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Research paper

ANALYSIS OF INSULATION AND ORIENTATION IMPACT ON ENERGY CONSUMPTION IN DETACHED HOUSES

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Abstract

Modern architectural practice faces the complex challenge of balancing aesthetic, functional, and environmental requirements in the context of the global climate crisis. The focus of this research is to analyze the impact of thermal insulation, spatial orientation, and macroclimatic conditions on the annual energy consumption for heating and cooling of single-family residential buildings, which, due to an unfavorable shape factor, exhibit exceptional sensitivity to external microclimatic factors. Using advanced software tools for dynamic thermophysical simulations, EnergyPlus and OpenStudio within the SketchUp environment, a reference model of a two-story residential building (GF+1) with 11 independent thermal zones was developed. The parametric analysis encompassed a matrix of 18 simulation cycles generated by crossing three independent levels of thermal insulation, two spatial orientations, and three different European climate zones represented by the cities of Niš, Copenhagen, and Athens. Dynamic simulations confirmed that applying uniform thermal protection solutions, regardless of the geographical context, leads to energy and economic inefficiency. Shifting from an uninsulated to a standard insulated model generates massive energy savings for heating in colder climates. Conversely, further investment in an advanced level of insulation yields minimal and negligible benefits. Research proves that thermal insulation alone cannot ensure optimal summer energy performance in warm climates and should be complemented by effective ventilation and solar control strategies, confirming that energy-efficient architectural design requires a balanced and location-specific approach.

Key words: *energy efficiency, thermal envelope, dynamic simulations, single-family houses, climate zones, spatial orientation*

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1. INTRODUCTION

Modern architecture faces the complex challenge of balancing aesthetic, functional, and environmental requirements. In the context of the climate crisis and energy market instability, optimizing building energy performance has become a primary focus of research in civil engineering and architecture [1]. The building sector accounts for over one-third of global final energy consumption, with detached single-family houses contributing the largest share of greenhouse gas emissions [2]. Due to an unfavorable shape factor—specifically, a higher surface-to-volume ratio—these houses are exceptionally sensitive to external climatic conditions and heat losses [3].

The building envelope directly dictates the thermal behavior of the structure, acting as a filter between indoor comfort and dynamic outdoor microclimate [3, 4]. The uniform application of thermal protection solutions ignores the fact that the same architectural model generates fundamentally different energy needs depending on the climate zone [5]. Northern Europe is dominated by the need to reduce transmission heat losses during long heating seasons, the Mediterranean region faces building overheating and high cooling demands due to intense solar radiation [6, 12], while the moderate continental climate of the Balkans requires balanced solutions addressing both winter and summer conditions [1, 14].

For reliable performance assessment during the design phase, dynamic thermophysical simulations have become an indispensable standard [7, 15]. High-resolution tools such as EnergyPlus (integrated via OpenStudio within the SketchUp environment) enable the calculation of hourly heat flows, accounting for meteorological data, solar radiation, internal gains, and air infiltration [8, 9].

However, techno-economic optimization of the building envelope remains an open issue. Increasing insulation thickness and implementing advanced glazing (with low-emissivity coatings and inert gases) linearly reduce the heat transfer coefficient, yet annual energy benefits exhibit a non-linear trend [10]. According to the law of diminishing returns, beyond a critical insulation thickness, further investment yields negligible energy savings alongside a sharp increase in material costs [11]. Furthermore, over-insulated houses in warmer climates can trap internal heat gains, paradoxically increasing cooling energy demand during summer months [6, 12].

The aim of this study is to evaluate the combined impact of envelope insulation, spatial orientation, and climate context on residential energy demand using dynamic OpenStudio/EnergyPlus simulations across three European climate zones (Copenhagen, Niš, and Athens).

