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Preliminary report/Short communication
Doi 10.61892/STP202601054R
ISSN 2566-4484

STEPGRAD
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ENERGY PERFORMANCE OF MEMBRANE SPORTS HALLS: COMPARATIVE ANALYSIS ACROSS CLIMATIC CONTEXTS

Abstract:

Due to their structural flexibility and rapid construction, membrane sports halls are an increasingly common solution for sports facilities. In this paper, the annual energy consumption of membrane halls in five different climate contexts was analyzed using simulations conducted in EnergyPlus: Prague, Cannes, Niš, Bergen, and Dawadmi. The research quantifies the energy needed to maintain suitable indoor conditions in membrane halls, distinguishing between heating and cooling demands. Results confirm that climate strongly influences energy balance: heating is predominant in cold climates, cooling is critical in warm, arid areas, and transitional climates like Niš experience high energy consumption, necessitating a comprehensive strategy.

Keywords: membrane halls, energy efficiency, climate context, EnergyPlus simulation

ЕНЕРГЕТСКЕ ПЕРФОРМАНСЕ МЕМБРАНСКИХ СПОРТСКИХ ДВОРАНА: УПОРЕДНА АНАЛИЗА У РАЗЛИЧИТИМ КЛИМАТСКИМ КОНТЕКСТИМА

Абстракт

Због конструктивне флексибилности и брзе изградње, мембранске спортске хале представљају све чешће решење за спортске објекте. У овом раду је помоћу симулација спроведених у софтверу EnergyPlus анализирана годишња потрошња енергије мембранских хала у пет различитих климатских контекста: Прагу, Кану, Нишу, Бергену и Давадмију. Циљ истраживања био је да се квантификује потребна енергија за обезбеђивање адекватних унутрашњих услова у овим објектима, уз јасно разликовање удела потрошње за грејање и хлађење. Резултати показују да климатске специфичности значајно утичу на енергетски биланс: у хладним контекстима доминирају потребе за грејањем, док у топлим и аридним условима хлађење представља главни енергетски изазов. У прелазним климатама, попут Ниша, потрошња је висока и захтева интегрисан приступ.

Кључне ријечи: мембранске хале, енергетска ефикасност, климатски контекст, EnergyPlus

1. INTRODUCTION

Membrane halls are increasingly found in sports centers, schools, and even industrial zones. They represent a fast, affordable solution, and over the last few decades, membrane halls have become the choice when it is necessary to provide a large, open space quickly and without many columns or a heavy structure [1], [2]. This paper specifically examines the energy efficiency of these structures across different climatic contexts and, based on this, provides practical advice on how to design and use them in all types of climates [3], [4].

In the initial phase, membrane buildings can lead to significant financial savings, but it is more complicated to estimate how much energy they use - especially across different climates. Whether a building retains heat or stays cool greatly affects how comfortable it feels, how much you pay to maintain it, and its environmental impact [5], [6]. Unlike brick or concrete buildings, which are heavy and let in little sunlight, membrane halls are lightweight and let in much more daylight. This means that the temperature inside can change quickly. This is great if you live in a temperate climate, but it can be a real pain in places with cold winters or hot summers in about an hour [7], [8]. Basically, the more sunlight and heat a material lets through, the faster the space warms up. Buildings made of brick or concrete heat up and cool down slowly, so you do not get affected by large temperature changes. However, membrane halls can become noticeably warmer or cooler in a short time. Sometimes this is beneficial, but it also means you will feel those ups and downs more than in a traditional building.

The selected material depends on the local climate, the purpose of the buildings, and the willingness to invest financially. Some studies have found that using double membranes or modern materials - such as Etilen-tetrafluoroetilen (ETFE) or multi-layer Polyvinyl chloride (PVC) - can help keep temperatures steadier and reduce energy loss in sports halls [9], [10]. While ETFE is lightweight, lets in a lot of light, and is weatherproof, making it a good choice for large, sunny spaces, multi-layer PVC retains heat better, lasts longer, and does not leak, making it practical if you need better temperature control. However, looking at the building as a whole means mixing and matching materials, which can help achieve the best energy performance. The building's shape and how you manage ventilation are also very important [6], [11], [12]. Adding heat-storing materials or installing solar panels can save even more energy and make the building more environmentally friendly [13]. All of this means a comfortable space that is also better for the environment.

