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Energy Efficiency of Residential Buildings in Cold and Dry Climates using Simulation-based Comparative Analysis: Case Study in Tabriz

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PAPER INFO

ABSTRACT

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Keywords: Cold and dry climate Comparative analysis Energy efficiency Optimum design Residential buildings The purpose of this research is to analyze the energy of a residential building in the city of Tabriz with a cold and dry climate using energy simulation to provide a model to minimize energy consumption. A comparative model of energy consumption analysis in a three-story building unit with dimensions of 181 square meters is presented using 5 layout modes in the wall, floor, ceiling, window and door. The number of 5 designs with different arrangement of rooms and different number of windows were compared in terms of energy conservation in 51 different diagrams and the optimal energy saving design is selected. In the next step, according to the obtained results, the design of the building in the desired site is discussed. At the end, in order to check the amount of energy absorbed in the building, energy diagrams will be obtained for the thermal region of the coldest day of the year. The results show that the most optimal energy consumption of 41767 Wh. After that, the designed plan A show the most optimal energy consumption in the building with fabric gains value of 41028 Wh in the month of July. The results of this research are useful for energy efficiency of residential buildings and environmental management in future.

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INTRODUCTION

Buildings are responsible for approximately 40% of the world's total energy consumption and carbon emissions, making this a critical and prevalent issue in today's global context (1). In fact, around 27% of carbon dioxide (CO₂) emissions in developing countries can be attributed to buildings, primarily due to heat loss within residential structures (2, 3). The significance of the built environment extends beyond energy consumption during construction and occupancy (4). It also garners substantial attention from governments, occupants, and stakeholders who are keen on improving the energy efficiency of buildings (5, 6). Building design strategies (BDS) play a pivotal role in addressing this challenge and are applied in three primary areas: environment, climate, and energy. These strategies are essential for achieving energy conservation goals (7). Building energy simulation stands out as a commonly employed method for quantitatively assessing the relationship between carbon emissions and various building designs (8). To gain a comprehensive understanding of building energy efficiency, a thorough review was conducted, encompassing previous research that utilized simulation software (9-11). Also, a series of researches have been done in the field of energy efficiency of residential buildings using energy simulation model (12-14). In addition to the mentioned researches, various studies have been conducted in connection with the performance of building material science in the efficiency of energy consumption and renewable energies (15, 16). Other studies have been conducted in connection with the management of building renewable energy using photovoltaic power plants system (17, 18). In other studies conducted by researchers, renewable energy management was implemented using dynamic decision-making algorithms

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(19, 20). In the latest research, scientists achieved optimal models of energy consumption through the Energy Plus (21-23), E-Quest (24), and DesignBuilder (25) simulation system in the building using validation tools. Some other researchers have reached the optimal models of energy consumption through the building information modeling system (26-28). The present study addresses the critical aspects of energy conversion and efficiency in the context of residential building design using Ecotect simulation software for modeling and simulation. A comprehensive analysis of prior research reveals a conspicuous gap in the literature: the absence of comparative studies on residential building designs and their impact on reducing gas consumption within cold winter zones worldwide, utilizing simulation software. While numerous studies have explored the enhancement of indoor thermal conditions in residential buildings, the primary focus has predominantly centered on buildings situated in moderate climates. Only a limited number of investigations have delved into the realm of residential buildings in cold and dry climate conditions, where computer simulations are employed to achieve energy efficiency (29). It is noteworthy that Tabriz city in Iran experiences distinctive seasonal and daily climatic patterns, characterized by average cold and dry temperatures, in contrast to the temperate climates of European cities. The principal objective of this study is to analyze the energy performance of residential buildings through energy simulations. The ultimate goal is to formulate a model that can effectively reduce energy consumption through design modifications. This comprehensive review was conducted in Tabriz city, Iran, during the period spanning 2020-2021.