2. METHODOLOGY

The first phase of the research encompassed geometric modeling and spatial definition of the building within the SketchUp software package, using the official OpenStudio extension [9]. Architectural and functional zoning of the interior was performed by assigning a dedicated thermal zone to each room on the ground and upper floors, resulting in a total of 11 independent thermal zones (Figure 1). To simulate realistic conditions, shared partition surfaces were precisely matched (Figure 2)

to define boundary conditions for heat transfer, while all ground floor surfaces were set directly on the ground. Following geometric preparation in OpenStudio, the model was imported into EnergyPlus [8], where detailed thermophysical configuration of all building envelope elements was conducted. Prior to running the simulations, occupancy profiles (*Schedule:Compact*) and the physical characteristics of the building materials were defined.

The simulation plan was based on a multidimensional matrix of 18 cycles, generated by crossing three independent variables: envelope insulation thickness, spatial orientation, and geographic-climatic location. The physical characteristics of the unventilated thermal envelope and transparent elements were defined across three energy efficiency levels: The first variant (V1) represents an uninsulated model (0 cm of thermal insulation on external walls and flat roof) with standard single glazing featuring a high overall heat transfer coefficient of $U = 5.8\ \mathrm{W/m^2K}$. The second variant (V2) represents a standard level of protection, with 10 cm of insulation on external walls, 15 cm on the roof, and standard double glazing with $U = 1.5\ \mathrm{W/m^2K}$. The third variant (V3) was defined as an advanced high-efficiency model, with 15 cm of insulation on external walls, 30 cm on the flat roof, and triple glazing featuring a low heat transfer coefficient of $U = 0.5\ \mathrm{W/m^2K}$. Furthermore, no dynamic external shading devices, overhangs, or internal blinds were included in the simulation models, allowing an unhindered evaluation of direct solar gains on the building's thermal zones.

Each of the three variants was simulated under two orientation scenarios (by rotating the main axis by 180°), shifting the heavily glazed living room between north and south to analyze the impact of solar radiation. These parametric boundary conditions were selected because the primary glazed areas and main living spaces are concentrated along these two key facades. By isolating the north orientation (minimal direct solar gains) and south orientation (maximum controllable solar radiation), the model captures the maximum physical contrast in solar irradiance. The matrix of 6 variants (three insulation levels × two orientations) was fully replicated for three cities representing distinct European macroclimatic conditions: Niš (moderate continental climate), Copenhagen (cold climate), and Athens (Mediterranean climate), using standardized meteorological files (.epw format) [15].

This methodological approach established the geometric and thermophysical baseline for tracking heat flows, mapping heat transition, and conducting a detailed comparative analysis of the final annual energy consumption for the building's heating and cooling demands.

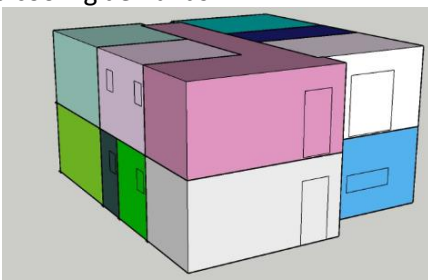

Figure 1: Thermal Zones in OpenStudio program, Source: Author

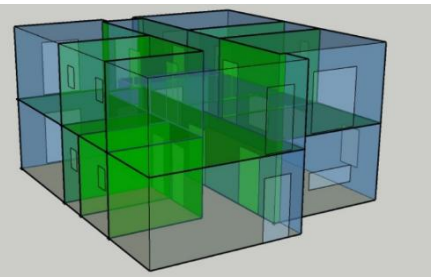

Figure 2: Matched surfaces OpenStudio program, Source: Author

2.1 CONCEPTUAL DESIGN OF THE REFERENCE MODEL FOR SIMULATION PURPOSES

For the purpose of conducting dynamic energy simulations, a reference model of a detached single-family residential building was developed, featuring a ground floor and one upper floor (GF+1), a flat roof, and a compact, orthogonal geometry. In order to precisely map internal thermal loads and occupancy profiles within the EnergyPlus software package, the functional spaces were integrated into separate thermal zones.