Some research shows that membrane halls can actually retain heat pretty well in the winter, since they warm up quickly when you need them to. In hotter places, they might even use less energy than regular brick buildings because they do not trap heat as much [12], [14], [15]. There is no perfect solution – both membrane and wall sports halls have their advantages and limitations, which largely depend on local climatic conditions. Membrane halls heat up and cool down faster, which can be an advantage in conditions of frequent weather changes, but at the same time, exposes them to large temperature fluctuations and a possible increase in energy consumption if the systems are not tested. This is precisely why it is crucial to design these facilities in accordance with local climate conditions. The choice of materials, the orientation of the building towards the sun or shade, as well as properly dimensioned and controlled ventilation, have a major impact on comfort and energy efficiency. Even details like the shape of the hall, where the windows and doors go, and how you deal with drafts matter a lot [6], [16].

In modern construction, energy-saving is becoming a key priority. Although membrane halls are increasingly used due to their fast construction and structural flexibility, there has been insufficient research into how they function in different climates and how much the climatic context affects their energy consumption. The existing literature mainly focuses on the constructive aspects of user comfort, while systematic comparative analysis of energy consumption across different climate zones remains limited. This is where the research gap arises: it is necessary to determine which factors contribute most to the energy efficiency of membrane sports halls and how their performance varies by location. This paper presents the comparative energy consumption of membrane sports halls in five different climate contexts (Prague, Cannes, Niš, Bergen, and Dawadmi) through EnergyPlus simulations (version 24.2.0, developed by the U.S. Department of Energy) [17]. The analysis focuses exclusively on energy needs to ensure adequate indoor conditions, without changing the membrane type or considering user comfort. This provides a clear picture of how climate conditions directly determine energy performance and why it is necessary to adapt the design to each location individually.

This work offers a framework for understanding the energy performance of membrane halls across different climate conditions, identifies key challenges, and provides a basis for future research and optimization. In this way, a research gap is addressed, and practical recommendations are provided for designers and researchers working on the energy efficiency of sports facilities.

2. METHODOLOGY

In this study, a practical simulation method was applied to estimate the annual energy consumption of membrane sports halls. The simulations were carried out in EnergyPlus (version 24.2.0), which allows detailed modeling of energy flows in buildings and direct comparison of results across different climatic conditions [17]. The analysis aimed to quantify the energy required to maintain indoor conditions that meet acceptable thermal comfort standards (adequate indoor conditions were defined as 20 °C during the heating season and 26 °C during the cooling season, with relative humidity between 40–60%).

The selection of the analyzed locations in this study was based on the need to include different climatic regimes that directly affect the energy performance of membrane sports halls. The aim was to demonstrate how ventilation and heat losses, as well as solar gains and air conditioning strategies, behave in continental, Mediterranean, transitional, and cold-humid climates. This provides a comparative analysis that highlights universal design principles and the specific requirements for each analyzed climatic zone.

Continental climates are characterized by cold winters (average January temperatures often below 0 °C) and warm summers, with a long heating season typically lasting 5–6 months. Mediterranean climates have mild winters (average January temperatures around 8–12 °C) and hot, dry summers with high solar radiation, where cooling demand dominates. Transitional climates, such as those between continental and Mediterranean zones, exhibit large annual temperature amplitudes, with both heating and cooling requirements significant. Cold-humid climates are marked by frequent precipitation, high relative humidity, and low solar radiation, with heating demand prevailing throughout most of the year. These differences directly influence the energy balance of membrane halls and the strategies required for ventilation, shading, and HVAC operation.

As representatives of these climatic regimes, the following cities were selected for analysis: Prague (continental), Cannes (Mediterranean), Niš (transitional continental-Mediterranean), Bergen (cold-humid), and Dawadmi (hot desert climate) (Figure 1).

Prague was chosen as a representative of the continental climate with marked seasonal differences. Key features are cold winters (average January temperature −1 °C, heating season about 6 months) with frequent temperature inversions, and warm summers (average July temperature 19 °C) with significant solar gains. Such conditions emphasize the need for strong heating in winter and control of solar gain in summer, with the possibility of efficient night cooling.

Cannes was chosen as a typical example of the Mediterranean climate. Mild winters (average January temperature 9 °C) and warm, sunny summers (average July temperature 23–26 °C) with high solar radiation (over 1800 kWh/m² annually) make cooling the dominant factor. Daytime temperature amplitudes make room for nighttime cooling, but success depends on relative humidity and nighttime temperatures. This location is key to analyzing the impact of solar gain through transparent membranes and shading efficiency.

