



Research

Cracking the code: mapping residential building energy performance in rural Central Asia through building typologies



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Received: 30 July 2023 / Accepted: 14 November 2023

Published online: 20 November 2023

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Abstract

Buildings in rural Central Asia have unique characteristics as they were built during the Soviet era (during 1950–1960) without any energy efficiency measures. The special and aged building stock pose a crucial challenge on energy security and energy supply. However, accurate scientific data on their energy usage is lacking, highlighting a research gap about robust and validated methodology to determine the energy use of rural Central Asian buildings. In response to this need, this research paper proposes a set of generalised residential building typologies for rural Central Asia, with a focus on Kyrgyzstan. The study combines quantitative and qualitative methods, including household surveys, energy demand modelling, EnergyPlus simulations, and result validation. It derives energy-based building typologies from construction year and building envelope characteristics. Through numerous validated simulations, it was identified that the heat demand for rural Kyrgyz houses is 3–5 times here compared to European houses (250–400 kWh/m²). The study revealed the estimated heat demand for homes in rural Kyrgyzstan, indicating a significant potential for improving building energy efficiency in the region. These results can inform specific approaches, such as building renovation plans, energy certification, and renovation strategies. Furthermore, the validated methodology introduced offers opportunities for researchers in the field of building energy efficiency and can be applied to similar regions in Central Asia with comparable building stocks and climates.

Article highlights

- Novel energy-based building typologies for Kyrgyzstan, using quantitative & qualitative methods.
- Valuable insights from energy modelling & simulation using EnergyPlus.
- Significant potential for improving building energy efficiency in rural Kyrgyzstan.

Keywords Energy demand modelling · Energy use in building · Central Asia · Cold-climate · EnergyPlus · Building simulation · Building typology

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SN Applied Sciences

(2023) 5:349

| <https://doi.org/10.1007/s42452-023-05607-1>

SN Applied Sciences
A **SPRINGER NATURE** journal

1 Introduction

1.1 Background and context

Energy demand is considered a key input to design an energy supply system. The absence of precise energy demand data is a critical challenge for energy planning [1, 2]. This becomes very important for the developing regions which are not yet been on focus of researchers. Lack of knowledge about energy demand in such regions can hinder the development of an efficient and sustainable energy supply system and creates difficulties to meet the ambition to reduce Green House Gas (GHG) emissions. This is especially true for rural areas in developing regions, such as Central Asia, rural building stock faces unique energy challenges compared to other regions of the developing world [3, 4].

High-altitude and/or cold climatic Central Asian countries such as Kyrgyzstan, Tajikistan and Kazakhstan where winter is very harsh and extended up to nine months where space heating demand is primary need of locals building structure plays a crucial role. Central Asia is home to a variety of different building types and construction styles. Most of the rural buildings in the region are made from materials such as mud brick, adobe, and rammed soil built during the Soviet era (50–60 years ago). Maintaining thermal comfort inside the aged and uninsulated building stock is crucial for locals [5].

Out of Central Asian counties, Kyrgyz residential buildings are the highest energy consumers [6] and consume the largest amount of energy for space heating [7]. Less than 20% of the Kyrgyz Republic is suited for comfortable leaving due to mountainous characteristics and elevation fluctuation. Thus, the vast majority of the building stock (approximately 85%) is concentrated in very limited areas as rural villages or urban clusters [8]. In addition, rural Kyrgyz building stock is unique from a building construction point of view due to several factors [7]. The buildings in rural Kyrgyzstan are typically constructed using earthen materials such as adobe, which is a mixture of clay, sand, and straw which is common practice across rural Kyrgyzstan due to limited access to modern building construction materials. In Kyrgyzstan, where homes are often found in rural locations, up to 80% of the houses are made of clay materials. Hence, residential buildings in rural areas of Kyrgyzstan are heavily dominated by uniform and vernacular buildings without consideration of proper insulation parameters, inadequate maintenance and the absence of proper thermal insulation [9, 10].

Also, the buildings in rural Kyrgyzstan have a unique architectural style that reflects the region's cultural and

historical imprints. For example, despite being in the cold climatic zone, the majority of the rural homes are with uninsulated walls and wooden beam ceilings as well as open gable roofs. This is due to building construction process in rural areas does not involve skilled laborers but it is usually built with help of neighbours and local laborers who learned the building construction techniques which have been passed down from generation to generation. Figure 1 represents the unique characteristics of rural Kyrgyz buildings to distinguish them from typical rural buildings from another regions/developing world. Energy expenses were low between 1950 and 1960 (during the Soviet era), and residential structures were built without any energy efficiency measures [11]. Due to remote locations and the low construction rate of new buildings, knowledge about building energy efficiency and modern (proper) construction techniques is not yet reached rural Kyrgyz areas. Therefore, self-made earthen houses remain the common practice in rural areas across the country territory.

By given the cold climate and high-altitude, heating energy is a primary need of local people [6]. However, there is no scientific information available about the exact heat demand of such houses. Due to isolated locations, rural households do not have access to modern heating services. Hence, rural Kyrgyz households use very low-energy efficient traditional heating stoves operated by non-sustainable solid fuels to maintain thermal comfort. The possible thermal leakages from two types of rural Kyrgyz houses are shown in Fig. 2 through on-site performed thermography.

Yet, maintaining thermal comfort inside rural homes requires a significant quantity of heat energy due to the outdated and uninsulated building stock. This high energy consumption not only results in increased heating fuel expenditure for the occupants but also significantly contributes to greenhouse gas emissions, which have adverse effects on the environment and local ecosystem. Figure 3 represents the typical traditional heating stoves used in rural Kyrgyz houses and the storage of coal and firewood.

The excessive use of non-sustainable solid fuels and heavy dependency on them is the strong factors for inducing climate change in Kyrgyzstan making it one of the most vulnerable countries in Central Asia to its effects. Hence, it is necessary to think about establishing sustainability to meet the ambitious goals to mitigate climate change. The residential building stock plays a critical role in this effort, as it accounts for the highest energy consumption of any sector in Kyrgyzstan. However, there is a lack of accurate scientific information regarding the heat energy demand.

There is no dedicated methodology available that can help to identify the heat demand of unique rural Kyrgyz

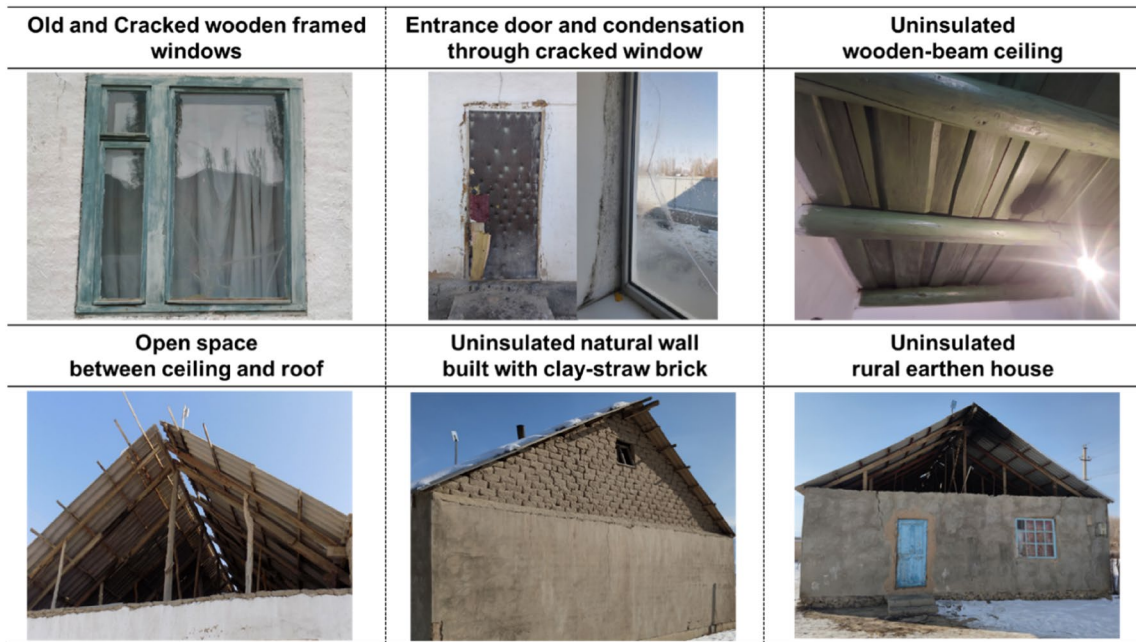


Fig. 1 Unique characteristics of rural Kyrgyz buildings



Fig. 2 Thermal images of rural Kyrgyz houses during the winter month



Fig. 3 Storage of non-sustainable solid fuels (left) and traditional heating stove (right)

houses. In that case, literature review indicates that building typology/archetype is an established methodology and useful for energy performance calculation and strategic planning. The archetype-based approach does not depend on historic data as data availability is an issue for Kyrgyzstan [12]. Further to this, this model determines the end-use energy consumption by building type/rating which quantifies the impact of different energy consumers on the synthesised level. Due to such features, an archetype-based approach is recommended by the scientific community. However, this model needs validation to develop energy demand on a community scale [13, 14].

