.02:2022 “Building Energy Performance”, which sets minimum thermal transmittance (U-value) requirements for building envelopes and systems. These regulations directly influence renovation priorities, often focusing on insulation, window replacement and heating system upgrades. However, despite a solid legal framework, implementation speed is strongly dependent on available funding and municipal capacity.

Poland

Poland’s regulatory framework is characterised by a strong focus on large-scale renovation of existing building stock, supported by national programmes aligned with EU climate and energy policy. Energy efficiency requirements are regulated through national construction law and energy efficiency acts, which also implement the EPBD.

Poland has placed particular emphasis on public-sector renovation obligations, with schools frequently included in national and regional energy modernisation programmes. While EPC systems are in place, Poland’s approach often prioritises incremental efficiency gains through renovation rather than full transformation to nZEB standards. This has resulted in relatively high renovation coverage, though often with moderate depth compared to Lithuania’s stricter requirements for new public buildings.

Greece

In Greece, energy efficiency legislation is also fully aligned with EU directives, implemented through national energy performance regulations such as KENAK (Regulation on the Energy Performance of Buildings). EPCs are mandatory for public buildings, including schools, and minimum performance standards apply to both new construction and renovation projects.

Due to Greece's Mediterranean climate, national regulations place greater emphasis on cooling demand, solar protection, shading systems and passive design strategies. Legal requirements strongly support the integration of solar energy systems, particularly solar thermal collectors, which are widely promoted by national policy instruments. However, similar to Lithuania, the practical implementation of legal requirements is often constrained by financial resources and administrative capacity at municipal level.

Comparative perspective

Although Lithuania, Poland and Greece share a common EU legislative foundation, differences in national laws, climate conditions and funding mechanisms result in varying renovation strategies and outcomes in school buildings. Lithuania's framework promotes high energy performance standards, Poland focuses on renovation scale and reuse of existing stock, while Greece adapts legal requirements to address heat stress and cooling needs.

Overall, the legal framework plays a decisive role in shaping renovation depth, technology choice and implementation speed in school buildings. Where legal obligations are combined with strong financial instruments and technical support, energy efficiency improvements are implemented more consistently and effectively.

2.6 Optimisation of energy efficiency solutions using artificial intelligence

Artificial intelligence is increasingly recognised as a supportive tool for optimising energy efficiency in school buildings, primarily through data analysis, forecasting and decision support. In the context of sustainable construction, AI does not replace traditional energy efficiency measures but enhances their effectiveness by enabling more precise control of energy flows and operational parameters.

In Poland and Greece, AI-related solutions are already referenced in connection with advanced energy management systems, particularly in renovated or newly constructed public buildings. These solutions are mainly applied to optimise heating, cooling and lighting schedules based on usage patterns, external weather conditions and historical consumption data.

In Lithuania, the application of artificial intelligence in school buildings is still at an early stage. Current practices focus mainly on energy monitoring, data collection and basic analytical tools rather than fully autonomous AI-driven systems. Nevertheless, the increasing availability of smart meters and digital monitoring platforms creates favourable conditions for the future integration of AI-based optimisation solutions, especially within large public building portfolios such as schools.

Overall, AI in this stage functions as an enabling layer that supports evidence-based decision-making, improves energy efficiency outcomes and prepares school buildings for more advanced digital and automated solutions discussed in later chapters of this report.

2.7 Digitalisation, IoT and automation in energy-efficient school buildings

Digitalisation and automation play an increasingly important role in improving energy efficiency in school buildings across Lithuania, Poland and Greece. The integration of digital technologies enables more precise control of energy consumption, supports data-driven decision-making and enhances overall building performance. Although the level of implementation differs between countries, digital solutions are becoming a key component of sustainable school infrastructure.

In Poland, digitalisation of school buildings is the most advanced among the three countries. Polish examples highlight the use of Building Management Systems (BMS), which integrate heating, ventilation, air conditioning and lighting into a single automated control platform. These systems rely on networks of sensors and Internet of Things (IoT) technologies to monitor indoor conditions, occupancy levels and energy consumption in real time. Automated lighting systems, motion sensors and programmable heating schedules allow schools to reduce unnecessary energy use while maintaining indoor comfort.

Lithuania demonstrates a rapidly developing approach to digitalisation and automation in schools. While comprehensive BMS solutions are not yet widespread, Lithuanian schools increasingly implement smart meters, monitoring platforms and automated control elements for heating and ventilation systems. Data collected through these systems is used for energy consumption analysis, optimisation of operating schedules and identification of inefficiencies. In several cases, digital tools are integrated into educational activities, particularly within STEAM education contexts, where students analyse real energy data and participate in sustainability-focused learning processes.

In Greece, digitalisation and automation are primarily oriented towards cooling management and thermal comfort. Automated shading systems, temperature sensors and smart cooling controls are used to respond to high outdoor temperatures and reduce peak energy demand. Greek school buildings increasingly rely on sensor-based control of ventilation and cooling systems to balance indoor comfort with energy efficiency, especially during extended heatwave periods.

Across all three countries, automation of lighting, heating and ventilation systems contributes to significant energy savings by aligning system operation with actual building use. Sensors detect occupancy and environmental conditions, enabling systems to adjust automatically rather than relying on manual control. This reduces energy waste and supports more stable indoor environments for students and staff.

Overall, digitalisation, IoT technologies and automation represent a critical step towards smarter and more energy-efficient school buildings. Poland demonstrates the strongest integration of comprehensive BMS solutions, Lithuania shows dynamic growth in monitoring and data-driven energy management, while Greece focuses on automated cooling and climate-responsive controls. Together, these approaches illustrate how digital technologies can support sustainable construction and prepare school buildings for future energy and climate challenges.

3. Renewable energy sources in school buildings on the example of schools in Poland, Lithuania and Greece.

3.1 Overview of RES integration in school buildings

The integration of renewable energy sources (RES) in school buildings has become a key instrument for improving energy efficiency, reducing greenhouse gas emissions, and increasing energy independence across Europe. Poland, Lithuania and Greece all actively promote the use of RES in public buildings, including educational institutions, although the pace, scale and technological focus differ significantly due to climate conditions, national policies and existing building stock.