MATERIALS AND METHODS

The initial phase of our methodology encompasses data collection and site analysis conducted during the coldest period of winter within a cold-dry climate. This phase comprises two key components: first, the compilation of annual temperature data, and second, the gathering of comprehensive information regarding building components. This information encompasses the properties of building materials, construction details, and foundational design elements. These datasets serve as the basis for generating computer simulations designed to evaluate various design options explored in this study. Subsequently, we proceed to the next stage, which involves a comparative analysis of energy consumption models within a three-story building unit spanning 181 square meters. We explore five distinct layout configurations, considering variations in the arrangement of walls, floors, ceilings, windows, and doors. We compare these five designs, each with differing room arrangements and window counts, across 51 different scenarios, with the goal of identifying the most energyefficient design. To accomplish this, we leverage building energy simulation tools such as EnergyPlus, Ecotect, and eQuest, which play a pivotal role in modeling the energy performance of existing structures and investigating retrofit options (30). Based on the findings derived from our analyses, we engage in a comprehensive discussion concerning the building's design within the specified site. In conclusion, to assess the building's energy absorption capacity, we generate energy diagrams that depict the thermal characteristics of the building during both the coldest and hottest days of the year.

Weather data

The city of Tabriz, located at coordinates 38°.08' N and 46°.15' E, is situated at an elevation of 1350 meters above sea level. Tabriz experiences a cold-dry climate characterized by extremely low temperatures during the winter months, particularly from December to February. Conversely, summer temperatures are quite moderate, with a maximum typically reaching 26 °C (31, 32). For reference, the maximum and minimum temperatures recorded in Tabriz during the coldest month of the year, January, over a span of ten years (2010-2020), ranged from 15 °C to -19.6 °C (31, 32). Figure 1 illustrates the weather data collected over this decade, sourced from local weather stations, and serves as a representative dataset for the region (33). These weather data points are crucial inputs for our thermal modeling efforts, allowing us to predict annual energy consumption for various weather scenarios. This, in turn, enables us to evaluate potential energy-saving strategies for atrium design options. To perform this analysis, we input the relevant weather data into the Ecotect weather tool, which can automatically generate detailed climate analysis results specific to Tabriz.

The city of Tabriz positioned at a latitude of 38.8° north, 46.28° east. Its geographical location places it in a highly advantageous position for receiving solar



Figure 1. The maximum and minimum air temperature of Tabriz city

radiation. As a result, assessing the duration of sunshine hours and the angle of solar radiation throughout the day across different seasons is a critical aspect of calculating and evaluating the amount of solar radiation available for various applications. Figures 2 and 3 provide valuable visual representations of this information. Figure 2 displays the direction of the sun, indicating its path across the sky, while Figure 3 illustrates the changing angles of solar radiation throughout the day. These figures, sourced from (31, 32) are instrumental in understanding the solar dynamics in Tabriz, aiding in the design and utilization of solar energy systems, as well as in various other applications that rely on solar radiation data.

The initial output of the software, which encompasses essential data such as wind and sun information, is visually represented in the following four figures: Figures 4 and 5 provide insights into this data. To ensure the accuracy and reliability of the input data, we employed Climate Consultant 6.0 software. This software offers a comprehensive analysis of climate data and allows for a more thorough validation of the climate conditions in Tabriz. The climate data used in Climate Consultant 6.0 was directly extracted from the Ecotect website, guaranteeing the precision and authenticity of Tabriz climate data utilized in our analysis.

Case study

The energy simulation is conducted on a residential building comprising three-story. The building unit covers an area of 181 square meters and has a length of 3 meters. The building has a door on the east side with an area of 1.8 square meters.

These specifications provide the necessary details for the energy simulation, enabling the assessment of the building's energy performance and its response to various design and climate factors. Table 1 presents the required materials for modeling and simulation.

In the context of residential usage, it is assumed that there are five occupants in each story of the building, and these occupants are present full-time throughout the entire year. Additionally, it's mentioned that there is ample natural lighting available for all spaces within the



Figure 2. The direction of the sun of Tabriz city



Figure 3. The angel of the sun of Tabriz city



Figure 4. Climate data analysis in Ecotect software

building. This assumption implies that the building's design and layout are such that it maximizes the use of natural daylight, reducing the reliance on artificial lighting during daytime hours. This approach not only promotes energy efficiency but also enhances the overall comfort and livability of the residential spaces.

Input data parameter

In the process of selecting the best design for a cold climate, the following steps were undertaken:

Model Drawing and Material Selection: The design of the building was created, and appropriate materials were selected to ensure energy efficiency and thermal performance.