1.2 The current state-of-the-art and gap in the research

For building typologies for Kyrgyz buildings, most of the study was performed to assess the earthquake vulnerability of the Kyrgyz buildings. The research focus is on seismic scale/vulnerability rate because Kyrgyzstan is situated in an active seismic zone, and most of the building stock is outdated and exposed to risk. Hence, the focus of the existing literature on Kyrgyz building typologies is on earthquake vulnerability. There are few if any energy-based residential building typologies, which is a gap in current knowledge. To show the gap in the research, the literature related to the Kyrgyz building typologies are described consequently.

Lang, Kumar, Sulaymanov, Meslem [15] developed building typologies based on the earthquake vulnerability of Central and South Asian building stocks. Based on comprehensive field research in various locations, the author classified the building stock into regional building typologies and try to provide information on the earthquake vulnerability scale of buildings according to Central Asian and south Asian countries.

Pittore, Parolai [16] investigated and provided the information that more than 50% of the buildings in Kyrgyzstan are represented by masonry structures and around 40% of the buildings stock is constructed by earthen/adobe structures (especially in rural areas). The building stock of Kyrgyzstan has an impression of Russian design and has a bad degree of conservation. The research classified building types according to exposure to seismic risk.

Fodde [17] provided a comprehensive overview of the primary earthen materials used for house construction in Central Asia. The article demonstrated how Russian cultural imprints reflect on the construction style. The research described the variety of contemporary vernacular architecture techniques of Central Asian houses. Moreover, the article recommended that building types can be helpful to characterise Central Asian buildings from various points of view.

The review of literature reveals that although there are numerous studies on the seismic vulnerability of buildings in Kyrgyzstan, there is a lack of research on energy-based building typologies to identify the energy performance of the rural Kyrgyz buildings. This can be considered as gap in the research.

In response to that, the presented research article aims to fill the existing research gap by developing energy-based residential building typologies for rural Kyrgyzstan. There is a lack of knowledge in this area, which is essential to improve thermal efficiency and reducing GHG from the building sector. Hence, the main objective of the presented paper is to develop generalised building typologies by considering the local boundary conditions of Kyrgyzstan to analyse how that influenced the building stock and energy consumption. As rural building stock from the construction point of view is typically identical throughout the country, the generalised building typology can be transferable to any rural part of Kyrgyzstan.

2 Research design

2.1 Research question

To achieve the research goal, the presented article positions and answers several research questions that are crucial to the development of building typologies to map the energy performance of rural Kyrgyz houses.

- What is the building construction status and their impact on the energy for performance?
- What are the key parameters that can be used to develop generalized energy-based residential building typologies for rural Kyrgyzstan?
- How to identify the energy performance of the unique rural Kyrgyz buildings?

The research questions that the paper addresses include the identification of the existing residential building typologies in rural Kyrgyzstan and their energy performance characteristics. The paper also explores the main energy-related challenges and opportunities for improving the residential building stock in rural areas of Kyrgyzstan. It further investigates the key parameters that can be used to develop generalised energy-based residential building typologies, and how they can be applied to assess the energy performance of existing buildings and identify potential energy savings. It is essential to consider these variations when developing energy-based residential building typologies for rural Kyrgyzstan. The typologies should be flexible enough to account for the different building styles, years of construction, building materials, heating technologies as well as income levels that can be applied across the region.

2.2 Materials and research methodology

The method used in this paper was to collect statistical data from the different rural buildings in a typical rural village of Kyrgyzstan through the on-site household survey. For the case study area of this presented research work, Ak-Tal was strategically selected to serve as a representative sample of high-altitude rural communities within the Naryn region, located in central Kyrgyzstan. The rationale for this selection stems from several compelling factors. Firstly, the Naryn region is well-known as one of the coldest regions in Kyrgyzstan, a climatic characteristic that directly aligns with the core focus of this thesis. Hence, it brings valuable insights into

the real-world challenges experienced by high-altitude communities with extreme cold temperatures, thereby enhancing the relevance and applicability of the study. Moreover, the selection of Ak-Tal was motivated by its high-altitude setting, low population density as well as old uninsulated building stock, characteristics shared by many rural areas in Kyrgyzstan. Consequently, Ak-Tal serves as a representative model for high-altitude rural communities.

The community of Ak-Tal is situated in a centre of Kyrgyzstan and located approximately 80 km downstream from Naryn city. The community of Ak-Tal is home to approximately 1500 people, with almost 235 single-family houses. This study aims qualitative household survey and therefore the sample size and selection were determined based on the total number of households in the community. Detailed information on the sample size selection and calculation is described in the previous work of the author [18, 19]. Eventually, 40 houses were selected as a sample size and interviewed to get detailed information about their building characteristics (c.f. Figure 4).

More than 60 questions were asked during each interview to gain detailed information about rural buildings. The question includes general information about buildings (material, construction type, year of construction, the thickness of wall, number of rooms, orientation, size of the windows, floor area etc.), residents' behaviour patterns, housing situation and energy efficiency measures, opinions on heating and type of heating system as well as question about the use of solid fuels (for example, coal, firewood and cow dung) for space heating. The objective of the data collection was to understand the various building aspects of typical rural Kyrgyz houses.

The various questions were asked and analysed to categorize buildings. The analysis was used to develop an overview and create the building typology of rural Kyrgyzstan based on the age band. That also reveal important information about local building construction techniques of each typology. Later, all 40 interviewed houses were modelled in EnergyPlus software for simulation.

As the presented approach was a first attempt to develop energy-based residential building typologies, there was a need to validate the results (heat demand). The simulated heat demand was validated with heating fuel used in each house (based on the calorific value and thermal efficiency of the stove). Based on validated simulation results, the article finally assigns the generalised energy performance of the houses based on the developed typologies. Figure 5 showcases the graphical presentation of the methodology of the research article.