In all three countries, schools are increasingly seen not only as energy consumers but also as demonstrators of sustainable solutions. The most commonly applied RES technologies include photovoltaic (PV) systems, heat pumps, biomass-based heating systems and, more recently, energy storage solutions combined with digital monitoring.

While Lithuania and Poland primarily focus on reducing heating demand and improving winter energy performance, Greece prioritises solutions that address cooling needs and high solar exposure. These differences strongly influence the selection and effectiveness of RES technologies in school buildings.

3.2 Solar energy solutions

Solar energy is the most widely implemented renewable energy source in school buildings across all three countries.

In Lithuania, rooftop photovoltaic systems are increasingly installed in public schools as part of national climate and energy programmes and EU-funded initiatives. Typical installations range from 30 kWp to 100 kWp, depending on roof area and electricity demand. For example, schools equipped with 50 kWp PV systems can generate approximately 45,000–55,000 kWh of electricity per year, covering up to 40–60% of annual electricity consumption. This leads to substantial reductions in operating costs and CO_2 emissions.

In Poland, photovoltaic installations in schools are often implemented within broader renovation programmes. PV systems are frequently combined with building insulation upgrades and lighting modernisation. Installed capacities are similar to Lithuania (often 20–50 kWp per school), but the overall impact is amplified by large-scale renovation projects and advanced energy management systems. Poland also demonstrates a strong link between PV deployment and urban sustainability strategies.

In Greece, solar energy plays an even more dominant role due to high solar irradiation levels. In addition to photovoltaic panels, solar thermal systems for domestic hot water preparation are widely used in schools. PV systems in Greek schools can achieve high annual yields, often exceeding 1,500 kWh per installed kWp, making solar installations highly cost-effective and reducing reliance on grid electricity during peak summer demand.

3.3 Heat pumps and heating systems

Heating systems remain a critical component of school energy performance, particularly in Lithuania and Poland, where heating accounts for a significant share of total energy consumption.

In Lithuania, schools increasingly adopt air-to-water and ground-source heat pumps, often in combination with renovated building envelopes. Heat pumps are frequently used to replace outdated gas or oil boilers, reducing both energy costs and emissions. When powered partly by on-site PV systems, heat pumps significantly enhance overall energy efficiency and move schools closer to low-emission or nearly zero-energy building (nZEB) standards.

In Poland, the transition towards heat pumps is more gradual due to the large existing stock of district-heated and coal-based systems. However, renovated schools increasingly integrate hybrid systems, combining heat pumps with existing infrastructure. Biomass boilers also remain an important renewable heating solution, especially in smaller towns and rural areas.

In Greece, heating demand is lower, but reversible heat pumps are widely used for both heating and cooling. These systems are particularly effective in Mediterranean climates, providing year-round thermal comfort while reducing electricity consumption compared to traditional air-conditioning units.

3.4 Energy storage and monitoring solutions

Energy storage and monitoring solutions play a critical role in maximising the effectiveness of renewable energy systems in school buildings. In Lithuania, Poland and Greece, these solutions are increasingly recognised as essential tools for improving self-consumption rates, reducing peak energy demand and enabling data-driven energy management.

In Lithuania, energy monitoring systems are more widely implemented than energy storage technologies. Many schools equipped with photovoltaic installations use smart meters and digital monitoring platforms to track electricity production and consumption in real time. These systems allow school administrations and municipalities to analyse daily, monthly and seasonal energy patterns, identify inefficiencies and optimise operating schedules. In several Lithuanian schools, photovoltaic self-consumption rates typically range between 30% and 40% without storage, depending on building use profiles. The introduction of battery storage systems, such as the lithium-ion storage solution installed at Joniškis “Saulės” Gymnasium (approximately 100 kWh capacity), enables a significant increase in self-consumption by shifting surplus daytime electricity generation to evening peak demand periods. This improves energy independence and reduces reliance on grid electricity during high-tariff hours.

In Poland, energy monitoring and control systems are more systematically integrated into school infrastructure, particularly in buildings renovated under national modernisation programmes. Polish schools frequently operate Building Management Systems (BMS) that integrate energy monitoring, heating, ventilation, lighting and, in some cases, renewable energy production into a single control environment. These systems rely on smart meters, IoT sensors and automated control logic to continuously optimise building performance. Polish case studies indicate that the use of BMS and advanced monitoring can reduce overall energy consumption by approximately 15–25% in renovated public buildings. While battery storage systems are still less common in Polish schools, the high level of digital monitoring enables efficient alignment between photovoltaic production and building demand, leading to higher operational efficiency even without large-scale storage.

In Greece, energy storage solutions are currently limited, but monitoring plays a crucial role in managing cooling-related electricity demand. Smart meters and digital monitoring platforms are increasingly used to track energy consumption during peak temperature periods, allowing school managers to adjust cooling schedules and shading systems accordingly. Photovoltaic systems in Greek schools primarily support real-time electricity consumption, with self-consumption rates often exceeding 50% during daytime operation due to high solar irradiation and concurrent cooling demand. Although battery storage is not yet widespread, the strong alignment between solar generation and cooling needs reduces grid dependency during peak summer hours.

Across all three countries, energy monitoring systems serve not only as technical tools but also as educational instruments. In Lithuania and Poland in particular, energy dashboards and consumption data are used within STEAM-oriented educational activities, enabling students to analyse real energy flows and understand the relationship between renewable generation, storage and consumption.

From a comparative perspective, Poland demonstrates the most advanced integration of monitoring systems through comprehensive BMS solutions, Lithuania shows rapid development of smart metering and emerging battery storage applications, while Greece achieves high photovoltaic self-consumption through climate-driven demand alignment rather than storage. These differences highlight that effective energy storage and monitoring strategies must be adapted to local climatic conditions, building use profiles and technological maturity.

3.5 Examples of schools (good practices)

The integration of renewable energy sources in school buildings is most effectively demonstrated through concrete examples that combine technological solutions, financial mechanisms and measurable outcomes. Across Poland, Lithuania and Greece, schools increasingly function not only as energy consumers but also as active energy producers and learning environments for sustainable development.