The spatial layout of the ground floor (Figure 3) is structured so that the total volume is divided into a primary, dynamic living area with a dining room and a kitchen, and a more passive zone comprising one bedroom, a restroom, and a bathroom. All rooms are directly connected via a central hallway that extends along the longitudinal axis of the ground floor, generating the main circulation artery of the building, within which the vertical circulation core with a double-flight staircase is positioned. The upper floor (Figure 4) is fully conceptualized as a night zone; its spatial structure consists of three edrooms and two bathrooms. The internal communication system on the upper floor consistently follows the layout matrix of the ground floor, where all rooms are again organized around a central longitudinal hallway connected to the vertical staircase core, thereby achieving continuity of the circulation tract throughout the entire volume of the building. The entire indoor volume is modeled as a fully conditioned space.

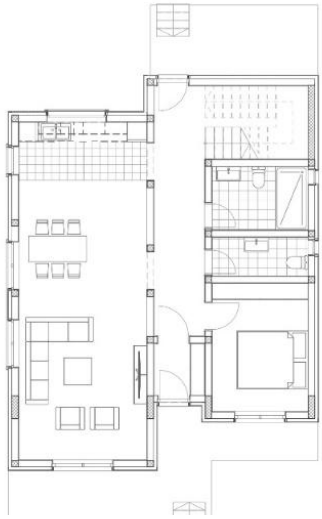

Figure 3: Ground floor, Source: Author

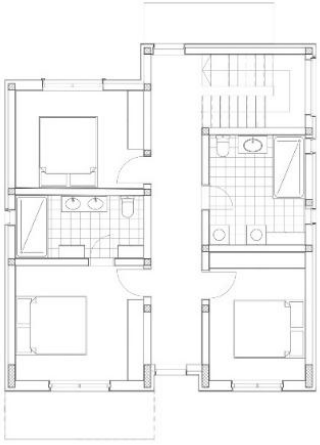

Figure 4: First floor, Source: Author

3. RESULTS AND DISCUSSION

A total of 18 simulations were conducted across 3 different cities in distinct climate zones: Niš, Athens, and Copenhagen. For each city, 6 simulations were carried out, consisting of 3 simulations with varying insulation levels—where V1 represents an uninsulated building, V2 a well-insulated building, and V3 an excellently insulated building (Table 1). The remaining 3 simulations per city were generated by rotating the

building by 180°, thereby shifting the orientation from north to south. Within the simulations, a north or south orientation signifies that the living room is facing that respective direction. To assess the economic feasibility and simple payback periods for the thermal envelope upgrades across the three locations, representative average electricity and heating tariffs were applied: €0.13/kWh for Niš (Serbia), €0.17/kWh for Athens (Greece), and €0.40/kWh for Copenhagen (Denmark). These financial evaluations account for local energy market pricing to reflect realistic operational cost reductions.

Table 1: Parameters applied in the simulation, Source: Author

Alternative solutions – Insulation of external elements			
	V1	V2	V3
External walls – Insulation thickness (cm)	0	10	15
Roof – Insulation thickness (cm)	0	15	30
Windows - U value (W/m2 K)	5.8	1.5	0.5
Conditioned floor area:	Ground floor: 85 m^2	First floor: 80 m^2	Total: 165 m^2
HVAC Setpoints	Cooling: 26 °C (constant) / Heating 22 °C (constant)		
Infiltration & Ventilation	0.5 ACH (Air changes per hour)		
Internal heat gains	Lighting: Equipment: Occupancy		
Building orientation			
0° i 180° (north and south)			
Location			
Niš Athens Copenhagen			

3.1 SIMULATION RESULTS IN NIŠ

Niš is located in a climate where the energy consumption for heating is twice as high as the energy consumption for cooling in an uninsulated detached house. With the introduction of thermal insulation, the energy required for heating drops significantly because the building retains heat better and cools down more slowly; however, in return, the cooling energy demand increases.