Niš lies in a transition zone between continental and Mediterranean climates. It is characterized by summer heat waves, with July averages around 23–25 °C, and winter cold, with January averages near 0 °C, resulting in high annual amplitudes exceeding 25 °C and significant heating and cooling needs. This location was chosen because it requires balanced strategies: heat recovery, Demand Controlled Ventilation (DCV), shading, and reversible Heating, Ventilation, and Air Conditioning (HVAC) systems.

Bergen has a cold, humid climate with average annual precipitation > 2000 mm, an average July temperature of 15 °C, an average January temperature of 1–2 °C, and low solar radiation compared to continental regions. In such conditions, heating dominates the energy balance, while ventilation and conduction losses are key factors. Because of the high humidity, condensation and moisture control are important aspects of envelope and ventilation system design. Bergen was included to assess the effectiveness of recovery and improved jackets in extremely cold, wet conditions.

Dawadmi in Saudi Arabia is a desert region with extremely high summer temperatures (summer maximums often exceeding 45 °C, average July temperature 36 °C), low relative humidity (below 20%), and intense solar radiation (annual solar radiation > 2200 kWh/m²). Cooling is the dominant load, and solar gains through the membranes are a key factor. This location was chosen to demonstrate the performance of membrane halls in extremely hot conditions and to test the effectiveness of shading, high-coefficient-of-performance (COP) cooling systems, and the integration of photovoltaic energy sources.

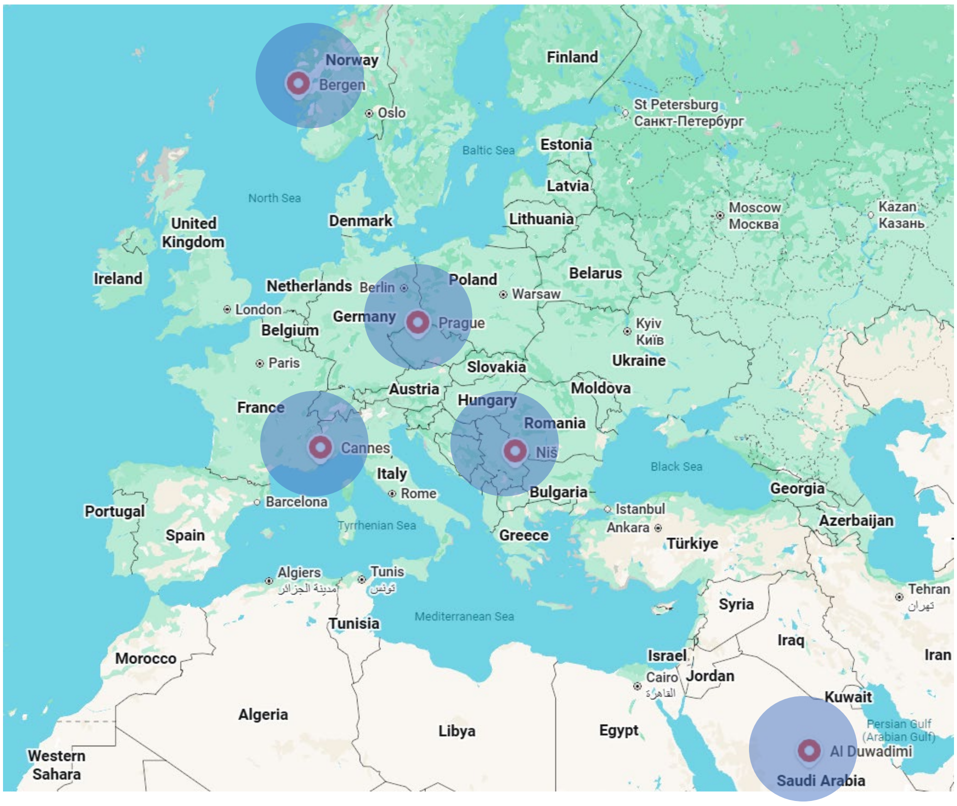

Figure 11. Selected cities as representatives of continental, Mediterranean, transitional, cold-humid, and desert climates (drawing by author).

For each of these, detailed weather data - such as temperature, humidity, sunlight, and wind—were used throughout the year to ensure the simulations were as close as possible to the conditions these buildings face on a daily basis [18]–[20].
Local Typical Meteorological Years (TMYx) [21] were used in the simulations, which contain hourly values of external temperature, relative humidity, global and diffuse radiation, wind speed, and cloud cover, because it is the variability of daily and seasonal amplitudes that directly affects the performance of the membrane envelope.