Good practices from Poland

Poland presents some of the most advanced and data-rich examples of renewable energy integration in school buildings, often embedded within broader vocational and technical education frameworks.

A flagship example is the Electrical School Complex in Białystok ("Zespół Szkół Elektrycznych"), commonly referred to as the "Electrician" school. The school operates a hybrid renewable energy system consisting of three small wind turbines (3 kW each) and two photovoltaic installations with a combined capacity of approximately 20 kW. The system supplies a significant share of the school's electricity demand for lighting, laboratories and technical equipment.

The total investment cost amounted to approximately PLN 839,000, of which around 75% was financed from the school's own resources. What makes this project particularly valuable is its strong educational dimension: students actively participate in energy production monitoring, data analysis and system maintenance as part of their vocational training. The school functions as a living laboratory for renewable energy technologies, linking infrastructure investment with workforce development.

Another large-scale example is the city-wide photovoltaic programme in Białystok, where 12 public school buildings were equipped with rooftop PV installations. Individual system capacities range between 29.9 kW and 49.4 kW per school. According to municipal data, these installations have generated over 202,487 kWh of electricity, resulting in estimated financial savings of approximately PLN 370,000. This example demonstrates the effectiveness of coordinated municipal action, economies of scale and long-term planning in reducing operational costs of educational infrastructure.

Additionally, Primary School No. 26 in Białystok has established a renewable energy eco-laboratory, funded with PLN 75,000 from the Voivodeship Fund for Environmental Protection and Water Management. The eco-lab integrates photovoltaic systems, smart meters and monitoring tools, enabling students to analyse real-time energy data within STEAM-oriented educational activities.

Good practices from Lithuania

In Lithuania, renewable energy integration in schools is primarily driven by photovoltaic systems, energy storage solutions and biomass-based heating, often supported by national funding schemes and municipal co-financing.

A strong example is Alytus "Volungės" Progimnazija, where a rooftop photovoltaic power plant with a capacity of 50 kWp was installed. The total project cost was approximately EUR 39,182, of which EUR 31,346 was financed by the Environmental Project Management Agency (APVA), with the remaining costs covered by the municipality. The system generates around 65,000 kWh of electricity annually, covering a substantial share of the school's daytime electricity demand and reducing electricity costs by approximately 50%. The project demonstrates the effectiveness of targeted state support combined with local investment.

An innovative Lithuanian example is Joniškis “Saulės” Gymnasium, which implemented a lithium-ion battery energy storage system with a capacity of approximately 100 kWh. Although the system does not generate energy itself, it significantly improves self-consumption of electricity by storing surplus energy and using it during peak demand periods. This solution reduces dependency on the electricity grid and enhances energy flexibility, especially when combined with future photovoltaic installations.

Urban schools also contribute to renewable energy development. Vilnius Žirmūnai Gymnasium has installed photovoltaic panels to cover part of its electricity demand, while Klaipėda “Ąžuolyno” Gymnasium underwent comprehensive energy renovation, including thermal insulation upgrades and modernisation of heating systems. These measures resulted in lower energy consumption and improved indoor comfort, illustrating the benefits of combining RES with deep renovation.

In rural areas, several Lithuanian schools have transitioned from fossil fuel boilers to biomass-based heating systems, using locally sourced biofuels such as wood pellets. This approach is particularly effective in regions where heating accounts for the largest share of total energy consumption and where biomass resources are readily available.

Good practices from Greece

In Greece, renewable energy integration in school buildings is strongly shaped by climatic conditions, with solar energy and cooling-related solutions playing a dominant role.

Greek schools increasingly use photovoltaic systems and solar thermal collectors to meet electricity and domestic hot water demand. Due to high solar irradiation levels, these systems achieve high annual yields and contribute significantly to reducing electricity consumption from the grid. Photovoltaic installations are often designed to support cooling systems during peak summer periods, helping to mitigate energy demand spikes during heatwaves.

Renewable energy solutions in Greek schools are frequently combined with passive design measures, such as external shading systems, natural ventilation and light-coloured reflective materials. Although detailed capacity figures are less consistently documented than in Poland or Lithuania, the widespread adoption of solar technologies reflects a systemic response to climate-driven energy challenges rather than isolated pilot projects.

Greek examples also highlight the integration of renewable energy systems into broader climate adaptation strategies. Solar installations are used alongside architectural shading devices and automated cooling controls, improving indoor comfort while limiting the need for energy-intensive air conditioning.

3.6 Comparative assessment: what works best where and why

The comparative analysis of renewable energy sources integration in school buildings in Lithuania, Poland, and Greece clearly demonstrates that while all three countries pursue similar strategic objectives aligned with European Union climate and energy policies, the effectiveness of specific solutions strongly depends on climatic conditions, building typology, funding mechanisms, and institutional capacity.

In Lithuania, renewable energy solutions in schools are most effective when combined with energy monitoring and educational integration. Photovoltaic installations on school roofs, such as those implemented in Vilnius Žirmūnai Gymnasium, Alytus schools, and Joniškis "Saulė" Gymnasium, show tangible benefits in reducing electricity consumption from the grid, particularly when paired with energy storage systems. Battery systems allow surplus electricity generated during daytime to be used during peak demand hours, increasing self-consumption and reducing operational costs. Lithuania's strength lies in linking technological solutions with educational outcomes: energy monitoring data is increasingly used as a learning tool, fostering students' awareness of energy efficiency and sustainability. However, the overall impact is often constrained by limited financial resources and uneven implementation across regions.

Poland demonstrates the most advanced and systemic integration of renewable energy solutions in school buildings among the three countries. The Electrical School Complex in Białystok ("Electrician") is a particularly strong example, combining photovoltaic panels and wind turbines with a clear educational and research function. The scale of implementation in Poland, including multiple photovoltaic installations across public school buildings, results in measurable energy production figures and significant financial savings for municipalities. Polish schools benefit from relatively strong institutional support, access to national and regional funding, and the integration of renewable energy systems into vocational education profiles. As a result, renewable energy installations in Polish schools often function not only as infrastructure upgrades but also as long-term educational and innovation platforms.