By improving the thermal envelope through the transition from V1 to V2 layers, the required heating energy is reduced by approximately 90 %, while the cooling energy demand increases by only about 20 %, resulting in an annual energy saving of around 20,000 kWh, which would result in annual financial savings of around €2,700 under Serbian conditions. Subsequently, when moving from V2 to V3 layers, the heating energy demand decreases slightly compared to the previous comparison, while the cooling energy demand remains approximately the same, around 3200 kWh less. This results in an annual saving of around €435, while the additional investment in improving the thermal envelope would cost approximately €3,300. To pay off the investment, a simple payback period of 8 years is required. It can be concluded that energy-efficient architectural design can make a major difference in a building's energy

performance, provided that the building is high-quality insulated. This does not necessarily imply optimizing heating through orientation alone; it is also possible to reduce the required cooling energy by implementing natural ventilation principles—such as cross ventilation, the stack effect, wind catchers, etc.—which were not applied in these simulations.

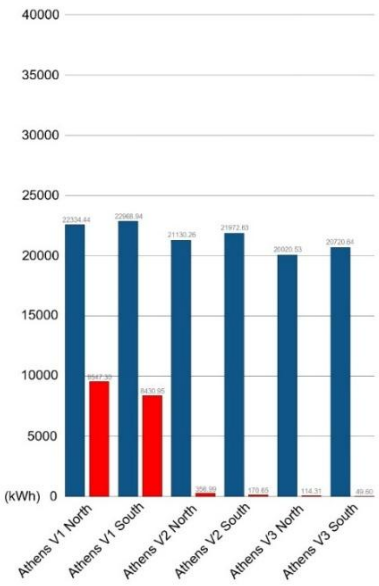

Figure 5: Annual energy consumption for heating and cooling (kWh), Niš, Source: Author

Table 2: Annual energy consumption for heating and cooling (kWh), Niš, Source: Author

Niš / kWh		North	South
V1	Cooling	12,847.12	12,706.19
	Heating	27,005.99	26,099.27
V2	Cooling	16,108.92	16,331.18
	Heating	3,054.83	2,480.42
V3	Cooling	16,032.98	16,247.75
	Heating	1,427.73	1,036.04

3.2 SIMULATION RESULTS IN ATHENS

The Mediterranean climate of Athens implies hot, dry summer days with an average temperature of 35 °C, while winters are rainy with an average temperature ranging from 10 to 15 °C; consequently, the majority of the building's energy consumption is attributed to cooling. Improving the thermal envelope through the transition from V1 to V2 layers resulted in energy savings of approximately 5 % for cooling and around 96 % for heating, resulting in an annual energy saving of around 10,000 kWh, which would result in annual financial savings of around €1,700 under Greek conditions.

Furthermore, it is noticeable that the differences in energy consumption between the V2 and V3 simulations are almost non-existent (Figure 6), making the V3 simulation inefficient due to its far more expensive materials compared to V2, while yielding identical energy performance. The transition from V2 to V3 would cost an additional €4,000, yielding annual savings of only about €250, requiring a payback period of approximately 16 years for this investment to break even [10, 11].

It can be concluded that in dry and warm climates, such as the one in Greece, building thermal insulation does not represent as energy-efficient of a solution as natural and contemporary, artificial ventilation systems would [4, 6].

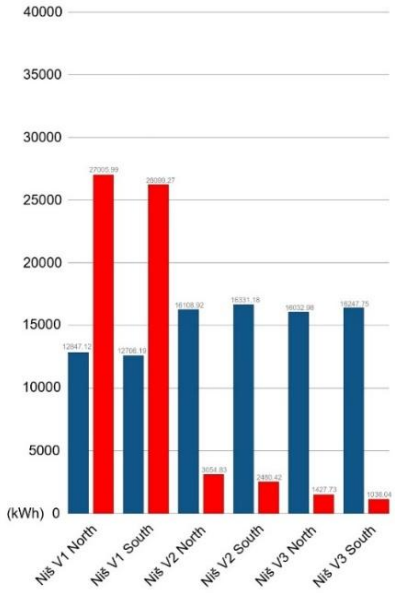

Figure 6: Annual energy consumption for heating and cooling (kWh), Athens, Source: Author