Hourly Weather Data: Hourly weather data for the city over the past ten years were obtained from the internet. This data is crucial for conducting accurate thermal analysis.

Thermal Analysis with Ecotect: The thermal analysis process was initiated using Ecotect software. Ecotect provides various outputs and insights, including:

- Hourly temperature changes graph.
- Building external cover radiation for different times and months.
- Distribution of energy attraction and thermal waste in the building's area.
- Temperature distribution in different areas of the building.
- Calculation of thermal interchange attraction and construction waste for each month.

Thermal Comfort Analysis: The study also involved the calculation of thermal comfort conditions. These calculations were based on Ecotect analysis, taking into account both personal and environmental factors. Figure 6 illustrates the steps involved in entering data into the software.

Table 2 provides information on the settings and limitations used to define thermal comfort areas within the building.

These comprehensive analyses and calculations are crucial for optimizing the building design to ensure that it



Figure 5. Monthly average thermal insulation and average temperature in Ecotect software

	U-Value (w/m2k)	Admittance (w/m2k)	Solar Absorption (0-1)	Visible Transmittance (0-1)	Thermal Decrement (0-1)	Thermal Lag (hrs)	(SBEM) CM1	(SBEM) CM2	Thickness (mm)	Weight (kg)	Emissivity	Specularity	Roughness	Refractive index of Glass	Alt solar Gain (Heavywt)	Alt solar Gain (lightwt)
Wall: brick cavity concrete block plaster	1.720	4.220	0.428	0	0.41	7.8	0	0	280.0	408565	0.9	0	0	-	-	-
Glaze: double glazed alum frame	2.700	2.800	0.81	0.639	-	-	-	-	0	0.000	0.78	0	0	1.74	0.42	0.56
Floor: concrete slab on ground	0.880	6	0.467	0	0.3	4.6	0	0	0	0	0.9	0	0	-	-	-
Void	5.618	10	0.001	0.999	1	0	0	0	0	0	0.86	0	0	-	-	-
Ceiling: plaster insulation suspend	0.500	0.900	0.368	0	0.32	0.7	0	0	210	13.295	0.9	0	0	-	-	-

Table 1. The definitions of the materials

Table 2. Software configuration

Setting of the areas thermal comfort limitations

1) People clothes in work continuous situation

2) Internal relative humidity amount with due attention to field studies and comfort domain

3) Wind current speed

4) Weather data watch to watch ten years of considered cities accordance to ECOTECT format

5) lightening amount for passageway space and lights inter

6) Average of present people number in light thermal area

7) Energy inexpert for walking activity into light

8) Amount of internal attraction

9) Accessible amount of the wind

10) Schedule of beginning works and time and keep silent installation in light adjacent spaces

11) Comfort domain of official spaces temperature

meets thermal comfort standards while also maximizing energy efficiency in a cold climate. By systematically assessing these variables and conducting thorough analyses, the study aims to recommend the most suitable building design for residential buildings in cold and dry climates. The goal is to optimize lighting, energy efficiency, and thermal comfort to create comfortable and sustainable living spaces.

RESULTS AND DISCUSSION

Ecotect software

The choice of Ecotect software for conducting simulations in the research is well-founded and supported by previous studies and research practices (34, 35). Here

are some key points highlighting the advantages and capabilities of Ecotect. High Accuracy: Ecotect simulations are widely recognized for their high level of accuracy. The trust placed in this software by researchers is a testament to its reliability in predicting building performance (36). Comprehensive Analysis: Ecotect offers a comprehensive set of performance analysis functions, making it a versatile tool for evaluating various aspects of building performance, including thermal, lighting, and acoustic analyses (37). 3-D Design Interface: The software combines a user-friendly 3-D design interface with analysis functions, making it intuitive for designers and architects to work with. This feature aids in integrating performance analysis seamlessly into the design process (38). Performance Metrics: Ecotect provides a range of performance metrics, including hourly thermal comfort, monthly space loads, natural and artificial lighting levels, acoustic reflections, reverberation time, project costs, and environmental impact. This wealth of data enables researchers to assess building performance comprehensively. Sustainability and Cost Benefits: Ecotect simulations can contribute to designing buildings that reduce global warming potentials and lower operational costs. This is a significant advantage, especially in today's environmentally conscious and cost-conscious building industry. Early-Stage Analysis: The ability to simulate building performance during the design stage is invaluable. It allows architects and designers to make informed decisions that can lead to more sustainable and efficient building designs. Environmental Analysis: Ecotect is particularly well-suited for environmental analysis, including solar exposure, energy distribution, temperature distribution, and heat loss/gain assessments. This capability is essential for understanding a building's