In Greece, renewable energy solutions in school buildings are primarily shaped by climatic conditions, with solar energy playing a dominant role. High solar irradiance makes photovoltaic systems particularly effective, especially when combined with passive solar design, shading systems, and cooling-oriented strategies. Greek schools focus strongly on reducing overheating and cooling demand rather than heating efficiency, which distinguishes them clearly from Lithuania and Poland. Renewable energy solutions in Greece are most effective when integrated with architectural adaptations such as shading devices, reflective materials, and natural ventilation strategies. However, despite strong solar potential, implementation is sometimes limited by older building stock and fragmented funding structures.

From a comparative perspective, photovoltaic systems emerge as the most universally effective renewable energy solution across all three countries, although their operational role differs. In Greece, they primarily support cooling and electricity demand during hot periods; in

Poland, they are part of broader hybrid systems and vocational education ecosystems; in Lithuania, they are increasingly combined with energy storage and monitoring to maximize efficiency in variable climatic conditions.

Heat pumps and energy storage systems are most effective in Lithuania and Poland, where heating demand dominates energy consumption. In Greece, their role is more limited and context-specific. Monitoring and data-driven management appear as a key success factor in Poland and emerging practice in Lithuania, while Greece remains more focused on passive solutions and solar optimization.

Overall, the comparative assessment shows that the most successful renewable energy solutions in school buildings are those that are climate-responsive, financially supported, and integrated into educational processes. Poland excels in scale and systematisation, Lithuania in educational integration and emerging smart solutions, and Greece in climate-adapted solar strategies. These differences highlight the importance of tailoring renewable energy solutions to local conditions rather than applying uniform models across countries.

4. Culture of saving and managing energy in school buildings in Poland, Lithuania and Greece.

4.1 Behavioural aspects in schools

Behavioural patterns in schools play a significant role in overall energy consumption, regardless of the technological level of the building. In Lithuania, Poland and Greece, everyday habits related to heating, ventilation, lighting and equipment use directly influence energy efficiency outcomes.

In Lithuanian schools, behavioural challenges are often linked to traditional ventilation practices and limited awareness of energy-saving routines. Windows may be opened during the heating season for extended periods, lights and electronic equipment are sometimes left on after lessons, and energy-saving practices depend largely on individual teacher behaviour rather than systematic rules. However, schools that have introduced basic monitoring systems or internal guidelines demonstrate improved awareness and gradual behaviour change.

In Poland, behavioural aspects are more frequently supported by structured systems and school-level procedures. Polish schools increasingly use automated lighting controls, scheduled heating and clearly defined rules for energy use in classrooms and common areas. Behavioural change is therefore reinforced by technology, reducing reliance on individual habits alone. This approach contributes to more consistent energy-saving outcomes across schools.

In Greece, behavioural aspects are shaped by climatic conditions, particularly high temperatures and heat stress. Schools focus strongly on managing cooling behaviour, including controlled use of air conditioning, shading and ventilation timing. Teachers and students are often encouraged to adapt daily routines to reduce overheating, such as closing blinds during peak sunlight hours and prioritising natural ventilation when outdoor conditions allow.

Overall, behavioural aspects remain a critical but unevenly addressed component of energy efficiency. While Poland demonstrates more systematic integration of behaviour and technology, Lithuania and Greece show growing awareness but still rely heavily on individual practices.

4.2 Educational initiatives supporting energy efficiency

Educational integration plays a critical role in shaping long-term energy-saving culture in schools. All three countries demonstrate initiatives linking energy efficiency with learning processes, although the depth and structure of integration vary.

In Lithuania, educational initiatives form one of the strongest elements of energy management culture. Programmes such as Active Learning (AL), MEPA (Model European Parliament), STEAM activities, and national initiatives like “Tvari mokykla 2030” actively involve students in monitoring, analysing, and interpreting energy consumption data. In several schools, data from photovoltaic systems, smart meters, or battery storage is used directly in mathematics, physics, and environmental education lessons. This approach strengthens students’ understanding of energy systems while promoting responsible behaviour.

In Poland, renewable energy installations are frequently embedded within vocational and technical education. Schools such as the Electrical School Complex in Białystok integrate photovoltaic panels, wind turbines, and energy monitoring systems into curricula for electricians, energy technicians, and automation specialists. This creates a strong link between infrastructure, skills development, and labour market needs. Energy efficiency education is therefore practical, competence-based, and closely aligned with professional training.

In Greece, educational initiatives focus primarily on climate awareness and adaptation, reflecting national climate challenges. Topics such as heat stress, urban overheating, shading strategies, and water efficiency are commonly included in environmental education programmes. Renewable energy education is often framed within broader sustainability and climate resilience themes rather than technical system operation.

Overall, Lithuania stands out for its integration of energy monitoring into general education, Poland for its strong vocational focus, and Greece for its climate-oriented sustainability education.

4.3 Role of school’s management and municipalities

School management and local municipalities play a decisive role in shaping energy-saving culture by setting priorities, allocating resources and supporting long-term strategies.

In Lithuania, school management often operates under limited technical and financial capacity, relying heavily on municipal decisions and external funding programmes. While school leaders increasingly recognise the importance of energy efficiency, systematic energy management plans and long-term monitoring strategies are not yet uniformly applied. Nevertheless, municipalities involved in national or EU-funded projects tend to demonstrate higher organisational maturity and stronger results.

In Poland, municipalities play a more active and coordinated role. Energy efficiency measures are frequently implemented at municipal scale, allowing standardised solutions, shared monitoring systems, and long-term planning. School management benefits from clearer frameworks, technical support, and access to funding mechanisms, which contributes to more consistent outcomes across regions.

In Greece, governance structures are often fragmented, which can slow down implementation despite high solar potential. School-level initiatives may depend strongly on individual leadership and local engagement rather than systematic national frameworks. However, where municipal support exists, schools are more likely to integrate energy-saving practices with building adaptation measures.

Across all three countries, effective energy-saving culture emerges where school leadership, municipalities, and educational stakeholders cooperate, supported by clear responsibilities, data availability, and long-term planning.

From a comparative perspective, the culture of saving and managing energy in school buildings is most effective when behavioural practices, education, and management structures are aligned.