Table 3: Annual energy consumption for heating and cooling (kWh), Athens, Source: Author

Athens / kWh		North	South
V1	Cooling	22,334.44	22,968.94
	Heating	9,547.30	8,430.95
V2	Cooling	21,130.26	21,927.63
	Heating	356.99	170.65
V3	Cooling	20,020.53	20,720.64
	Heating	114.31	49.50

3.3 SIMULATION RESULTS IN COPENHAGEN

Although Copenhagen is located at a similar latitude to Moscow and Southern Alaska, its climate is milder and more temperate; therefore, the winters are not as harsh. As this is the northernmost city in the simulation, the heating demand accounts for the highest energy consumption in its simulation cycles. Improving the thermal envelope through the transition from V1 to V2 layers resulted in a heating energy saving of 85 %, which amounts to approximately 32,000 kWh—by far the largest reduction among all heating simulations. Conversely, cooling energy consumption increased with the improvement of the thermal envelope, recording a rise of 80%, or about 6,500 kWh. The pronounced surge in cooling demand following the application of thermal insulation in Copenhagen can be attributed to the physical phenomenon of trapping internal heat gains (generated by occupants, lighting, and electrical equipment) [12, 13]. In an uninsulated building (V1), this internally generated thermal energy naturally dissipates into the outdoor environment through highly conductive walls and single-pane glazing. However, once high-efficiency thermal insulation and multi-pane glazing are implemented (V2 and V3), the building envelope acts as a barrier that hinders this natural heat dissipation during

warmer summer periods.

Consequently, internal heat remains trapped within the thermal zones, forcing the automated HVAC systems to consume additional energy for active space cooling.

Taking all this information into account, the total energy savings for HVAC transitioning from V1 to V2 layers amount to around 27,000 kWh, meaning that the implementation of a thermal envelope is a significant investment, despite the sharp spike in cooling energy consumption. This level of energy efficiency would result in an annual cost reduction of approximately €10,800.

With the subsequent transition from V2 to V3 layers, a slight increase in cooling energy and a minor decrease in heating energy consumption are observed, resulting in the transition from V2 to V3 requiring an additional investment of around €4,500 and yielding annual savings of approximately €750, with a payback period of about 6 years.

The simulation in Copenhagen demonstrates that this type of climate achieves the greatest benefit from improving the building's thermal envelope (Figure 7).

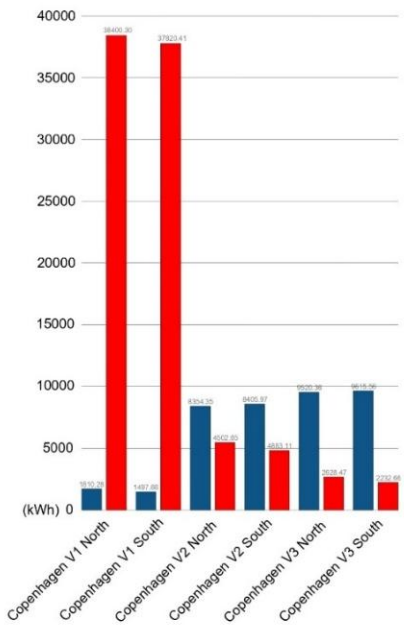

Figure 7: Annual energy consumption for heating and cooling (kWh), Copenhagen, Source: Author

Table 4: Annual energy consumption for heating and cooling (kWh), Copenhagen, Source: Author

Copenhagen / kWh		North	South
V1	Cooling	1,810.29	1,497.68
	Heating	38,400.30	37,820.41
V2	Cooling	8,354.35	8,405.97
	Heating	4,502.65	4,883.11
V3	Cooling	9,520.38	9,615.56
	Heating	2,628.47	2,232.66

4. CONCLUSION

The comprehensive analysis reveals how different physical mechanisms dominate the building's energy balance depending on the insulation level and climate. In uninsulated baseline models (V1), heat transfer is overwhelmingly dominated by transmission losses through the envelope due to high thermal transmittance ($\boldsymbol{U}$-values). Under these conditions, building orientation plays a negligible role, as high transmission losses mask any energy contributions from solar heat gains [10, 15].