environmental impact and energy efficiency (39). Overall, the selection of Ecotect as the analysis software for the study appears to be a sound choice, given its robust capabilities and track record in building performance analysis. It aligns well with the goals of improving building sustainability and reducing operational costs while providing accurate insights into various performance aspects.

Modeling

In the first step of the research, a base design inspired by existing buildings in Tabriz city was used as the starting point. This base design was then replicated across multiple floors. Let's take a closer look at the different design plans mentioned:

Plan A: The initial design is characterized by a parking lot and a staircase on the first floor. The upper floors feature bedrooms in the northern part of the building and a hall area in the southern part. This design aims to preserve the existing building pattern and layout.

Plan B: In this variation, the interior design of the second floor was modified. Changes were made to the location and number of windows on this floor.

Plan C: Plan C involves simultaneous changes to the second and third floor layouts, including alterations to the number and placement of windows.

Plan D: This plan introduces changes to the layout of rooms, the kitchen, and the placement of windows.

Although the general layout across the three floors remains the same, it differs from the basic design in specific aspects.

Plan E: In Plan E, the location of the kitchen on the first floor is shifted, while the layouts of the other two floors remain unchanged.

Figure 7 provides a visual representation of the base design (Plan A) of the residential building in Tabriz city. Figure 8 showcases the modeling of the base plan of the building in various design modes, which are intended for analysis and comparison of energy consumption using Ecotect software.

These different design plans offer a way to explore how variations in building layout and interior design impact energy consumption and overall building performance. By comparing these plans, it can identify which design best aligns with the objectives in terms of energy efficiency, comfort, and functionality in the context of a cold and dry climate.

Figure 8 displays the modeling of Plan A, the base design, in various design modes. These different design modes are analyzed and compared using Ecotect software to evaluate their energy consumption and performance. This comparative analysis aims to identify which design mode offers the most efficient and sustainable energy use within the context of the cold and dry climate of Tabriz city.



Figure 7. Plan A of residential building in Tabriz city



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Figure 8. Design of 4 different modes of residential buildings in Tabriz city for analysis and comparison of energy consumption in Ecotect

Software analysis and simulation

The simulation results, based on the analysis of four different modes in the residential building of Tabriz city, provide valuable insights into energy gains and losses. Figure 9 illustrates the graph of fabric gains, with the left side showing working hours and the right side displaying the values of fabric gains. In this graph, yellow represents absorption, while blue represents thermal waste. Here are some key findings from the energy analysis:

Energy Changes Throughout the Day and Year: The analysis evaluates energy absorption changes over a 24hour period and across twelve months of the year. This comprehensive approach allows for a detailed understanding of how energy performance varies with time.

Variations in Building States: The study assesses five different simulated building states, which likely represent variations in room arrangement and window configurations. These variations are important for understanding how design choices impact energy absorption.

Significance of Room and Window Arrangement: The research highlights the significance of changes in the arrangement of rooms and windows in influencing energy