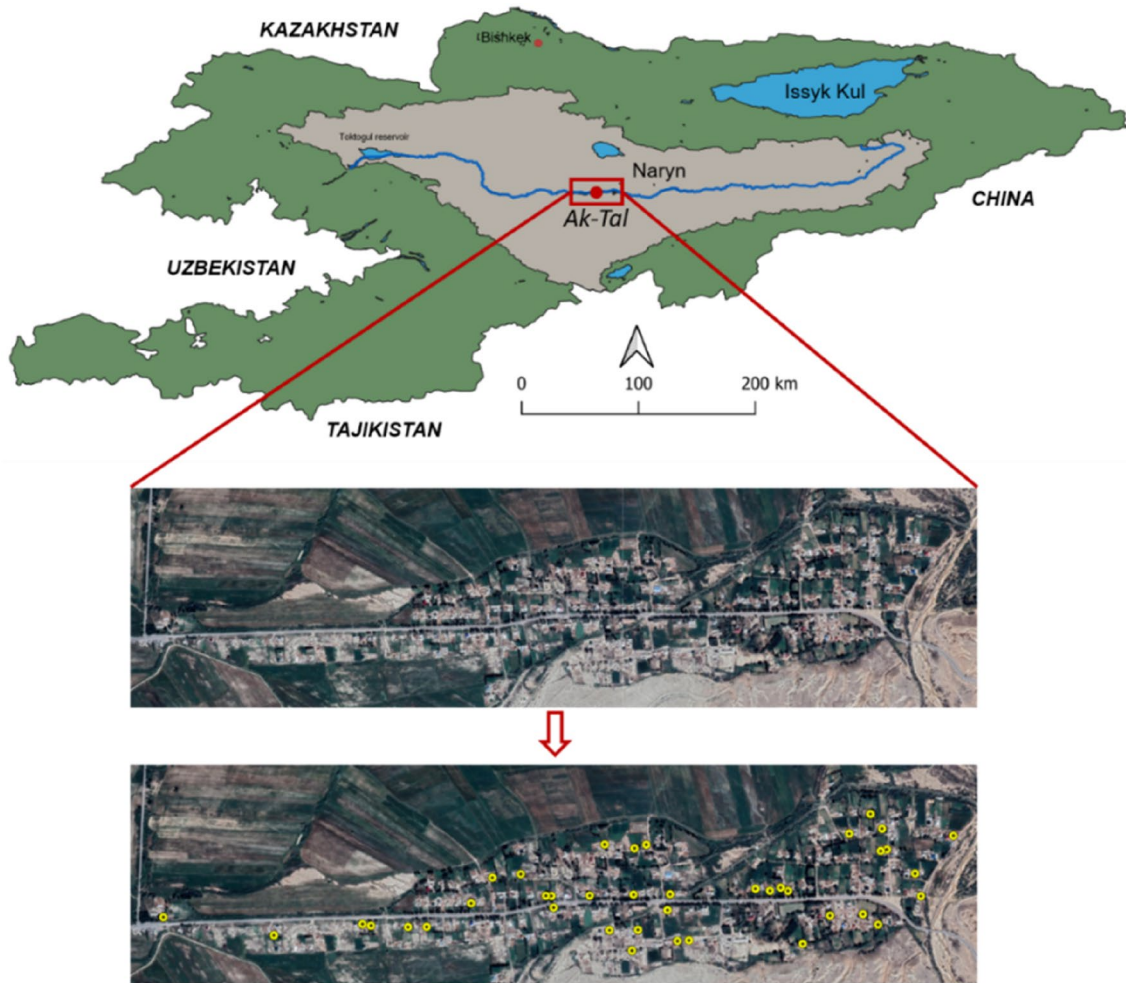
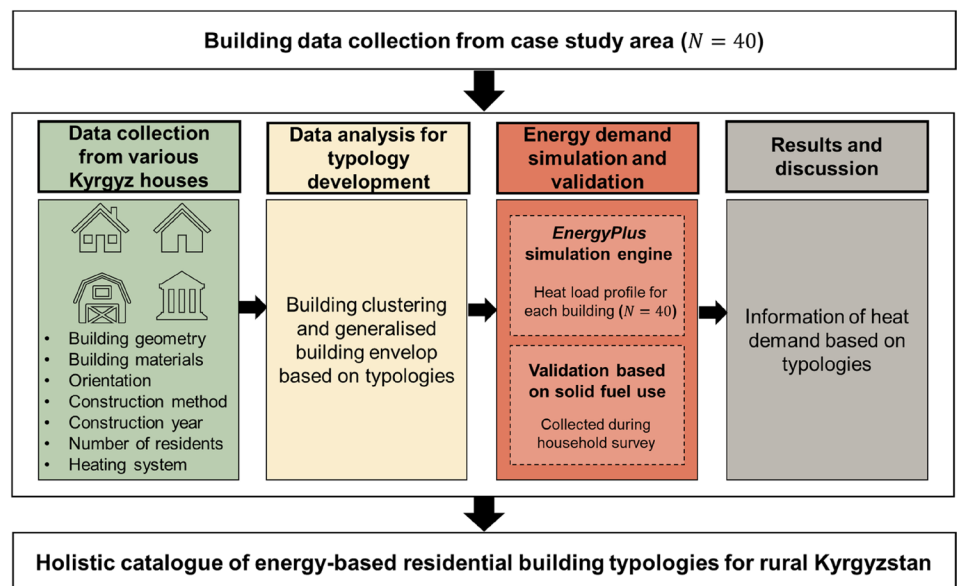


Fig. 4 Representation of the case study area and locations of the interviewed households

Fig. 5 Graphical representation of the research methodology



2.3 The novelty of the presented research

The presented study is the first attempt to derive validated energy-based residential building typologies which is not only limited to Kyrgyzstan but (partially/fully) transferable to other Central Asian regions based on the local boundary conditions. Eventually, this article helps to map the heat demand based on the various aspects of Kyrgyz households and provides a comprehensive understanding to international readers.

By using a mixed-methods (quantitative and qualitative) approach, this study tailors the local knowledge for building typology development. This study also provides in-depth information about the energy demand modelling of unique Central Asian rural houses. The research findings contribute to the knowledge base on building typologies and energy demand, providing valuable insights for future researchers, decision-makers, and local stakeholders alike.

3 Development of building typologies

Typical rural communities in Kyrgyzstan mainly consist of residential/single-family houses. There are very few public and commercial buildings. Therefore, the presented work focuses on the development of residential building typologies. According to the survey data it was observed that residential houses can be classified into three types based on wall material: (a) mud/adobe brick; (b) Soil wall and (c) Clay-straw brick. High-altitude rural residential buildings may be classified according to the

building materials. Despite different building materials, the houses look identical from the construction point of view. Also, it was challenging and inaccurate to derive the typologies based only on the building materials as it does not allow for considering unique features of Kyrgyz houses such as open roofs, heating technologies, fuel usage, level of thermal comfort etc.

An alternative way to categorize houses is by their residential area/floor area. Typically, rural houses have a floor area ranging between 90 and 100 m² (resulting in four to five rooms). However, it was noticed from the household survey analysis that most of the house have floor areas ranging between 95 and 110 m². Therefore, that classification also does not allow for detached buildings.

At the same time, the data analysis showed interesting variations in house construction, energy pattern, level of thermal comfort, construction technologies and heating technologies based on the construction year associated with building envelope characteristics, especially before and after a few years of independence (1991). The different features were helpful to cluster the buildings and form the building typologies. The detailed information is discussed consequently. The interviewed buildings were classified into three types: (a) House construction before 1990, not renovated (i.e., old buildings); (b) House construction between 1991 and 2020 (i.e., new buildings) and (c) House construction before 1990 but renovated since 2000 (i.e., renovated buildings). Figure 6 represents the indoor and outdoor view that helps to understand the derived building typologies.

	Constructed before 1990 (Type A- Old buildings)	Constructed during 1991-2020 (Type B- New Buildings)	Constructed before 1990 but renovated (Type C- Renovated buildings)
Outdoor view			
Indoor view			

Fig. 6 Classification of studied households and indoor and outdoor view which shows building structure and building materials are different for individual building typology

3.1 Type A: old-constructed buildings

Type A category considered the houses built before 1990 in the community. The data analysis gave an insight into the construction techniques of the old rural houses. The summarise information on each building element construction is presented here with on-site evidence.

Traditionally, buildings in rural areas were constructed with natural stones / directly on the ground, without a trench foundation. However, these techniques were found to be inadequate to bear earthquakes. To enhance the stability of the foundation, a trench can be excavated and filled with boulders. This type of rural house typically has earthen floors with a layer of natural stone for stability. These floors are usually around 0.25 m to 0.50 m thick without insulation measures. To construct the floor, a stone boundary is created, and medium-sized gravel is filled inside stone frame to act as a moisture barrier. Long wooden beams are placed on top of the frame, and pine floorboards are attached to the beams. Walls of this type of house are constructed with earthen materials without insulation, resulting in thicker walls ranging between 0.35 and 0.50 m. Adobe brick and soil walls are commonly used. Rammed earth is a popular wall construction material in Central Asia, along with adobe bricks. To make a rammed earth wall, loose soil is compacted with a wooden support fixture to the desired wall thickness. The compressed soil

is left to dry naturally in the sun for 5 to 7 days to form a solid structure.

Compared to mud bricks, rammed earth walls are more durable against rising water, but their thermal qualities depend on the compression technique. Traditional natural floors with stone foundations are vulnerable to moisture, even with low rainfall and snowfall. Rising dampness through capillary action can cause mould development and damage to plaster or painted walls, especially in older buildings. Clay or silicate plaster is commonly applied to protect soil-based walls, but poor-quality materials and environmental effects can lead to cracking and erosion, making the walls susceptible to moisture penetration. The (spruce) wooden-beam ceiling is common in older houses and constructed similarly to the floor with beams placed on walls at 10–15 cm spacing, covered with planks, loose soil, and straw. Typical old-constructed houses in Kyrgyzstan have a metal roof placed on a wooden beam ceiling, but the gables are usually open from both sides, creating open space between the ceiling and the roof. This induces high heat loss windy and cold days [5]. Old-constructed houses usually have double-glazed windows with wooden frames, but many are leaky due to cracked panes and poorly fitting frames, which allow draughts. These windows often cause high heat losses. Due to income issues, Type A houses use low efficient traditional heating stoves that placed in the corner and heat the floor area

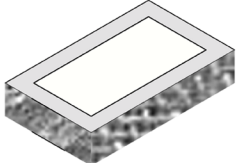
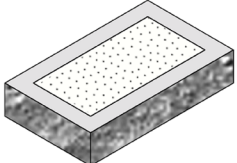
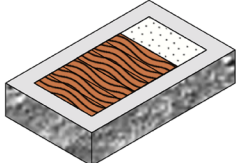

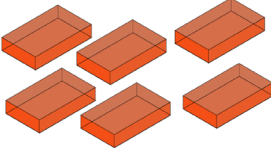
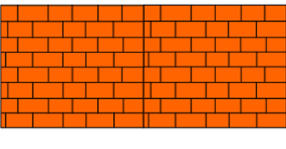
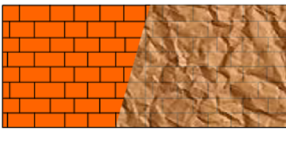





Floor & foundation				
	Stone based foundation frame	Gravel / stone filling with air gap	Installed wooden floor	Earthen floor foundation
Earthen walls				
	Self-made soil-based bricks	Earthen walls	Very thin layer of clay / silicate wall plaster	Earthen walls with wooden framed windows
Wooden ceiling				
	Wooden beam structure	Wooden beam with a wooden plank	Wooden beam ceiling with a clay layer	Open roof earthen old houses

Fig. 7 The construction process of individual building features of Type A house (old constructed house) in rural Kyrgyzstan

by radiation. To save the heating fuel expenditure, households often heat up only one to two room. Figure 7 shows the construction process of individual building features of Type A house (old, constructed house) in rural Kyrgyzstan based on the evidence from the site visit.