While transitioning from an uninsulated model to a standard insulation level (V2) yields massive energy savings—reducing wall and roof transmission losses by up to

90%—upgrading further to an advanced level (V3) offers diminishing returns. Once a high-quality thermal envelope is established, the primary winter energy balance shifts toward ventilation losses (air infiltration), while summer dynamics are dominated by solar radiation and internal heat gains. Thus, proper orientation and passive solar management become effective tools only after basic thermal insulation is secured, maximizing passive winter gains in cold and temperate climates like Copenhagen and Niš.

Table 5: Total annual energy consumption per simulation for north and south orientation (kWh), Source: Author

kWh		V1	V2	V3
Niš	North	39,853.11	19,163.75	17,460.71
	South	38,805.46	18,791.60	17,283.79
Athens	North	31,881.74	21,487.25	21,134.84
	South	31,399.89	22,143.28	20,770.24
Copenhagen	North	40,210.56	12,857.00	12,148.83
	South	39,315.07	13,289.08	11,848.22

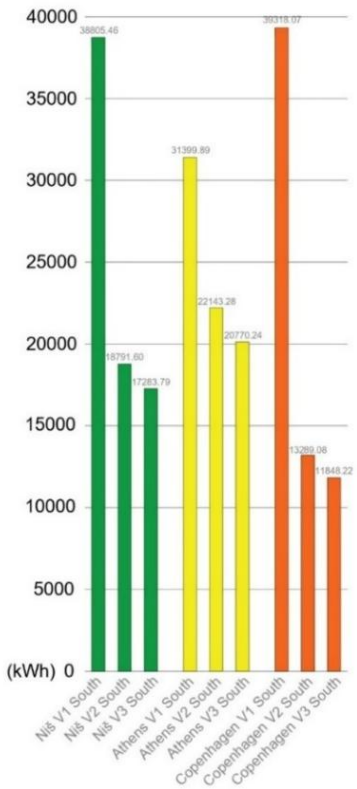

Figure 8: Total annual energy consumption per simulation for north orientation (kWh), Source: Author

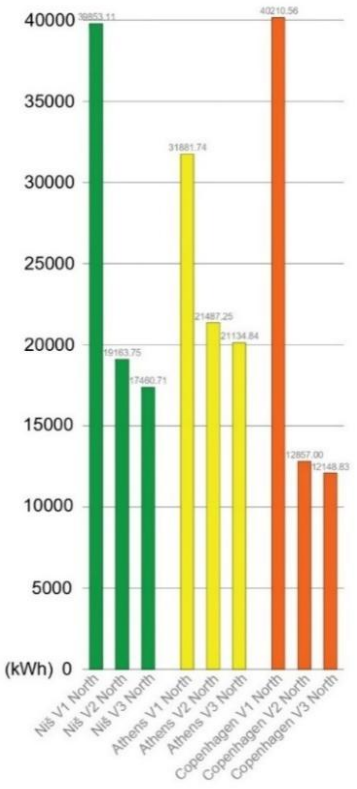

Figure 9: Total annual energy consumption per simulation for south orientation (kWh), Source: Author

Conversely, in warm Mediterranean climates like Athens, the energy consumption difference between V2 and V3 is negligible, making V3 economically unjustified due to high material costs. Furthermore, extensive insulation traps internal heat gains generated by occupants, lighting, and equipment during warmer periods. While uninsulated envelopes allow natural heat dissipation, highly insulated envelopes hinder it, forcing HVAC systems to consume additional energy for space cooling. Therefore, in warm climate zones, thermal insulation cannot replace essential strategies such as solar shading and natural ventilation (e.g., cross-ventilation and the stack effect) [4, 6].

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