All building models were kept the same size (18 m x 42.8 m) so that any differences in results would come down to the construction itself, not the size. The analysis included a PVC single-layer membrane, building usage based on everyday activities such as sports, recreation, or school activities, and consideration of how people, equipment, and lighting affect the indoor environment throughout the day. Heating and cooling setpoints were selected in accordance with sports facility standards and then fine-tuned based on research on comfort in lightweight buildings. Both natural and mechanical ventilation were tested, and the heating, cooling, and air-circulation systems were kept simple and practical. Because lightweight buildings can lose energy quickly through drafts or leaks, air infiltration was treated as a key factor-something recent studies have also highlighted as necessary [16], [22].
Unlike studies that consider different scenarios of changes in insulation, infiltration, occupancy patterns, and local energy mix within the framework of sensitivity analyses, this work focuses exclusively on the quantitative assessment of annual heating and cooling energy consumption for membrane sports halls across five climate contexts. In this way, the results obtained provide a clear indicator of the impact of climate on energy performance, without introducing additional variables that could obscure the analysis's main objective. [5], [23]. While computer modeling always involves some simplification and cannot predict every possible situation, extra care was taken to keep the analysis as realistic and practical as possible. The main goal was to offer findings that genuinely help with the design and management of membrane halls in everyday conditions.

2.1. VENTILATION

Ventilation regimes affect the overall energy balance of lightweight structures. In warm climates, daytime ventilation was considered a potential factor that could increase the cooling load by introducing warm outdoor air during occupancy. In contrast, nighttime ventilation was analyzed as a passive cooling strategy to dissipate accumulated heat and reduce peak loads during the regular day. In temperate-continental conditions, ventilation was treated as a system with dual functions: ensuring indoor air quality and, at the same time, serving as a significant energy load, especially during the seasonal period. In cold, humid climates, the impact of increased heat losses after ventilation was analyzed, with an emphasis on the need for a system with high heat recovery efficiency.

In extremely warm climates, the efficiency of daytime and nighttime ventilation was examined as a function of the temperature drop during the night, which prompted consideration of the need for adaptive control and modern system ordering. This methodological setup allowed for a systematic assessment of the impact of ventilation regimes on achieving acceptable thermal conditions while minimizing energy consumption.

2.2. HVAC SYSTEMS

HVAC systems must be adapted to local climate conditions. In Prague, systems with variable COPs and the possibility of nighttime setback are essential to reduce heating needs, while in Cannes, the HVAC must be sized for high summer loads, with an emphasis on the chiller's seasonal COP and on integrating photovoltaic systems. Modeling inverter heat pumps with reversible operation is recommended in Niš, since the climate requires both heating and cooling. In Bergen, systems with high seasonal COP and the integration of local renewable sources provide significant savings, with mandatory indoor humidity control to prevent condensation. Finally, in Davádmi, the HVAC must be sized for extreme peak cooling loads, with high COP units and PV integration to reduce grid load.

2.3. DCV (DEMAND CONTROLLED VENTILATION)

Implementing a DCV strategy can lead to significant savings across the analyzed locations. For example, in Prague, DCV allows for a realistic quantification of the ventilation heat load and reduces unnecessary losses during periods of low population. In Cannes, DCV combined with night cooling reduces annual cooling needs and optimizes outdoor air intake. In Niš, DCV is particularly effective, reducing winter heating losses and unnecessary summer cooling, with the potential for integration with shading. In Bergen, DCV strategies reduce unnecessary losses during periods with fewer people present and improve the recuperator's efficiency. In Davidmi, DCV must be carefully implemented to avoid the intake of extremely warm air during the day, while at night it can help reduce the indoor temperature.

3. RESULTS AND DISCUSSION

The EnergyPlus (version 24.2.0) analysis showed that the energy performance of membrane halls depends heavily on climate and control factors, including ventilation, infiltration, and building use. In this study, the abbreviation EE (kWh/m²) refers to the annual specific energy consumption per square meter of floor area, used as an indicator of energy efficiency (Table 1). Recent studies also confirm that using numerical simulations and parameter optimization is effective for analyzing the thermal performance of membrane envelopes [24], [25].