3.2 Type B: newly constructed buildings

Type B category considered the houses built after 1991 in the community (after the independence of Kyrgyzstan). The typical characteristics of the newly constructed rural houses are presented below.

Newly constructed houses typically use concrete-based foundations instead of stone. These foundations are stronger and capable to withstand earthquakes, but also more expensive due to the use of cement and iron bars. The outer frame of the foundation is made of concrete and can be up to 200 cm in height. To prevent humidity, medium-sized gravel is placed inside the frame, creating a barrier for the floor. Also, small openings are then made in the outer frame to ensure natural ventilation to avoid moisture/humidity from the floor to wall or another building envelope. Newly constructed houses commonly use wooden floors as they are easy to build and do not require specialized knowledge or materials. However, natural ventilation during winter can lead to cold floors as air from outside circulates underneath. To address this, ventilation

holes are often blocked in winter and thick wool carpets are used to keep feet warm.

For wall construction, it was observed that Type B houses are mostly built with clay-straw brick. This brick is made by mixing clay and straw with water until it forms a firm shape. Usually, livestock manure is often added to this mixture in small quantities to prevent premature hardening. Clay-straw walls become common practice for wall construction due to their easy preparation and construction. Newly constructed houses generally have thicker and better-quality wall plaster than older ones. Households with high income prefer to decorate the façade with expensive materials (usually imported from neighbouring countries). In contrast, middle-income and low-income households opt for clay plaster or whitewash for both exterior and interior walls. Hence, Type B houses have a variety of façade designs based on income.

Newly constructed houses have similar ceiling construction to old houses, although Type B houses have an additional layer of cardboard and a vapour barrier to prevent moisture. Often, loose straw or reed panels are placed on top of the ceiling structure to reduce heat losses, followed by a thick layer of slag or clay mortar for protection. Open roof designs are common, but closed gable roofs may have leaks or be partially closed to reduce heat losses. Newly constructed houses mostly have PVC double-glazed windows, while some type B houses have a combination of

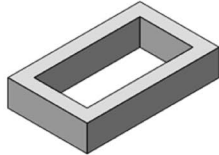
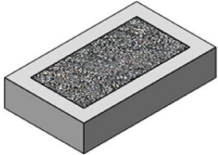
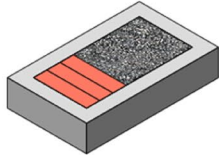

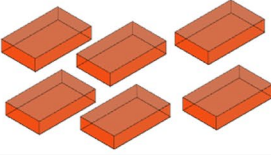
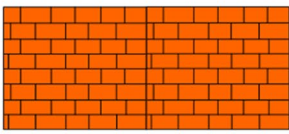
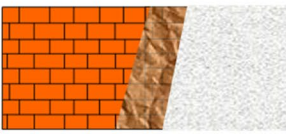





Floor & foundation				
	Concrete based foundation frame	Gravel / stone filling with air gap	Installed wooden floor	Concrete floor in construction
Earthen walls				
	Self-made soil-based bricks	Earthen walls	silicate wall plaster with whitewashed walls	Earthen wall construction with PVC windows
Wooden ceiling				
	Wooden beam structure	Wooden beam with a wooden plank	Wooden beam ceiling with a clay and slag layer	Partially closed roof houses

Fig. 8 The construction process of individual building features of Type B house (newly constructed house) in rural Kyrgyzstan

PVC and wooden framed windows. Initially, all windows in newly constructed houses were wooden framed due to financial constraints, but some have since been replaced with PVC windows as finances allowed. Figure 8 shows the construction process of individual building features of Type B house (Newly constructed house) in rural Kyrgyzstan based on the evidence from the site visit.

Type B houses use either use low efficient traditional heating stove or stove that placed between two walls to heat up two rooms simultaneously. This is somehow improved heating technology at allows to use two rooms at the same time by using the same amount of heating fuels.

3.3 Type C: old but renovated buildings

Type C houses are those built before 1990 but renovated in the last 10 years (since 2010). Here renovation does not necessarily include thermal modifications. Instead, depending on income, households may renovate the façade, interior walls, and ceiling/roof. The foundation and floor are usually unchanged due to the high cost of excavation. Façade renovation is prioritized to attain the social status, resulting in more decorated exteriors in the renovated houses. However, the original wall construction looks like Type A and B houses but with better render/façade. Renovated houses still use wooden-beam ceilings, but with thicker clay and mud as an external layer. Renovated houses commonly have properly closed roofs with metal-based (galvanised iron) materials, which is affordable for high-income families. Most renovated houses have PVC windows, which reduce heat leakages compared to older houses.

As Type C houses mostly refers to high-income families and therefore can afford the either stove placed between two walls or high-efficient stoves/low pressure boiler with heat radiator-based heat distribution system to heat up entire houses. In some cases, electric radiators can be used as an auxiliary heat supply.

4 Validated building energy modelling for rural Kyrgyz houses

4.1 Input parameters for detailed building energy modelling

The previous chapters provide detailed information about the uniqueness (i.e., open gable roof, combination of PVC and wooden windows, earthen materials etc.) of rural Kyrgyz buildings. This was a complex and challenging task to develop a simulation model within the simulation environment. Hence, the presented

demand modelling approach itself is a novel contribution on modelling level as it reveals the knowledge on how to develop a simulation model of such unique rural Kyrgyz buildings. So far, there is no such contribution was noticed in the literature review. All 40 interviewed houses have been separately modelled in the EnergyPlus software [20]. Figure 9 shows the design of an integrated simulation manager with developed input parameters.

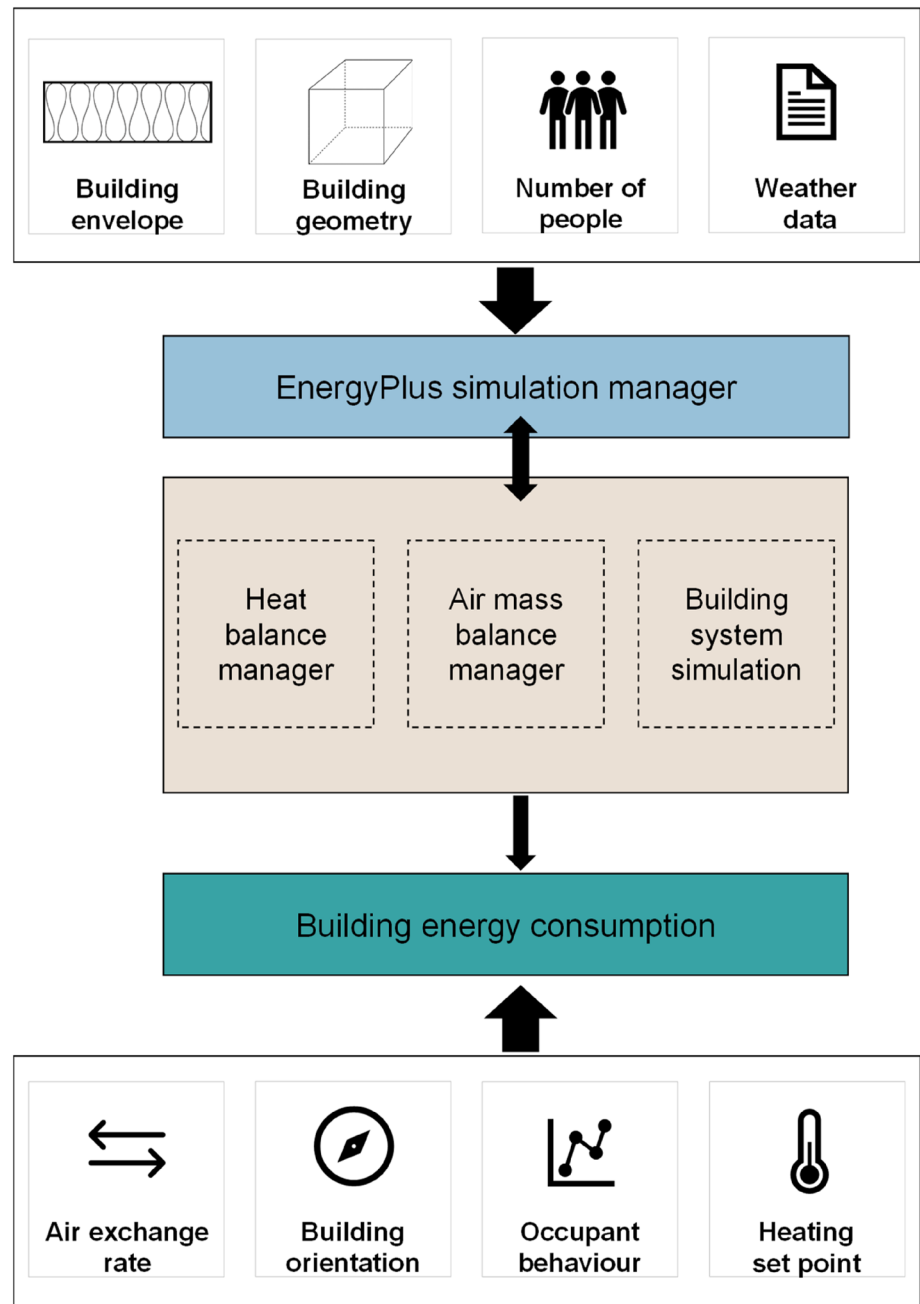
EnergyPlus employs a heat balance algorithm that integrates DOE-2 and BLAST (Building Loads and System Thermodynamics) simulation engines to compute heat demand of the building which is widely adopted as a reliable method for simulating building energy consumption. The model estimates the heat gain/loss of individual thermal zone by considering various parameters such as heat losses through different building components (i.e., walls, floor and ceiling), local climate, occupant's behaviour, internal gains, external solar gains etc. The model then calculates temperature changes over time, based on the heat gain or loss in each thermal zone. EnergyPlus predicted heating demand for the building over the course of a year, based on the thermal characteristic of building the outside air temperature.

