Effect of roof types on energy use in residential buildings in cold climates

Rashid Gaitov[1], Serik Tokbolat[2], Mohamad Mustafa[3], Rajnish K. Calay[3]

[1] Nazarbayev University, 53 Kabanbay Batyr Ave, Nur-Sultan, 010000, Kazakhstan
[2] Nottingham Trent University, 50 Shakespeare Street, Nottingham, NG1 4FQ, UK
[3]UiT The Arctic University of Norway, Narvik, 8514 Norway
serik.tokbolat@ntu.ac.uk

Abstract. The role of residential building envelope components is significant in terms of supporting a structure and transferring associated loads, providing aesthetic appearance, and controlling the flows of matters and energy. The control function is particularly important in terms of energy use as poorly designed and constructed envelopes can negatively affect the overall performance of a building. Among others, roofs play a critical role due to their area of coverage, direct interaction with precipitation, and a significant share of total heat transfer. This is especially true in case buildings located in countries with cold climate conditions. This study aimed to investigate the impacts of different roof types on the energy use of residential buildings in Nur-Sultan city, Kazakhstan. Moreover, it aimed at performing a cost analysis to compare the four roof types. The building models roof types of roofs such as flat roof, green roof and gable roof with finished and unfinished attics were simulated and compared in terms of their energy use. The findings indicate that the most energy and cost efficient two-storey building has gable roof with finished attic. The green roof is the most energy efficient choice for a one-storey building. It consumes 4.5% less energy and will pay off in 9 years.

Keywords: Roof Types, Energy Consumption, Cold Climate, Building Energy

1 Introduction

Roofs have traditionally played a critical role in the lives of humans from the early ages. The major function of any roof has always been to protect the inhabitants from precipitation and to provide shelter from the natural environment [1]. Ancient people built basic shelters and primitive huts. Central Asian nomads, for example, lived in so called “yurts”, which are common in Kazakhstan even at present and popularized as a part of the national heritage. The yurts have a round roof structure and 2 meters height [2]. Turkey and Mexico is the countries known for their elongated houses with flat roofs. The roofs played a role of not only protection, but also as a suitable space to spend time with family [1].

A roof is commonly known as a building component located on the top of a building that serves to protect it from the precipitation and to keep the comfortable indoor temperature [1]. There are several types of roofs which vary depending on several parameters such as shape, slope and materials used in the construction [1]. This study considers the commonly used two roof types such as “flat” and “gable” roofs, or so called “pitched roofs”. At present, flat roofs are rising in popularity due to their modern designs. The flat roofs tend to have a slope not higher than 5 degrees [1]. Such roofs are also recognized for their higher levels of insulation that help to maintain the building temperature at desired levels and makes the heating of a building easier [3]. The additional advantage is the space on the roof which can be used for leisure and gardening activities, the latter leading to creation of a green roof “coating”.

The flat green roofs are currently gaining popularity around the world, particularly in densely populated cities such as, for example, Singapore, San Francisco, Beijing, Osaka, etc. [4, 5]. The green roof is a type of flat roofs that has a vegetation on top. To be called a green roof, it should be covered by vegetation partially or entirely over the insulation membrane [5]. The insulation and soil layers lead to lower levels of energy use and efficient harnessing of rainwater [5]. A recent study conducted in Singapore has shown that the green roofs could save up to 14.5% of the consumed energy [3]. Moreover, green roofs are ecologically friendly and can serve as gardens spaces, which are quite useful in densely populated cities where there is not much agricultural land. According to recent studies, green roofs are very sustainable in terms of usage of rainwater with the most vegetated green roofs re-using up to 87% of the rainwater, whereas the average green roofs re-use about 83% of water [4, 5]. In addition, such roofs are advantageous from the financial perspective. The rainwater re-use, energy savings and unwanted emissions reduction allowed saving about US $1.04 million (M), $0.87 M and $0.09-0.41 M pear year respectively in Washington DC, USA [6].

The gable roofs, also recognized as pitched roofs, are one of the most common type of roofs in Kazakhstan [7]. Due to the complexity of the construction process, the construction cost of the pitched roof tends to be higher than of the other roof types. However, the main benefit of the gable roof is that the structure of the roof creates a space under the roof, attic, which could be used as a living or storage area, thus, increasing the overall useful area of the building [8]. However, there are cases when the space under the pitched roof is left unfinished and unused. This creates a source of inefficiency in terms of energy use needed for heating and cooling.

There is a lack of research and literature around the topic of roof types and their impact on energy use and overall sustainability in Kazakhstan. Considering the specific climate conditions of Kazakhstan as well as the gap in the field, this article aimed to conduct a comparative analysis in which the assessment has been done for different roof types and their respective energy consumption levels. Two cases, specifically, with finished and unfinished attics were compared using numerical energy simulation tools to analyze the amount of energy used. Moreover, the study analyzed two types of flat roofs (flat/green) and compared them with the gable roof. The findings are deemed to be useful for construction industries of developing countries in terms of selection of roof types. Also, the study compared the expenses such as the construction cost and annual energy consumption expenses of all four roof types.