Table 1. Annual Energy Consumption of Membrane Sports Halls by Location

Location	Heating (kWh)	Cooling (kWh)	Total (kWh)	EE (kWh/m²)	Heating share (%)	Cooling share (%)
Prague (CZE)	64018	26187	90205	127	71%	29%
Cannes (FRA)	29628	33,031	62659	89	47%	53%
Niš (SRB)	58735	43100	101835	144	58%	42%
Bergen (NOR)	74700	16553	91253	127	82%	18%
Dawadmi (SAU)	17515	76510	94025	138	19%	81%

To better understand the simulation results, it is necessary to consider the climatic characteristics of each analyzed location. Monthly temperature averages provide a clear insight into seasonal variations and extremes that directly affect energy needs for heating and cooling. It is this climatic framework that provides the basis for discussing the obtained results and their interpretation (Figure 2). Figure 2 clearly illustrates the overall trend: heating dominates in colder climates such as Prague and Bergen, cooling dominates in hot desert conditions such as Dawadmi. In contrast, transitional and Mediterranean climates (Niš and Cannes) show a more balanced distribution between heating and cooling. This general pattern provides the context for the subsequent discussion of individual cities.

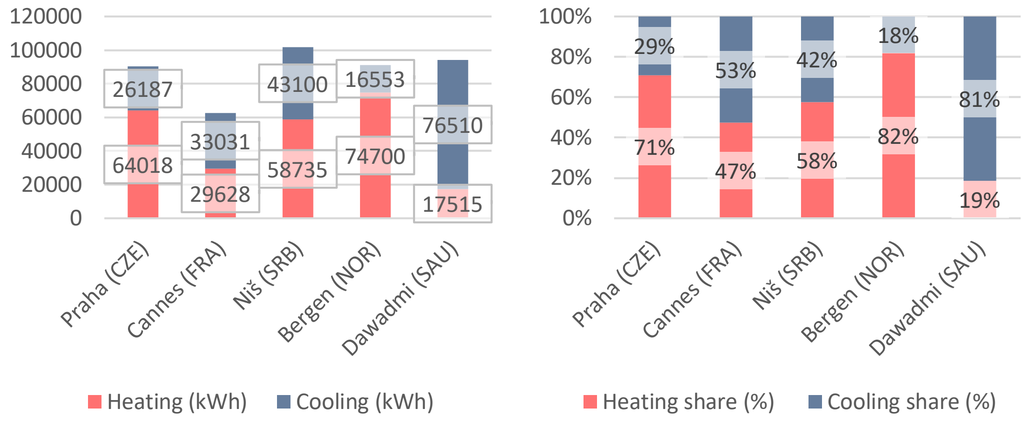

Figure 12. Heating and Cooling Energy Demand by Location [kWh](left) and Share of Heating and Cooling Energy Demand by Location [%] (right) (drawig by author).

Prague (continental climate): Heating constitutes a dominant part of the total consumption (71%). This is consistent with cold winters and frequent temperature inversions. The total specific consumption (127 kWh/m²) is in the middle range, indicating that conduction and ventilation losses are the key factors. Optimization strategies should focus on heat recovery and envelope improvement.

Cannes (Mediterranean climate): Cooling is slightly dominant (53%), which confirms that solar gains and hot summers have a decisive influence. The total consumption is the lowest among the analyzed locations (62 659 kWh), and the specific consumption (89 kWh/m²) indicates favorable climatic conditions. Night cooling and shading are key strategies to reduce the cooling load.

Niš (continental-Mediterranean crossing): The total consumption is the highest (101,835 kWh), and the specific consumption (144 kWh/m²) indicates unfavorable conditions with large amplitudes. Heating and cooling are both significant (58% vs. 42%), which confirms the need for balanced strategies: recovery, DCV, shading and reversible HVAC systems.

Bergen (cold humid climate): Heating is extremely dominant (82%), which is expected for a cold and humid climate with low solar radiation. Total consumption (91 253 kWh) and EE (127 kWh/m²) indicate a significant heating load. Heat recovery and envelope improvement are key measures, while cooling has a marginal impact.

Dawadmi (arid desert): Cooling makes up a dominant part of consumption (81%), which is in line with extremely high summer temperatures and intense solar radiation. Total consumption (94 025 kWh) and EE (138 kWh/m²) indicate high requirements for cooling systems. Optimization strategies should focus on shading, reflective surfaces, high COP of cooling units and integration of PV systems.