The information regarding floor construction, wall construction and ceiling construction was applied according to the building typology database which was developed from the author's on-site observation and in-depth discussion with building construction experts. The generalised information was developed for the building envelope based on the building typologies. However, wall materials and thickness of the wall were considered from the household survey results to be accurate while developing the demand modelling.

The in-depth discussion with the building construction experts as well as the inputs from the households served as the fundamental source to develop the simulation model of various building envelopes according to typologies. Also, extensive use of literature review supported the process. On top of that, a market survey of the building materials was performed to gain authentic information about the building materials used in the construction. Based on that, a comprehensive overview/illustration of individual sandwich layers of various building elements is presented below in tabular format. This became the input to develop simulation models in EnergyPlus. Table 1 provides comprehensive information about various building envelopes used in the simulation model.

As it was mentioned previously that most of the houses were built without insulation and therefore the simulation model did not consider any insulation parameters during modelling. However, total of 3 houses out of 234 houses are insulated and part of the household survey. In the 3

Fig. 9 Overall EnergyPlus structure and list of key inputs to the simulation engine




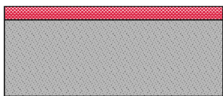




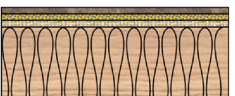


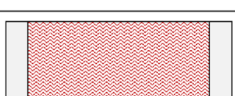
house simulation models, the insulation parameters were considered according to the data collected from the site.

Since the weather data was not available for the case study area (Ak-Tal village) due to its remote location, the weather data from Naryn city was used for the simulation purpose. Naryn city is located approximately 80 km away from the case study area and has a very similar climatic condition. Despite the location difference between Naryn city and Ak-Tal, the weather data from Naryn city was considered appropriate due to its close similarity in climatic conditions to Ak-Tal. Therefore, the simulation results are reliable for assessing the energy performance

of the rural houses in Ak-Tal. The hourly weather data file was retrieved from the Meteonorm database (hourly resolution) and was used for the simulation of building energy. Figure 10 represents the weather data of Naryn which was used in the simulation.

During the household survey, questions were asked regarding their routine behaviour (separated by morning, afternoon, evening and late evening) to understand the daily routine. After conducting daily observations of several houses, a generalized occupancy profile was developed that work as an input for building simulation.

Table 1 Input parameters used for EnergyPlus simulation modelling

Type	Building envelope	Structure	External to internal layer	Thickness [m]	Density [kg/m ³]	Conductivity [W/(mK)]	Capacity [kJ/(kgK)]	U -Value W/m ² K
A,C	Floor		Floor board	0.05	520	0.13	1.60	1.15
			Air	0.05	1	0.14	1.01	
			Gravel	0.25	2,200	2.00	1.00	
B	Floor		Floor board	0.08	520	0.13	1.60	1.07
			Plaster	0.05	1,800	0.76	0.84	
			Concrete slab	0.50	2,400	2.00	0.95	
A, B, C	Uninsulated clay-straw wall		Lime Render	0.02	1,400	0.87	1.00	1.11
			Clay Bricks	Survey data	1,200	0.47	1.00	
			Lime Render	0.02	1,600	0.91	1.00	
A, B, C	Uninsulated adobe wall		Lime Render	0.02	1,600	0.91	1.00	1.36
			Adobe Bricks	Survey data	1,600	0.58	0.80	
			Lime Render	0.02	1,600	0.91	1.00	
A, B, C	Uninsulated soil wall		Lime Render	0.04	1,600	0.91	1.00	1.87
			Soil	Survey data	1,700	0.90	1.00	
			Lime Render	0.04	1,600	0.91	1.00	
A, B, C	Insulated wall with Penoplex		Lime Render	0.02	1,600	0.91	1.00	0.50
			Penoplex	0.04	40	0.034	1.53	
			Adobe/ Soil	Survey data	1,500	0.66	1.00	
			Lime Render	0.02	1,600	0.91	1.00	
			Slag	0.03	790	0.23	0.92	
			Clay-straw	0.15	800	0.66	1.00	
A	Uninsulated wooden beam ceiling		Straw	0.02	150	0.04	2.10	0.79
			Spruce wood	0.05	450	0.13	1.60	
			Slag	0.05	790	0.23	0.92	
B,C	Uninsulated enhanced wooden beam ceiling		Clay-straw	0.15	800	0.66	1.00	0.62
			Straw	0.03	150	0.04	2.10	
			Vapor barrier	0.002	-	0.22	1.70	
A	Wooden framed old windows		Spruce wood	0.05	450	0.13	1.60	3.61
			Glass pane	0.006	-	0.90	-	
			air	0.0032	-	-	-	
B,C	Plastic framed new windows		Glass pane	0.006	-	0.91	-	2.66
			Argon	0.005	-	-	-	
			Glass pane	0.010	-	0.40	-	

The development of this occupancy profile was based on careful observation and analysis of the daily routines of various households in rural Kyrgyzstan. By collecting and analysing data on the patterns of household activities and behaviours, a comprehensive understanding of typical occupancy patterns was achieved. This information was then used to create a generalized occupancy profile that can be used in the modelling and analysis of energy

demand in rural Kyrgyz households. Figure 11 illustrates this profile, which represents the fraction of individuals present in the house at different times throughout the day.

Together with the occupancy profile, a generalised electricity gain profile was developed based on daily routines which are shown in Fig. 12.

All the building models were designed as single (thermal) zone models as there were no different thermal zones

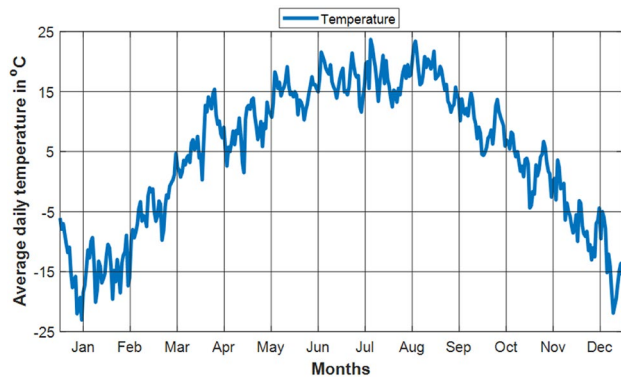


Fig. 10 Weather data of Naryn city used for the simulation

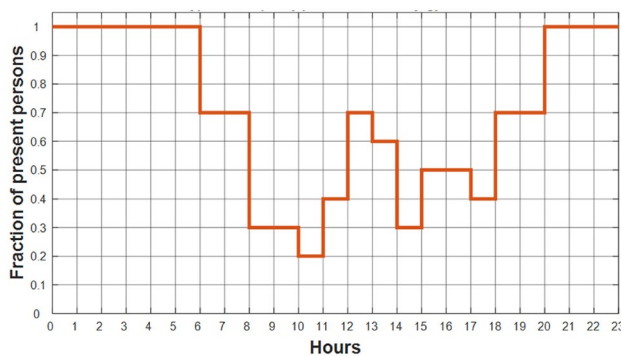


Fig. 11 Daily occupancy of a typical rural Kyrgyz house (1=full occupancy, 0.5=half of the total occupancy)