- Lithuania demonstrates strong educational engagement and growing use of monitoring data, but faces challenges related to consistency and regional disparities.
- Poland shows the most structured and institutionalised approach, combining behavioural management with automation and vocational education.
- Greece excels in climate-adapted behavioural practices, particularly related to cooling and passive design, although broader systematisation remains limited.

The analysis confirms that energy efficiency in schools cannot rely solely on technology. Sustainable results depend equally on informed users, engaged educators, and supportive governance structures.

5. Challenges and barriers (comparative)

Despite clear policy alignment with European climate and energy objectives, Lithuania, Poland, and Greece face a range of structural, financial, climatic, and organisational challenges that limit the pace and scale of energy efficiency improvements in school buildings. While many barriers are common across all three countries, their relative importance and impact differ significantly depending on national context.

5.1 Old building stock

One of the most significant challenges shared by Lithuania, Poland and Greece is the ageing stock of school buildings. A large proportion of educational facilities in all three countries were constructed several decades ago, often before modern energy efficiency standards were introduced. These buildings typically have poor thermal insulation, outdated windows and inefficient heating or cooling systems.

In Lithuania and Poland, many school buildings originate from the Soviet or early post-war periods, characterised by standardised designs and limited attention to energy performance. As a result, heat losses during the cold season remain substantial, and deep renovation is often required to achieve meaningful energy savings. In Greece, although climatic conditions differ, older school buildings also struggle to meet current comfort and energy efficiency requirements, particularly in terms of overheating and insufficient shading.

The scale of the old building stock significantly increases the complexity and cost of renovation programmes and slows down the pace of transformation towards energy-efficient school infrastructure.

5.2 Financial constraints

Financial limitations remain a critical barrier in all three countries. Energy efficiency renovations and renewable energy installations require high upfront investments, which are often beyond the financial capacity of individual schools.

Lithuania and Greece rely heavily on EU funding instruments, national climate programmes, and municipal co-financing. This dependence can lead to uneven implementation across regions, as municipalities with weaker financial capacity struggle to initiate or co-finance projects. In Poland, access to funding is generally more structured and stable, enabling larger-scale implementation, although competition for funds remains high.

In all three countries, limited long-term financing mechanisms slow down deep renovation projects and prioritisation is often given to partial or short-term solutions.

5.3 Climate-specific challenges

Climate-related challenges differ significantly between the three countries and directly affect energy efficiency strategies in school buildings. Lithuania and Poland face long heating seasons, low winter temperatures and increasing humidity, which intensify heat losses and place high demands on heating systems and building envelopes.

In contrast, Greece is increasingly affected by heatwaves and prolonged periods of high temperatures. Overheating, excessive cooling demand and indoor comfort during summer months are critical issues in Greek schools. These climate-specific challenges require different technical solutions and complicate the development of unified approaches to energy efficiency.

Climate change further amplifies these challenges, making it necessary for school buildings to adapt not only to current conditions but also to future climate scenarios.

5.4 Monitoring and data availability

Limited monitoring and insufficient availability of energy consumption data remain important barriers in all three countries. Accurate and continuous data on energy use before and after renovation is essential for assessing the effectiveness of energy efficiency measures, yet such data is often incomplete or fragmented.

In Lithuania and Greece, monitoring systems are still developing and are frequently implemented only in selected pilot projects. This limits the ability to evaluate long-term impacts and compare results across schools. Poland demonstrates more advanced use of monitoring systems in renovated buildings, although challenges related to data integration and standardisation persist.

The lack of consistent data reduces transparency, weakens evidence-based decision-making and makes it more difficult to optimise future investments in energy efficiency.

6. Innovations, digitalisation, AI and automation

Digitalisation and technological innovation are increasingly recognised as key drivers of energy efficiency in school buildings across Lithuania, Poland and Greece. Although the level of technological maturity differs between countries, all three demonstrate a gradual shift towards smarter, data-driven and automated solutions that support more efficient energy management and climate resilience.

6.1 Internet of Things (IoT) systems in school buildings

In all three countries, Internet of Things (IoT) solutions are increasingly used to improve energy efficiency in school buildings through real-time monitoring and control.

In Poland, IoT implementation is the most advanced among the three countries. Renovated schools are frequently equipped with sensor networks integrated into Building Management Systems (BMS). These systems allow continuous monitoring of heating, ventilation, lighting and electricity consumption. Polish case studies indicate that the introduction of IoT-based monitoring can reduce overall energy consumption in public buildings by approximately 15–25%, mainly by eliminating unnecessary heating, lighting and ventilation during non-occupancy periods.

In Lithuania, IoT solutions are developing rapidly but are usually implemented in a more modular way. Schools increasingly install smart meters, temperature sensors and basic monitoring platforms rather than full-scale BMS. These systems enable schools and municipalities to track electricity and heat consumption, identify abnormal usage patterns and optimise operating schedules. Although energy savings are typically lower than in fully automated systems, Lithuanian examples demonstrate reductions of 5–15%, particularly in electricity consumption and heating optimisation.

In Greece, IoT applications are primarily focused on thermal comfort management under hot climatic conditions. Sensors monitoring indoor and outdoor temperatures and solar exposure are commonly linked to automated shading, ventilation and cooling controls. These systems help schools respond dynamically to heatwaves and reduce excessive cooling demand, especially during peak summer periods.

6.2 AI-Based optimisation

Artificial intelligence is gradually emerging as a tool for optimising energy use in school buildings, although the level of implementation varies significantly. Unlike basic automation, AI enables predictive and adaptive control by analysing historical data, weather forecasts and occupancy patterns.

In Poland, AI-supported optimisation is already present in selected public buildings, including schools. AI algorithms embedded in advanced BMS platforms dynamically adjust heating and lighting schedules based on predicted demand. Studies referenced in national analyses show that AI-based optimisation can deliver an additional 5–10% energy savings beyond standard automation by reducing peak loads and improving system responsiveness.

In Lithuania, AI applications are still at an early stage but are clearly emerging. Energy monitoring platforms already collect large volumes of consumption data, creating favourable conditions for future AI deployment. Pilot initiatives focus on energy consumption analytics, anomaly detection and forecasting, which are essential precursors to AI-driven optimisation. Lithuanian schools therefore represent a transitional model, where data infrastructure exists but advanced AI control is not yet widespread.