2 Methodology

2.1 Location

The model analysis may vary due to the choice of a location. In this study, the location was chosen as Nur-Sultan city (formerly, Astana), the capital of Kazakhstan. The city is located in the northern Kazakhstan, on the banks of the Ishim river [9]. The city is ranked as the second coldest capital in the world [9]. Nur-Sultan has a very dry climate with high temperatures during summers and very low temperatures in winter. The lowest monthly-average temperature in Nur-Sultan is -24 º C in January and the highest is 33 º C in June and July. However, the temperature extremes may go down to - 34.7 º C in winters and up to 36.6 º C in summers (Table 1).

Table 1. Location details.

Page	Mean	Min	Max
Dry Temp. (°C)	4.3	-34.7	36.6
Wet Temp. (°C)	-2.4	-38.4	20.2
Relative Humidity (%)	64.9	10	100
Snow Depth (cm)	33.3	0	85

The city is surrounded by the hills from the East and West and located in a shallow basin. The capital city's altitude varies from 300 up to 500 meters and averages at 347 meters. The city has lines of trees on the North, West and East that protect it from the strong winds pertinent to the locality [9]. Nur-Sultan's cold weather during winters are affected by the Asiatic high, the pressure system that covers the region mostly in winter. It dominates starting from September, peaks in December and ends by May [9]. During this time, cold and dry winds move into the area from the East. In addition, the inversions caused by the Asiatic high save moisture and pollution and with the contribution of the shallow basin in which Nur-Sultan is located lower the visibility and result in cold air [9].

2.2 Software and Analysis

In this study, the site, source and heating energy consumptions were calculated using the EnergyPlus software. Also, the Building Energy Optimization (BEopt) energy simulation tool was used for the comparison of roof types and obtaining more accurate results. BEopt is a software used to find the most energy efficient building design [10]. The software allows the user to select the options to be included in the optimization. The design process allows to simply create a model and changing parameters such as, for example, wall and ceiling materials, HVAC system, windows, etc. The analysis results show the energy use, construction cost and allows choosing the optimal design in terms of energy use and cost efficiency according to the specific location [10].

BEopt applies the DOE2 and TRNSYS engines for simulation purposes and automates the process of finding the most efficient design by means of a sequential search strategy [10]. The discrete building methods allow identifying the most energy and cost-efficient design options. BEopt runs various scenarios defined by the user and identifies the most energy efficient one. The software calculates the energy use and savings according to a reference model, the user's own design or designed according to the integrated in the software Building America Benchmark [10].

BEopt 2.8 version uses a linear search method and finds positive and negative interactions between different categories, providing an optimal combination of options [10]. The approximate costs of the building constructions were calculated via BEopt 2.8.0 function. All of the materials' prices were taken as standard values inserted in the software. The authors of the research have previously used various simulation tools to perform energy performance simulations [11-15].

2.3 Building Model

This study aims to analyze the average annual energy use and cost of the average-sized two-story house in Kazakhstan. The typical house for Kazakhstan was assumed to have a gable roof and unfinished attic (Fig. 1.b). It was compared to building models with a flat roof, flat green roof and gable roof with finished attic (Fig. 1).

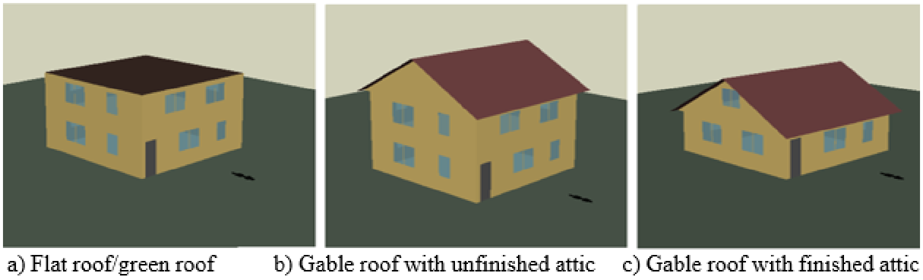

Fig. 1. Simulated building types.

The gable roof with unfinished attic is considered as a building with two floors of living space and a not usable attic. This is a commonly used type of roof and is included in this analysis to show the excess amount of energy that is dissipated comparing to different house types. All the building models have the same living area equal to 251 m^2. The building plan was generated automatically by the software and includes 3 bedrooms and 2 baths. All the building models were assumed to have the same parameters and components such as wall thickness, window openings, ceiling, floors, etc. The only structural difference between the models is the type of materials used in roof coating as the flat roofs tend to have better insulation.

Table 2. Simulation details.

Parameter	Value
Building Area	251 m^2
Duration of simulation	8760 hours (1 year)

The two models with gable roofs (Figures 1.b, 1.c) both have standard R-30C Fiberglass Batt insulation with R-value of 30.6 (Tables 3-4). Flat roofs were insulated with R-38C Fiberglass insulation, which has twice-higher R-value (61.2). The gable roofs were coated with dark-colored asphalt shingles, which have high absorptivity and emissivity (0.92 and 0.91 respectively). The flat roof has a PVC coating with low absorptivity (0.1) and emissivity (0.3), whereas the green roof has both absorptivity and emissivity values equal to 0.8. The rest of the materials are the same for all the models and were chosen based on the B10 Benchmark.