The energy efficiency of membrane sports halls primarily depends on local climatic conditions and occupancy levels, while the relationship between heating and cooling varies significantly with geographical location. That confirms that there is no universal solution applicable to all climate zones.

- In Prague and Bergen, where cold winters and a long heating season dominate, heating accounts for over 70% of total energy consumption according to the simulation results. This outcome reflects the influence of low outdoor temperatures and extended heating periods on the overall energy balance. In such climates, membrane systems, especially single-layer systems, have limitations compared to massive constructions due to their lower insulation capacity. Therefore, additional insulation layers or two-layer membrane systems are required to reduce heat transfer through the envelope and improve overall energy efficiency.

- In Cannes, the ratio of heating to cooling demand is almost balanced, whereas in Dawadmi, cooling accounts for more than 80% of total energy consumption. These results highlight the dominant role of cooling in hot, dry climates. Although solar gains were not separately quantified in this study, the high solar radiation typical of Mediterranean and desert regions makes shading strategies, solar-gain control, and the use of cooling systems with high seasonal coefficients of performance particularly relevant. In addition, integrating renewable energy sources, such as photovoltaic panels, is recognized as an effective measure to reduce operational carbon dioxide emissions, since peak cooling demand coincides with periods of peak solar energy availability.
- Niš proves to be the most demanding location, with high annual amplitudes and almost equal heating and cooling needs. The total specific energy consumption is the highest among the analyzed cities, which indicates the complexity of the transitional continental-Mediterranean climate. The identification of potential measures is based on the simulation results showing balanced heating and cooling loads, combined with established engineering practices for such climates. In these conditions, an integrated approach is required: heat recovery to reduce heating demand, demand-controlled ventilation (DCV) to adapt to varying occupancy levels, active shading to mitigate summer solar gains, and reversible HVAC systems to meet both heating and cooling needs efficiently.

In addition to climatic conditions, the way membrane halls are used significantly impacts their energy performance. Sports events, concerts, and other large gatherings often have high occupant densities, increasing ventilation requirements and internal heat gains. During sports activities, elevated metabolic rates of occupants increase fresh air demand, while long-duration events extend HVAC system operation. Intermittent use of the halls also creates periods of low occupancy, where demand-controlled ventilation (DCV) strategies can substantially reduce energy consumption. Therefore, building function and occupancy patterns directly influence ventilation loads, cooling demand, and overall energy efficiency, and should be considered alongside climatic factors when interpreting the results.

The present findings are consistent with recent simulation-based studies of membrane envelopes. Huang et al. [24] demonstrated through numerical optimization that the thermal performance of air-supported membrane buildings is highly sensitive to envelope properties and solar gains, and that targeted improvements to the membrane system can substantially reduce annual heating and cooling loads. Similarly, Hu et al. [25] showed that the thermostructural design of multi-layer membrane roofs must account for both thermal and operational demands to ensure acceptable performance under varying climatic and loading conditions. Together, these studies support our conclusion that envelope measures (improved insulation, multi-layer membranes, and solar-control strategies) combined with appropriate HVAC and control solutions are effective approaches for improving the energy performance of membrane sports halls across different climates; our work extends these results by providing a direct, cross-climatic comparison of annual heating and cooling demands for five representative locations.

4. CONCLUSIONS

Membrane halls can be an energy-sustainable option, but only if their design is carefully tailored to local climate conditions and accompanied by adequate technical measures. Based on the results, warm and temperate climates offer a practical, quick solution, whereas cold regions require additional steps to achieve sustainability. In arid conditions, cooling, shading, and the integration of renewable energy sources become a priority.

This study sets a framework for future research and decision-making, showing that reliable information on potential energy savings can be obtained through computer simulations. Further research should include long-term field measurements, model calibration, economic aspects, and life-cycle assessments of membrane halls across different climate and energy contexts.

The results also indicate that such analyses are important not only for the scientific community but also for practical actors, such as investors and designers. They enable early prediction of the energy balance and the optimization of management strategies at the initial stages of the project. In this way, membrane halls can become a competitive and sustainable alternative in the field of sports infrastructure, provided that their application is always viewed through the prism of the local climate and energy system.

ACKNOWLEDGMENT

This research was supported by the Science Fund of the Republic of Serbia, Grant No. 7363, Project title: Improvement of functional, energetic, lighting, and structural characteristics of closed and semi-closed halls covered by structural textile membranes - BALLOON-HALL-Optima.

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