In Greece, AI optimisation is primarily linked to cooling demand management. Predictive models use weather forecasts and indoor climate data to anticipate overheating risks and pre-adjust cooling systems, ventilation rates and shading devices. This approach helps reduce electricity demand during peak hours and improves indoor comfort during extreme heat events.

6.3 Automation and predictive maintenance

Automation technologies significantly enhance energy efficiency by reducing reliance on manual control and ensuring systems operate only when needed. Automated solutions include smart lighting systems, automated heating and ventilation controls and time-based or occupancy-based regulation.

Poland demonstrates the most advanced use of automation in school buildings. Automated lighting systems with motion sensors, programmable heating schedules and integrated BMS solutions are common features of renovated schools. In some cases, automation is combined with predictive maintenance tools, which analyse system performance data to identify potential faults before failures occur.

In Lithuania, automation is gradually expanding, particularly in lighting and heating systems. Schools increasingly replace traditional lighting with automated LED systems and introduce programmable heating controls. Predictive maintenance is still limited, but monitoring systems allow early detection of inefficiencies and equipment degradation.

In Greece, automation focuses primarily on cooling systems and shading mechanisms. Automated blinds, ventilation controls and cooling schedules help mitigate overheating and reduce energy consumption during peak summer periods. While predictive maintenance is less developed, automation contributes significantly to maintaining stable indoor conditions.

6.4 Comparative readiness of Poland, Lithuania and Greece

From a comparative perspective, Poland demonstrates the highest level of technological readiness, with widespread use of BMS, IoT sensors and AI-supported optimisation in school buildings. Lithuania is in a transitional phase, actively building digital infrastructure and data capacity that enables future AI and automation deployment. Greece shows strong application-specific readiness, particularly in cooling-related automation and climate-adaptive technologies.

Together, these national experiences illustrate different pathways towards smart, energy-efficient school buildings and provide a strong technological foundation for climate adaptation strategies.

7. Sustainable building materials – comparative view

7.1 Low-carbon materials

The selection of building materials plays a crucial role in reducing the overall environmental impact of school buildings, particularly when considering embodied carbon emissions. Embodied carbon refers to greenhouse gas emissions associated with material extraction, production, transportation, construction and end-of-life processes. In the context of sustainable school construction, reducing embodied carbon is increasingly recognised as equally important as reducing operational energy use.

In Lithuania, low-carbon material strategies are emerging mainly in new public buildings and pilot renovation projects. National discussions increasingly reference life-cycle assessment (LCA) and environmental product declarations (EPD) as tools for evaluating material sustainability. Engineered wood products, particularly cross-laminated timber (CLT), are identified as promising alternatives to reinforced concrete due to their significantly lower embodied carbon footprint. While reinforced concrete typically generates approximately 250–350 kg CO_2e per m^3, CLT structures can reduce embodied emissions by up to 40–60%, depending on sourcing and design assumptions. However, CLT is still not widely applied in Lithuanian school buildings and remains primarily at the conceptual or pilot stage.

In Poland, reducing embodied carbon is achieved mainly through large-scale renovation rather than material substitution. Polish school modernisation programmes prioritise the retention of existing structural elements, which significantly lowers embodied emissions compared to demolition and new construction. Although reinforced concrete remains dominant, deep thermal renovation of existing buildings reduces lifecycle emissions by extending building lifespan. While LCA-based material comparison is not yet standard practice, the renovation-first strategy delivers substantial embodied carbon savings at scale.

In Greece, embodied carbon reduction is closely linked to traditional construction practices and climate-adapted material use. School buildings frequently employ mineral-based and locally sourced materials such as stone, ceramics and lime-based finishes. These materials typically have lower embodied carbon than industrialised construction systems and offer favourable thermal properties in hot climates. Additionally, the reduced need for transportation contributes to lower lifecycle emissions, although formal LCA calculations are less commonly applied in public school projects.

Overall, Lithuania demonstrates growing awareness of embodied carbon and low-carbon materials through innovation-oriented approaches, Poland achieves embodied carbon reduction primarily through renovation scale, and Greece benefits from climate-adapted, material-efficient construction traditions.

7.2 Local resources and circular economy

The integration of local resources and circular economy principles contributes to both environmental sustainability and economic resilience in school construction projects. Circular economy approaches aim to minimise waste, maximise material reuse and extend the lifecycle of buildings and materials.

In Lithuania, circular economy principles are increasingly referenced in public procurement and EU-funded projects. Examples include the reuse of construction materials during renovation, recycling of demolition waste and preference for locally manufactured insulation and finishing materials. However, implementation remains inconsistent and often limited to projects with specific sustainability criteria. The use of EPD-certified materials is growing but not yet mandatory for school buildings.

In Poland, circular economy practices are embedded implicitly through renovation-focused strategies. By prioritising the modernisation of existing school buildings, Polish programmes significantly reduce material consumption and construction waste. Although explicit circular economy frameworks are rarely applied at school level, the avoidance of demolition and large-scale reuse of existing structures aligns strongly with circular principles. This approach is particularly effective given the size of Poland's school building stock.

In Greece, the use of local resources forms a natural foundation for circular economy practices. Locally sourced stone, ceramic materials and mineral finishes reduce transportation emissions and support regional supply chains. While formal recycling systems in school construction are less developed, the reliance on durable local materials contributes to long-term sustainability and reduced material turnover.

Comparatively, Lithuania shows the strongest alignment with formal circular economy concepts, Poland demonstrates large-scale material efficiency through renovation, and Greece applies pragmatic, locality-based sustainability practices.

7.3 Green roofs and water management systems

Green roofs and water management systems are increasingly relevant sustainable construction solutions, particularly in the context of climate change adaptation and urban resilience.

Poland represents the most advanced application of green roofs in school buildings among the three countries. Green roofs are implemented primarily in urban schools, where they contribute to improved thermal insulation, stormwater retention and mitigation of the urban heat island effect. Studies referenced in Polish practice indicate that green roofs can reduce roof surface temperatures by up to 30–40°C during summer and retain 50–80% of annual rainfall, significantly reducing runoff. In some cases, green roofs are integrated into educational programmes, serving as outdoor learning spaces.