Table 3. Differences in roofing materials

Parameter	Flat Green Roof	Flat Roof	Unfinished Attic	Finished Attic
Roof Insulation	R-38C Fiberglass Batt	R-38C Fiberglass Batt	R-30C Fiberglass Batt	R-30C Fiberglass Batt
Roof Coating	Green roof coating	PVC	Asphalt Shingles, Dark	Asphalt Shingles, Dark

Table 4. Properties of the materials used in roof insulations (obtained from the BEopt 2.8)

Material type	R-Value	Absorptivity	Emissivity
R-38C Fiberglass Batt	61.3	-	-
R-30C Fiberglass Batt	30.6	-	-
Asphalt Shingles, Dark	-	0.92	0.91
PVC	-	0.1	0.3
Green roof coating	-	0.8	0.8

3 Results and Discussion

3.1 Energy Consumption

Results show that one of the most common types of roofs in Kazakhstan, the gable roof with the unfinished attic, is the least financially preferable type of roofs and has the highest construction cost. In addition, it is the least ecologically friendly and has the highest annual energy consumption values. Table 5 shows the annual energy consumption of four different roof types. The flat roof has 2.9% higher annual site energy and 4% higher heating energy amounts than the flat green roof. EnergyPlus simulation showed that the flat roof has 286.9 GJ of source energy, 2.04% higher amount than the flat green roof model. However, the BEopt simulation provided only 0.28% difference.

The most energy-efficient type of roofs was found to be the gable roof with the finished attic. In case if the attic is used as a living space, the roof structure has a significant effect on the energy and cost savings. The flat green roof has a small difference from the flat roof in terms of the annual energy consumption. From the economic perspective, it will take about 9 years to return the installation cost of the green roof with the money saved from energy.

Table 5. Results obtained from 1-year simulation

	Flat Green Roof	Flat Roof	Unfinished Attic	Finished Attic
Site Energy [GJ]	201.62	207.61	215.59	170.91
Source Energy [GJ]	280.95	286.81	295.86	245.35
Energy Use for Heating [GJ]	146.96	153.12	160.93	117.39
Source Energy (BEopt) [GJ]	276.3	277.1	291.2	244.7

The results show that the unfinished attic model has the highest site, source and heating energy use equal to 215.6 GJ, 295.9 GJ and 160.9 GJ respectively. The space under the roof left as a non-residential leading to 20.7% increase in terms of site energy, 17.1% increase in source energy and 27.1% increase in heating energy consumptions comparing to the model with finished attic.

However, the gable roof is the most preferable only as a two-floor house. For the one-floor house, more than US $11,000 could be reduced from the construction price by building the 130 m^2 house with flat or the green roof instead of the gable roof with the unfinished attic.

Table 6. Differences in expenses depending on the roof type

Type of Expense	Flat Green Roof	Flat Roof	Unfinished Attic	Finished Attic
Installation cost [USD]	51951	50935	62825	46083
Annual Energy costs [USD]	2465	2576	2682	2323

Table 5 provides the construction and the annual energy consumption costs for four different roof types. The unfinished attic model has the highest installation and annual energy costs, equal to US $62,825 and $2,682 respectively. It has 26.7% higher construction cost and equivalent of US $360 higher annual energy consumption cost than the finished attic model. The green and flat roofs have medium construction costs totaling to US $51,951 and $50,935 respectively. As for the annual energy consumption, flat green roof has $111 lower costs than the flat roof.

Since the gable roof is the most difficult in terms of construction, there is no obvious economical explanation for its popularity amongst the residential house owners. One of the reasons for the popularity of the gable roofs in Kazakhstan could be the lack of knowledge in the construction sphere. Most of the people that build houses stick to the time-tested gable roof construction. As the results indicate, the selection of this roof type lead to extra expenses. This study should be followed by conducting the physical analysis of the similar-sized houses with different roof types. The software may have errors and the physical analysis will validate the results. The source energy values show that depending on the software, the results may have significant changes. Therefore, to obtain the more accurate results, further research using different software is preferable.

4 Conclusions

In this study, the flat roof, green roof and gable roof with finished and unfinished attics were compared. The results show that the gable roof with an unfinished attic has the highest installation and energy consumption costs. Conversely, the most energy efficient and low-cost type of roofs is the gable roof that has a finished attic. A one-storey house with a finished attic is the best choice for a medium-sized family. However, the gable roof is the most preferable only as a two-storey house. For the one-storey house, more than $11000 could be reduced from the construction price by building the 130 m^2 house with a flat or a green roof instead of the gable roof with an unfinished attic. The comparison of the green and flat roofs shows that green roof has a slight benefit in terms of energy efficiency. From the financial perspective, the green roof savings will pay back the installation cost in about 9 years.

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