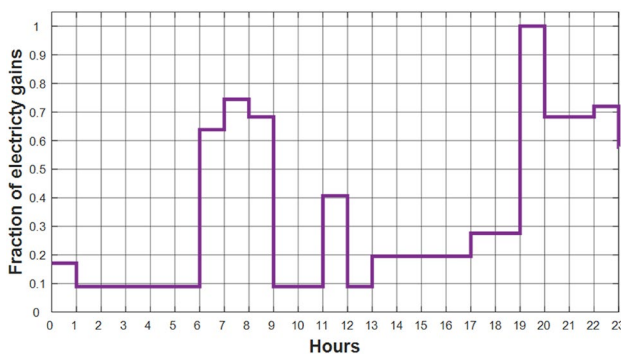


Fig. 12 Daily electricity gain of a typical rural Kyrgyz house (1=full occupancy, 0.5=half of the total occupancy)

identified in the houses in rural Kyrgyzstan. The heating set-point of all the houses was considered as 20 °C for all simulated houses [21]. Simulation models utilised standard settings for natural ventilation in EnergyPlus due to the unavailability of accurate data. The objective of energy demand modelling was to determine the overall heat demand for various building types in the context of community-level analysis, rather than individual houses.

Hence, calculating natural ventilation was not within the scope of the project. Additionally, for suspended floors, the simulation model assumes air filled cavity with a specific thermal conductivity, as many households close ventilation during winter to prevent cold floors.

Designing open-roof or partially closed-roof houses in a simulation environment was a difficult task. To simulate open roof houses in EnergyPlus, a house with an open roof space was developed as a rectangular-shaped single node model, where the exterior ceiling was not exposed to solar irradiation but to exposed to wind. However, designing a partially closed roof house was not possible in EnergyPlus, so it was simulated like a fully closed roof house with the assumption that the partial openings would cause extra heat leakage. Available literature suggests that such a roof has a 10% additional heat loss to the overall heat demand [22]. This factor was taken into consideration while estimating the overall heat demand for the study.

To accurately simulate the closed roof house, the simulation model was modified and designed with a rectangular-shaped single-node model that considered the distance between the gable roof and the ceiling. This enabled them to create a fully enclosed building geometry that would be representative of the closed-roof houses in rural Kyrgyzstan. Figure 13 represents the modelling approach for various roof conditions in EnergyPlus.

4.2 Results analysis and interpretation

Through batch simulation, 40 houses were simulated to calculate the heat demand of individual houses. The process of calculating the heat demand in EnergyPlus involved considering various factors such as heat losses through different building components including walls, floors, and ceilings, as well as the local climate, occupant behavior, and internal and external solar gains. By considering these factors, EnergyPlus identified the heat demand of the individual houses with hourly resolution.

It was identified that out of 40 houses, 17 houses were categorised in Type A. Within that a few houses were equipped with partially closed roofs. While a total of 16 houses out of 40 houses were categorised as Type B houses and have similar roof conditions to Type A houses. There is a very low renovation trend identified in the community due to high investment costs. Therefore, only 6 houses out of 40 houses were categorised as Type C houses. The comprehensive result according to building typologies in the form of the annual specific heat demand is presented in Table 2. For a better understanding, the results were categorised according to the roofing category so one can clearly understand the difference between heat demand. Also, to provide a simple presentation of results, the results were arranged from high to low heat demand.

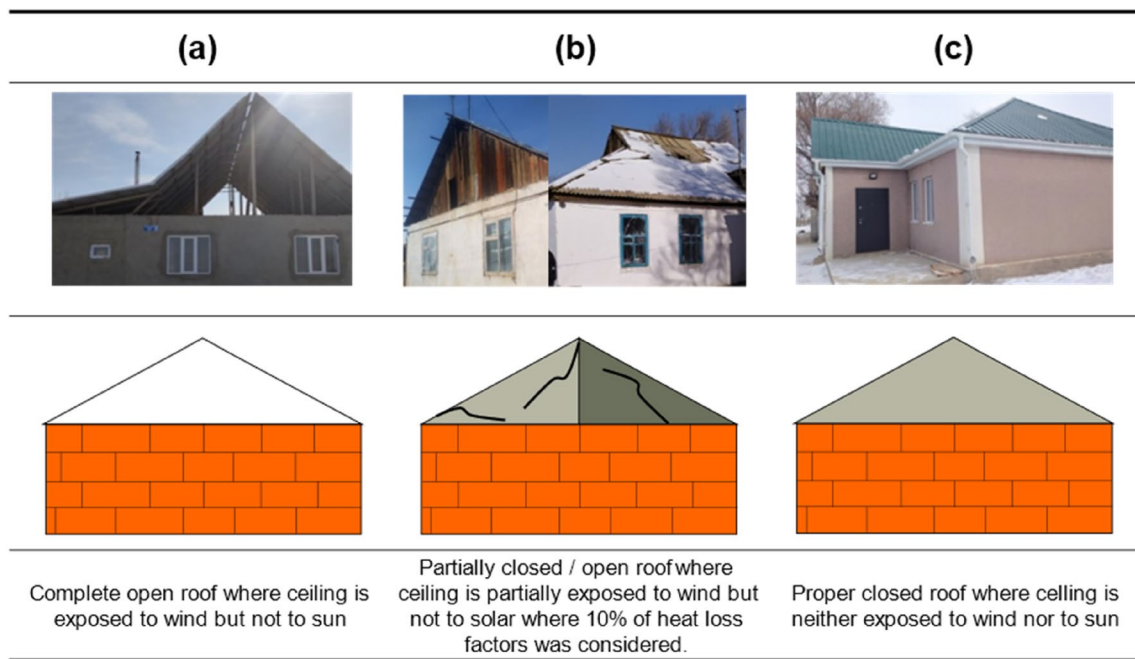


Fig. 13 An overview of roof modelling in simulation **a** open roof house **b** partially open/closed house and **c** completely closed roof house

It can be seen from the results that Type A houses in the community have the highest energy consumption due to aged, uninsulated and inappropriate building techniques. The outdated and earthen building materials are responsible for the high heat losses. Further to this, the open-roof house has even higher heat demand. The average heat demand of Type A house ranges between 250 and 400 kWh/m². Naturally, the range of heat demand is wide because several factors affect heat demand. It was noticed that houses that have a soil wall have a high heat loss compared to clay-straw brick construction.

Type B houses have upgraded construction techniques as they were built after 1991. And therefore, due to better floor design, plaster and ceiling design, the demand for Type B houses is lower compared to Type A houses. Also, it was noticed that the majority of Type B houses are either built with clay-straw bricks or adobe bricks. The average heat demand of Type B houses ranges between 150 and 260 kWh/m². It was noticed that two high-income houses of Type B in the community have considered the insulation parameters while housing construction. The insulation parameter of these houses reduces the overall heat demand (c.f. Table 4–2 (B) H-8, H-14). As discussed earlier, the renovation of the houses considers thermal modifications in combination with closing the open roof space. However, the consideration of such effective thermal modifications is limited to the high-income families in the community as low-income households cannot afford it. Due to

thermal modifications, Type C houses have average heat demand which ranges between 170 and 210 kWh/m².

4.3 Limitations and assumptions

The inputs used in the simulation are already presented in the previous section. However, generalised inputs were developed from the interview of the 40 different houses, the author's observation and an interview with a building construction expert. Naturally, individual building design is different because it was observed and concluded that the building construction/facilities are directly linked with household income. Hence, this can be considered as the limitation of simulation results. Also, due to inappropriate roof structure (especially with the partially opened/closed roof), and cracky/broken windows, educated additional heat loss was assumed. By considering the limitations and assumptions of the developed simulation models/results, it was important to validate them. The validation model is disused consequently.