In Lithuania, green roofs are still relatively rare in school buildings, but water management systems are gaining importance due to increasing rainfall intensity. Sustainable drainage systems, rainwater retention tanks and controlled runoff solutions are increasingly discussed in renovation planning. These systems help reduce flood risk, protect building foundations and support climate adaptation, although implementation remains limited to selected projects.

In Greece, water management systems are shaped primarily by water scarcity and overheating risks rather than excess rainfall. School buildings increasingly use rainwater harvesting systems for non-potable purposes, such as irrigation. While extensive green roofs are less common due to structural and climatic constraints, vegetation-based shading and green courtyards are used to improve microclimatic conditions and reduce ambient temperatures.

In comparative terms, Poland leads in green roof implementation, Lithuania prioritises rainwater management in response to changing precipitation patterns, and Greece focuses on water efficiency and cooling-related landscape solutions.

8. Climate change adaptation in school buildings

Climate change increasingly affects the performance, safety and comfort of school buildings across Europe. Lithuania, Poland and Greece face different climate-related risks, which require distinct adaptation strategies in the design, renovation and operation of educational facilities. Climate adaptation in school buildings is therefore not only an environmental issue but also a matter of long-term functionality, health and energy security.

8.1 Climate risks affecting school buildings

In Lithuania and Poland, climate change manifests primarily through colder winters interspersed with sudden temperature fluctuations, increased precipitation and more frequent extreme weather events. School buildings are exposed to higher heating demand, moisture-related structural risks and greater stress on insulation and heating systems. Poorly adapted buildings experience increased energy losses, higher operational costs and deteriorating indoor comfort, particularly in older facilities.

In Greece, climate change is driven mainly by rising average temperatures, prolonged heatwaves and intensified solar radiation. School buildings increasingly face overheating risks, especially during late spring and early autumn periods when schools are fully operational. High cooling demand, thermal discomfort and increased electricity consumption during peak hours are major challenges, particularly in buildings originally designed for milder climatic conditions.

Across all three countries, climate change also increases the frequency of extreme events, such as heavy rainfall, storms and prolonged droughts. These phenomena affect school safety, infrastructure resilience and the reliability of energy systems, making climate adaptation a prerequisite for long-term sustainability.

8.2 Adaptation strategies in cold and temperate climates (Lithuania and Poland)

In Lithuania and Poland, climate adaptation strategies in school buildings focus primarily on improving thermal resilience and protecting buildings from moisture-related risks. Deep renovation measures such as enhanced insulation, airtight building envelopes, high-performance windows and modernised heating systems play a central role.

Thermal insulation upgrades significantly reduce heat losses and stabilise indoor temperatures during cold periods. In renovated school buildings, heating energy demand can be reduced by 30–50%, depending on the depth of renovation. Airtightness improvements and controlled ventilation with heat recovery further enhance energy efficiency while maintaining indoor air quality.

Water management has also become increasingly important. Heavy rainfall events require improved drainage systems, rainwater retention solutions and protection of building foundations and façades. In Poland, green roofs and permeable surfaces are increasingly used to mitigate runoff and reduce flood risk, particularly in urban school environments.

These adaptation measures not only reduce energy consumption but also protect buildings from long-term climate-related damage, ensuring that energy efficiency investments deliver lasting benefits.

8.3 Adaptation strategies in warm and hot climates (Greece)

In Greece, climate adaptation in school buildings is primarily oriented towards mitigating heat stress and reducing cooling demand. Passive cooling strategies are central to this approach, as they allow schools to maintain thermal comfort without excessive reliance on mechanical air conditioning.

Key measures include external shading devices, architectural overhangs, reflective and light-coloured façades, and improved natural ventilation. These solutions can reduce indoor temperatures by several degrees Celsius, significantly lowering cooling energy demand during peak periods.

Shading systems are particularly effective in classrooms with large glazed areas, where direct solar gains can cause overheating. By reducing solar radiation entering the building, shading contributes to both energy savings and improved learning conditions. In some Greek schools, the combination of shading and natural ventilation reduces the need for mechanical cooling during large parts of the school year.

Climate adaptation in Greece is also closely linked to energy security. During heatwaves, electricity demand for cooling increases sharply, making energy-efficient and passive solutions essential for preventing system overloads and ensuring uninterrupted school operation.

8.4 Why climate adaptation is essential for energy efficiency

Climate adaptation and energy efficiency are deeply interconnected. Energy-efficient buildings that are not adapted to climate risks may fail to perform as intended under extreme conditions. Conversely, climate-adapted buildings can significantly enhance the effectiveness of energy efficiency measures.

For example, insulation improvements in cold climates reduce heating demand, but without moisture protection and ventilation control, they may lead to condensation and indoor air quality problems. In hot climates, energy-efficient cooling systems must be supported by shading and passive design to prevent excessive energy use during heatwaves.

From an educational perspective, climate adaptation directly affects learning outcomes. Overheated classrooms, excessive cold or poor air quality negatively impact students' concentration, health and academic performance. Climate-resilient school buildings provide stable indoor conditions that support both well-being and effective learning.

8.5 Comparative perspective: different climates, shared responsibility

The comparative analysis shows that while Lithuania, Poland and Greece face different climate-related challenges, climate adaptation is equally essential in all three contexts. Lithuania and Poland focus on protecting schools from cold, moisture and heating-related risks, while Greece prioritises heat mitigation and cooling resilience.

Despite these differences, a common conclusion emerges: climate adaptation must be integrated into all energy efficiency and renovation strategies. Without adaptation, energy efficiency gains may be temporary or insufficient. With adaptation, schools become more resilient, cost-effective and capable of supporting long-term climate and education goals.

In this sense, climate adaptation is not an optional addition but a core component of sustainable construction. The experiences of Lithuania, Poland and Greece demonstrate that context-specific adaptation strategies, combined with energy efficiency measures, are essential for creating future-proof school buildings across Europe.