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22 80 ANNUAL LOADS TABLE Fabric Gains Qs - Qc All Visible Thermal Zones - Monthly Averages HOUF 100 MAY (Wh) JUN (Wh) JUL (Wh) AUG (Wh) SEP (Wh) OCT (Wh) NOV (Wh) DEC (Wh) (Wh) (Wh) Е (Wh) (Wh) 00 46630 -42178 -29589 -16977 -6432 -1897 1403 1459 -490 -11297 -27659 40972 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 20 22 22 23 -47418 -42665 30693 -18268 -7369 -2441 447 666 -791 -12455 -28563 -41370 -42005 -43161 -43021 -43828 65 -130 -396 1334 19365 -2921 -1219 -1806 -3500 48230 31686 -8363 -9188 353 113 1347 29449 -48715 -49346 -41826 -42265 -42783 14425 29873 -33788 -22123 -10606 - 3934 -230 15929 -30833 -49751 -44171 -22629 -9510 -2012 250 -4451 -16734 -31325 -42951 34484 -49903 -44256 -33435 -19675 -5419 3194 6193 4082 -1779 -15440 -31359 -43059 -48501 -41649 28016 -14206 1156 10618 12081 9869 5410 -9672 - 27994 -42182 -48501 -44936 -40412 -35876 6578 13418 18606 -3625 2583 9972 - 37042 - 32099 -22467 -22467 -16735 -9175 16396 25395 18214 26757 15600 11075 16274 -22922 -39026 -34918 22636 3385 17692 2734 32823 23538 -26929 -10349 31808 28727 -12485 30913 -30973 -20909 -4544 7864 23330 35914 37285 33358 28822 15361 -6077 -26629 -28167 -18218 -1107 11023 25649 37600 39526 35975 31143 18034 -3270 -24668 39947 38356 34837 -3021 -4772 -8277 -24008 -24118 -25047 -27689 -26916 -18012 11860 25810 37384 36339 30405 17992 27225 22268 16367 -27254 -29341 -19315 -22569 -1141 -4245 10742 7974 23616 19792 34743 30057 34660 31346 15189 10314 -33606 -26975 -8993 4000 14832 24115 30277 26604 4748 -13611 -31772 -35591 - 30740 -13157 -198 10028 18592 25549 22161 11394 883 -14889 -32407 36830 31809 16011 -4346 5289 13126 20349 17267 8109 - 38 -16132 33405 -38130 -40875 -43359 -18011 -18146 -20934 -23548 7811 5731 4215 6627 5066 3266 -33577 -6489 2176 14226 13342 -1726 -18023 -34770 -8901 -11253 483 -1305 10581 8163 -4497 -8152 -21668 -37799 -39150 35805 11518 38510 9323 -44714 -39776 -26174 -13675 -15370 -3101 2471 -1256 7404 5949 2833 678 -9320 -25857 -40228 -45490 -40883 -27838 -5296 2943 -174 -10561 -27087 -40957

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Figure 9. Analysis of fabric gains data, four different modes

absorption and thermal performance. Different room and window configurations can lead to varying levels of energy gain or loss.

Mode B: High Energy Absorption: The analysis indicates that Mode B exhibits the highest energy absorption during the months of December to January, particularly between 12:00 and 14:00. These hours represent a peak period of energy absorption across all samples, with variations in the amount of energy absorption depending on the specific design mode.

Overall, these results suggest that the arrangement of rooms and windows has a substantial impact on energy absorption in the building. Mode B appears to excel in terms of energy absorption during specific times and months, emphasizing the importance of design choices in optimizing energy efficiency and thermal performance in the context of Tabriz city's climate.

Figure 9 clearly demonstrates that Mode B exhibits the highest absorption of solar energy and the lowest transmission of solar energy into the building during the months of December to January. This finding underscores the effectiveness of Mode B in capturing and utilizing solar energy for heating or other purposes, while also minimizing the amount of solar energy that escapes or penetrates the building during the coldest months of the year. This outcome suggests that Mode B is particularly well-suited for optimizing thermal performance and energy efficiency in the context of Tabriz city's cold climate during this specific time period.

Comparative analysis

Table 3 presents the analysis results for all types of building models and facilitates a comprehensive comparison among them. The goal is to identify the best model based on the criteria of minimum solar energy transmission and maximum solar energy absorption in the specific context of Tabriz's cold and dry climate. The research's primary objective is to determine the optimal building model that can achieve energy savings during the cold seasons. According to the analysis conducted using Ecotect, the key findings are as follows:

High Solar Absorption Leads to Lower Energy Consumption: The analysis underscores the importance of high solar absorption in reducing energy consumption, particularly during the cold winter months.

Mode B is the Best Model: Among the various building models considered, Mode B stands out as the best model. It exhibits the highest solar energy absorption and the lowest energy losses during the cold winter, making it the most energy-efficient option for Tabriz's climate.