4.4 Validation model of the developed building typologies

As there was no previous data available on the heat demand in high-altitude Kyrgyz houses, it was a challenging task to validate the results from the simulation. However, during the household survey, data was collected about the heating fuel consumption, calorific value (from

Table 2 Simulation results based on building typologies

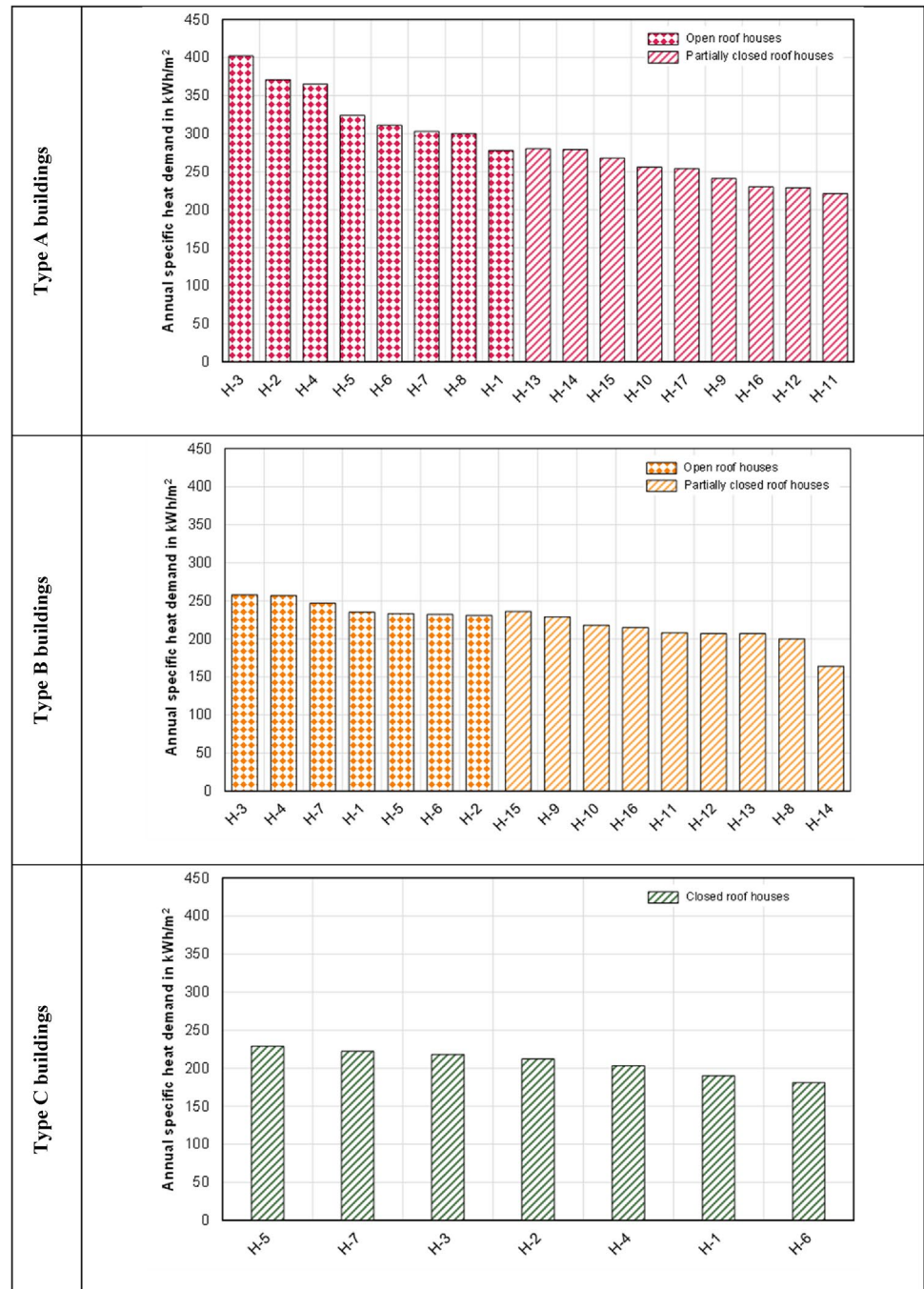


Table 3 Estimation of the calorific value for the validation model

Fuel type	Net calorific values (kWh/kg)	Density	Unit	Source
Coal	6.31	1000	kg/ton	[23]
Firewood	4.75	450	kg/m ³	[24]
Cow-dung	4.54	1000	Kg/ton	[25]

the literature review) and floor area of each house which is presented in Table 3.

Together with that the heating technologies, the thermal efficiency of three types of stoves (Stove placed in the corner, Stove positioned between two walls, and Stove with a water pipe system) were obtained from the report by the World Bank group. It mentioned the various stove efficiency used in Kyrgyzstan ranges between 30 and 40% [26]. The collected data from on-site allow us to calculate the actual heat demand consumption with the calorific

value of the heating fuel households used. This analytic model was used to calculate the actual heat demand of the houses. Later, this result was compared with the simulated results to check the accuracy of the simulation.

It can be seen from Fig. 14 that the average error in the simulation load profile was approximately 10% compared to the actual heat demand based on the heating fuel consumption. The simulation models in EnergyPlus were closely designed for the actual houses. As a result, the error observed in the validation model was negligible. The validation model clearly demonstrates the high degree of accuracy of the simulation model. Also, the identified energy use through the simulation model provides real energy consumption based on the developed typologies.

The existence of minor errors can be explained and affected by the following factors.

Fuel consumption The households were asked to provide information on their heating fuel consumption during the heating period. The households provide information about that based on what they spend/buy. However, there is no exact measure available that provides data on accurate heating fuel consumption. So, this might be one of the reasons for the minor error in the validation model.

Fuel quality Another important factor is fuel quality. The majority of the time, rural households receive low-quality/ loose coal. Households use self-prepared cow-dung to initialise house heating. The calorific value calculated was a generalised number for the heating fuels used for space heating (i.e., coal, cow-dung and firewood). The lack of accurate information about the calorific value of the heating fuels due to fuel quality, the minor error might occur.

Stove efficiency and heating set point Most of all households used the traditional heating stove for house heating which they bought from the local market. There is no documentation / technical information available about stove

efficiency as they are manufactured by the local craftsman. Hence, stove efficiency is subject to vary from household to household. Another aspect is heating set point/ level of thermal comfort. Most households start feeding heating fuel to the stove when they feel cold inside the house. There is no measure available that allows setting the heating temperature of the house. The manual fuel-feeding procedure often consumes extra fuel. Such factors do not allow for a precise calculation of the heating fuel consumption and might cause an error while validation.

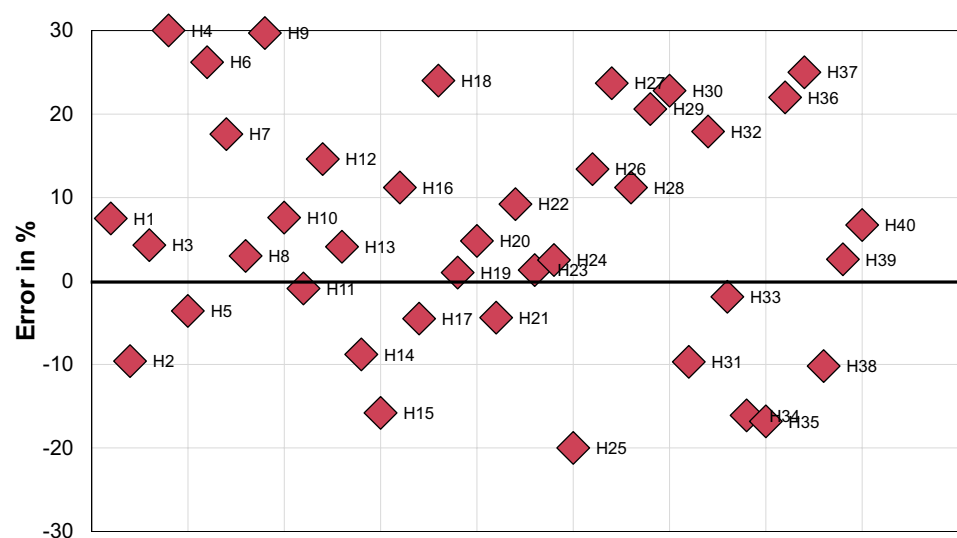
Heating area Most of the time to limit the heating fuel expenditure, households try to limit the heating area by closing the doors of other rooms. Sometimes they only heat 60% of the house (2 to 3 rooms out of 5). Even though, based on the questions asked during the household survey about the number of heating rooms/heating floor area during the heating season, the simulation load profile was adjusted accordingly. However, there was no constant pattern was identified throughout the season. Sometimes, if guests are coming, one more room will be counted for space heating. Hence, it was difficult to calculate the exact heating area of different houses. This might cause an error in the results.

5 Discussion

5.1 Novel outcome of the presented work

The developed building typologies and associated heat demand information not only contribute to the knowledge about building construction techniques but also to identifying other key information about Kyrgyz buildings to international readers. Summing up, the novel energy-based residential building typologies within the presented

Fig. 14 Graphical representation of the error while comparing the simulation results vs actual heat demand based on the heating fuel consumption



work provide comprehensive information about Kyrgyz buildings such as building materials, construction year, heating technologies, reported heating period, condition of building envelope etc. to understand energy use pattern of rural Kyrgyz buildings.

To summarise the detailed and accurate result, Fig. 15 represents the range of heat demand based on developed typologies. It was observed that the roof condition makes significant difference in the heat demand consumption. It was found that the heat demand of closed-roof houses was approximately 20% less compared to that of open-roof houses. To aid in categorizing the heat demand of Kyrgyz houses based on different indicators, the summarised

results were classified into two categories based on the construction of the house—open roof and closed roof.