9. Final comparative summary

This comparative report has examined energy efficiency in sustainable construction in school buildings across Lithuania, Poland and Greece, taking into account legal frameworks, technological solutions, renewable energy integration, behavioural practices and climate-related challenges. Although the three countries operate within a common European policy framework, the analysis clearly demonstrates that national approaches differ significantly due to climate conditions, building stock characteristics and institutional capacity.

The comparative findings are based on documented case studies, energy performance indicators (EPC classifications), installed renewable energy capacities and observed differences in technological and institutional maturity across the three countries.

Lithuania's approach to energy efficiency in school buildings is characterised by a strong focus on renovation, monitoring and gradual digitalisation. The country shows growing engagement with renewable energy solutions, particularly solar energy systems and energy storage, combined with emerging practices in data-based energy monitoring. Educational initiatives such as Active Learning, MEPA and STEAM contribute to raising awareness and shaping energy-saving behaviour among students and staff. However, the pace of implementation remains closely linked to available funding and municipal capacity, highlighting the importance of long-term investment planning.

Poland demonstrates the most systematic and large-scale implementation of energy efficiency measures among the three countries. Extensive renovation programmes, widespread application of Building Management Systems (BMS), EPC-driven renovation strategies and the integration of smart sensors and automation position Poland as a leader in practical implementation. The widespread use of green roofs, smart lighting and structured energy management reflects a mature approach that combines technological innovation with long-term maintenance strategies. Poland's experience shows how coordinated policy, funding mechanisms and technical expertise can significantly accelerate energy efficiency improvements in public school buildings.

Greece presents a distinct model shaped by climatic realities and increasing heat stress. Energy efficiency strategies in Greek schools prioritise cooling, shading and passive design solutions aimed at maintaining indoor comfort during hot periods. Renewable energy integration and material choices are strongly linked to local resources and climate-adapted construction traditions. While digitalisation and advanced monitoring systems are developing, the primary focus remains on reducing overheating and managing energy demand peaks during summer months.

The comparative analysis confirms that there is no single optimal model for energy-efficient school buildings applicable to all contexts. Instead, successful solutions are those that respond to local climate conditions, building characteristics and institutional frameworks. Cold-climate strategies in Lithuania and Poland emphasise thermal performance and heating efficiency, while Greece focuses on cooling and solar protection. At the same time, all three countries benefit from shared European objectives, legal frameworks and funding instruments that support sustainable construction.

One of the key conclusions of this report is that the integration of renewable energy sources, digital technologies and behavioural change initiatives delivers the greatest impact when implemented together. Technological solutions alone are insufficient without informed users, supportive management structures and reliable data. Conversely, educational and behavioural initiatives are most effective when supported by measurable energy performance improvements.

In summary, the comparative perspective highlights the value of cross-country learning and the exchange of good practices. Lithuania, Poland and Greece each contribute unique strengths to the broader European effort to improve energy efficiency in school buildings. By combining technological innovation, climate-responsive design and educational engagement, sustainable construction can play a central role in addressing climate change while creating healthier and more resilient learning environments.

10. Recommendations for training the trainers

Based on the comparative analysis of energy efficiency practices in school buildings in Lithuania, Poland and Greece, a clear need emerges for targeted and practice-oriented training of teachers and trainers. Training the trainers plays a key role in ensuring that technological solutions, sustainability concepts and climate adaptation strategies are effectively transferred to students and embedded in everyday educational practice.

The following recommendations identify the most important thematic areas, practical learning activities and innovative approaches that should be included in training programmes for teachers working in vocational education, general education and technical fields.

10.1 Key training topics for trainers

Training programmes for trainers should prioritise a combination of technical knowledge, practical skills and pedagogical approaches. The most important thematic areas include:

- Energy efficiency fundamentals in buildings, including building envelope performance, heating and cooling systems, ventilation and lighting efficiency.
- Renewable energy sources in schools, with a focus on photovoltaic systems, heat pumps, energy storage and self-consumption models.
- Digitalisation and smart energy management, covering Building Management Systems (BMS), smart meters, sensors, energy monitoring platforms and basic principles of data analysis.
- Climate change adaptation strategies, including heat stress mitigation, insulation strategies for cold climates, shading systems and water management solutions.
- Sustainable building materials, introducing concepts such as embodied carbon, life-cycle assessment (LCA), environmental product declarations (EPD) and circular economy principles.
- Behavioural aspects and energy culture, addressing how user behaviour influences energy consumption and how educational initiatives can support long-term change.

These topics should be adapted to national contexts, taking into account climate conditions, building stock characteristics and existing institutional frameworks.

10.2 Practical learning tasks and hands-on activities

To ensure effective knowledge transfer, training should be strongly practice-oriented. Recommended practical tasks include:

- Energy audits of school buildings, where trainers can analyse real energy consumption data, identify inefficiencies and propose improvement measures.

- Monitoring and data interpretation exercises, using smart meters or energy monitoring platforms to understand daily, seasonal and peak energy use.
- Simulation tasks, such as comparing energy performance before and after renovation or evaluating the impact of renewable energy installations.
- Case study analysis, based on real examples from Lithuania, Poland and Greece, highlighting good practices and lessons learned.
- Project-based learning, where participants design simplified energy efficiency or renewable energy solutions for a school building.

These activities help trainers develop practical competencies that can be directly transferred to classroom teaching and student projects.

10.3 Innovative teaching approaches and tools

Training programmes should encourage the use of innovative teaching methods that reflect current technological developments:

- Integration of STEAM-based learning, linking energy efficiency topics with science, technology, engineering and mathematics.
- Use of digital tools and dashboards to visualise energy data and support interactive learning.
- Application of problem-based learning, where trainers address real-life energy challenges in school environments.
- Introduction to basic AI-supported analysis, such as forecasting energy consumption trends or identifying anomalies in energy use.

These approaches help trainers modernise teaching practices and engage students more effectively.

10.4 Final remarks on training the trainers

The comparative analysis demonstrates that successful energy efficiency and climate adaptation strategies depend not only on technologies and funding but also on human capacity. Well-trained teachers and trainers are essential for translating complex technical solutions into meaningful educational experiences. By focusing on practical skills, digital tools, climate awareness and interdisciplinary teaching, training the trainers can significantly enhance the long-term impact of energy efficiency initiatives in schools across Lithuania, Poland and Greece.