Figure 10 provides visual representations of the plan and cross-section of the building in different floors for Mode B, showcasing the design that has been identified as the most effective in terms of energy savings and thermal performance during cold seasons. This research contributes valuable insights into optimizing building design for energy efficiency in cold and dry climates.

Table 3. Comparative analysis of absorption and losses	of solar
energy for difference modes in residential buildings	

Building models	Time	Fabric Gains (Wh)					
analysis	Time	July					
	12	40631					
Mode A	13	41028					
	14	39294					
	12	41415					
Mode B	13	41767					
	14	39979					
	12	39573					
Mode C	13	40008					
	14	38427					
	12	39808					
Mode D	13	40399					
	14	38989					
	12	39526					
Mode E	13	39947					
	14	38356					



Figure 10. Optimum design of residential building for energy efficiency in Tabriz, mode B

CONCLUSION

With the rapid development of construction in Iran and the growing concern over gas energy shortages, the focus on energy-efficient and sustainable building development has intensified. This shift in focus not only aims to enhance the comfort of occupants but also seeks to reduce the gas energy consumption of buildings. Ecotect, with its capacity to visually and clearly analyze solar radiation, hourly solar exposure, fabric gains, and energy distribution within buildings, plays a crucial role in this endeavor.

This paper investigates the optimal building design in residential buildings, particularly tailored to the cold and dry climate of Tabriz. Given that many cities in Iran experience dry and cold winters, the energy consumption of residential buildings tends to be significantly high. The research in Tabriz, which faces a cold and dry climate, seeks to identify the most energy-efficient building design for cold seasons.

Based on the analyses conducted using Ecotect, the findings reveal that high solar absorption leads to lower energy consumption. Specifically, "Plan B" emerges as the optimal model, exhibiting maximum absorption and minimal energy losses during the cold winter months. The results demonstrate that the design of "Plan B" achieves the highest energy conservation in residential buildings, with fabric gains reaching 41,767 Wh. Additionally, "Plan A" shows notable energy conservation, with average fabric gains of 41,028 Wh during July, particularly between 12:00 to 14:00.

Furthermore, by utilizing simulation software, designers can proactively consider various ecological energy-efficiency methods during the early stages of design, contributing to more sustainable and energyefficient building solutions.

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Persian Abstract

چکیدہ

هدف از این پژوهش تحلیل انرژی یک ساختمان مسکونی در شهر تبریز با اقلیم سرد و خشک با استفاده از شبیهسازی انرژی برای ارائه مدلی برای به حداقل رساندن مصرف انرژی است. مدل مقایسهای تحلیل مصرف انرژی در یک واحد ساختمانی سه طبقه با ابعاد ۱۸۱ متر مربع با استفاده از ۵ حالت چیدمان در دیوار، کف، سقف، پنجره و در ارائه شده است. تعداد ۵ طرح با چیدمان اتاقها و تعداد پنجرههای مختلف از نظر صرفهجویی در مصرف انرژی در ۵۱ نمودار مختلف با هم مقایسه شد و طرح بهینه صرفهجویی در مصرف انرژی انتخاب شد. در مرحله بعد با توجه به نتایج به دست آمده به طراحی ساختمان در سایت مورد نظر پرداخته میشود. در پایان به منظور بررسی میزان جذب انرژی در ساختمان، نمودارهای انرژی برای منطقه حرارتی سردترین روز سال به دست میآید. نتایج نشان میدهد که بهینهترین مصرف انرژی ساختمان مسکونی مربوط به طراحی پلان ب با مقدار بهره پارچه ۲۱۷۶۷ وات ساعت است. پروهش برای بهرموری انرژی برای منطقه حرارتی سردترین روز سال به دست میآن به دست آمده به طراحی ساختمان در سایت نتایج نشان میدهد که بهینهترین مصرف انرژی ساختمان مسکونی مربوط به طراحی پلان ب با مقدار بهره پارچه ۲۱۷۶۷ وات ساعت است. پرای میوری طراحی شده الف، بهینهترین مصرف انرژی را در ساختمان با مقدار بهره پارچه ۲۱۷۶۴ وات ساعت وات پی پرای مصرف انرژی را آن، پلان انرژی ساختمانهای مسکونی و مدیریت زیست محیطی در آینده مفید است.