To summarise and answer the research question raised within the presented article, Table 4 demonstrates a comprehensive summary of the different building typologies that have been developed. In addition, it provides deeper information about each building type, such as its construction period, building materials used, estimated energy use, length of the heating period, and the type of heating system installed. This information is important because it allows the reader to gain a better understanding of the characteristics of each building type and how they impact energy consumption. The estimated energy use

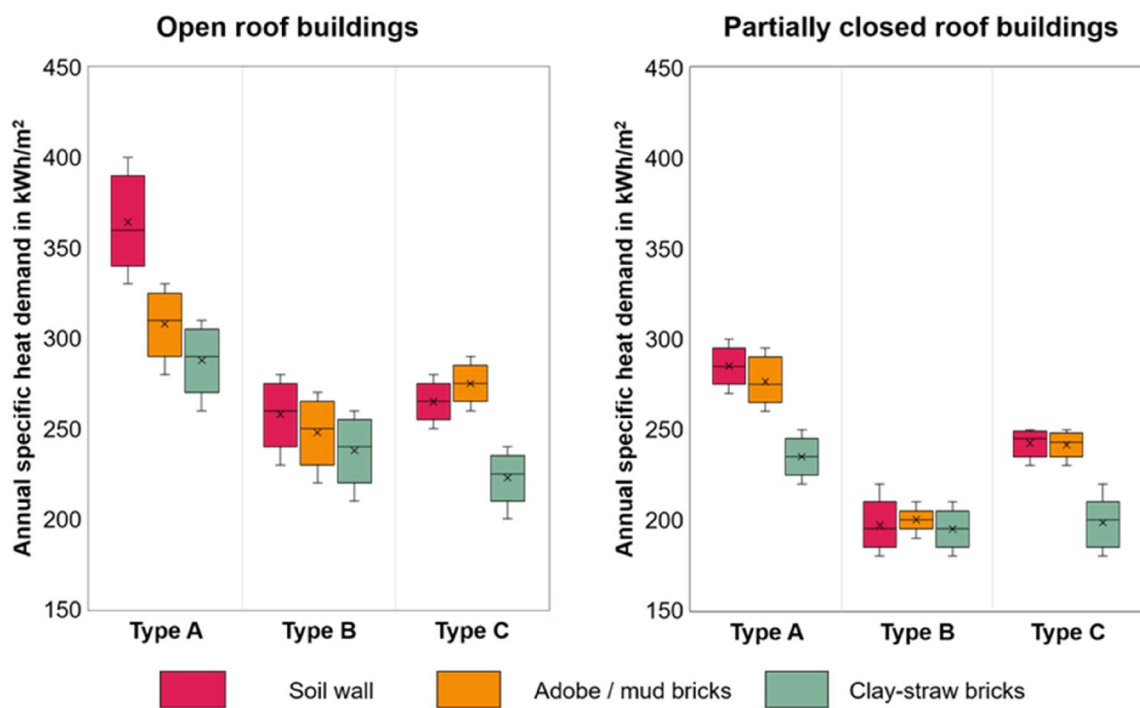





Fig. 15 Comprehensive overview of heat demand based on building materials and condition

Table 4 Estimation of the thermal efficiency of the heating stove for validation model based on [26]

Stove type used for space heating in houses	Stove placed in the corner	Stove positioned between two walls	Stove with a water pipe system
Visual impression of the stove			
Estimated average thermal efficiency	15%	30%	40%

and length of the heating period for each building type are based on the validated simulation described earlier.

Overall, Table 5 is valuable scientific novel information that presents important information about building typologies and their associated energy consumption. It is based on reliable data and can inform energy-efficient building design and decision-making. Researchers, architects, and policymakers may use this classification to better understand the energy consumption patterns of Kyrgyz homes and to identify key indicators that contribute to variations in heat demand.





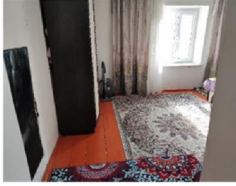
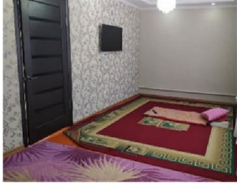
5.2 Directions for future research

Although the sample size for this study was limited to 40 out of a total of 234 houses in the Ak-Tal community, the methodology outlined here is intended to develop generalized building typologies. The necessary information was gathered from household surveys, and engineering assumptions were made as needed. To validate the simulated heat demand profiles, a validation model

was constructed using actual heating fuel consumption data from households. Nevertheless, future work could explore the inclusion of broader statistical data on the country’s building stock at a national level. Additionally, on-site measurements, such as recording indoor air temperatures, could enhance the accuracy of building energy performance assessments. As discussed in the research article, building energy efficiency is a critical factor in decarbonization efforts [27, 28]. However, the absence of suitable strategies and local knowledge poses a significant barrier to implementing building energy efficiency measures. Some of the future scope of the presented work is listed below.

- **Expanded Data Collection:** Conduct a comprehensive data collection effort encompassing a larger sample size and a more extensive geographical area within rural Kyrgyzstan/Central Asia. This would provide a more representative dataset for building energy modeling and typology development.

Table 5 Detailed overview of energy-based residential building typologies for rural Kyrgyzstan

	Type A Old constructed buildings	Type B Newly constructed buildings	Type C Old but renovated buildings
Outdoor view			
Indoor view			
Construction Period	Before 1990 (Between 1960 -1990)	After 1991 (Between 1991 - 2020)	Before 1990 but renovated in last 10 years
Typical characteristics	Earthen floor and walls with mostly open / partially closed roof	Mostly concrete floor with earthen walls with partially closed roof	Old but renovated buildings with improved façade design
Predominant building material	Adobe, clay-straw bricks, soil walls, clay, lime	Raw bricks, spruce wood, insulation material, decorative wall plaster	Gypsum plasterboard ceilings, putty of walls and ceiling, decorative wall
Condition of windows	Old and cracky wooden framed windows	Combination of wooden windows and plastic framed windows	Newly installed plastic framed windows
Reported heating period	7 to 8 months	6 to 7 months	5 to 6 months
Type of heating system	Stove placed in the corner (traditional stoves) or stove positioned between two walls	Stove placed in the corner (traditional stoves) or stove positioned between two walls	Stove positioned between two walls or radiator heat distribution system

- **Integration of Climate Data:** Incorporate climate change data and long-term climate projections into the analysis to assess the impact of changing weather patterns on energy demand in rural Kyrgyzstan/Central Asian buildings.
- **Energy Retrofit Strategies:** Develop specific energy retrofit strategies tailored to rural Kyrgyzstan/Central Asian buildings based on the newly developed typologies. Explore cost-effective measures that can be implemented to improve energy efficiency while addressing the unique challenges of the region.

6 Conclusion

Over 80% of rural buildings in Central Asia are uninsulated, aged, and constructed without proper building construction techniques. This leads to exceptionally high domestic heat energy consumption, especially in the cold climate of Kyrgyzstan. The present study offers a robust methodology for assessing the energy performance of these unique buildings through the development of residential building typologies, filling a significant research gap. As mentioned in the literature review, there was no scientific information available regarding energy-based residential building typologies. These typologies, derived from a combination of qualitative and quantitative household interviews, reveal energy demands. The result identified that Type A buildings, which are old-constructed buildings (before 1990), have energy demand ranging between 250 and 400 kWh/m², while Type B buildings (newly constructed buildings after 1991) have energy demand ranging between 150 and 260 kWh/m². Type C buildings (old but renovated buildings) have heat demand ranging between 170 and 210 kWh/m². These results underscore the substantial energy demands and highlight the potential for improving building energy efficiency. It is imperative that strategic measures for enhancing building energy efficiency are promptly implemented to decarbonize the building sector in Kyrgyzstan and Central Asia. This article serves as a foundational resource, offering insights into the energy performance of various building types for decision-makers, international readers, and researchers. In essence, this work makes a significant contribution to the field of energy planning by introducing an innovative method for assessing energy demand and informing energy planning strategies in rural areas.

Acknowledgements The work presented in this paper was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the CLIENT II funding programme International Partnerships for Sustainable Innovations under the project “ÖkoFlussPlan” (Project ID 01LZ1802A-F). The overall aim of

ÖkoFlussPlan is to preserve the alluvial forests along the Naryn river and to implement sustainable energy solutions for the local population. We also acknowledge support by the Open Access Publication Fund of Technische Hochschule Ingolstadt (THI).

Author contributions Conceptualization, K.M., W.Z.; methodology, K.M.; resources, K.M.; writing—original draft preparation, K.M.; writing—review and editing, K.M., W.Z.; visualization, K.M.; supervision, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. This study was supported by Bundesministerium für Bildung und Forschung, 01LZ1802A-F, 01LZ1802A-F.

Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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