# A Parametric Study on the Feasibility of Solar-thermal Space Heating and Hot Water Preparation under Cold Climates in Central Asian Rural Areas

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### Abstract

A large part of the Kyrgyz territory is covered by mountain ranges which result in extremely cold winter periods. The cold climatic conditions of Kyrgyzstan define heating as an essential need for Kyrgyz people. The majority of the residential buildings are constructed with poor thermal insulation or none at all, which yields high energy consumption in buildings to maintain thermal comfort. Especially in rural households, the heat demand is usually covered by solid fuels (i.e. wood, branches, coal and other solid fuels) burned in traditional stoves / boilers. The intensive use of solid fuels contributes to indoor and outdoor air pollution. Hence, there is a substantial need to provide sustainable and adequate heating services for residential buildings, particularly for the rural population. In response to this, the presented research article describes an investigation of solar resources to support space heating and domestic hot water preparation for single-family homes in rural Kyrgyzstan. Besides that, it identifies the thermal performance of typical single-family houses by considering local boundary conditions such as cold climate, high-altitude and routine behavior of the inhabitants. The determination of fuel savings by implementing solar-thermal domestic heating systems helps to explain the positive impacts on the environment. The investigation shows a significant solar-thermal energy potential available for domestic space heating and hot water preparation in Kyrgyzstan.

*Keywords: cold climate, building, solar-thermal energy, space heating, domestic hot water*

## 1. Introduction

The Kyrgyz Republic (Kyrgyzstan) is the former Soviet Union country located along the eastern edge of Central Asia, surrounded by Kazakhstan on the north, Uzbekistan on the west and southwest, Tajikistan on the southwest and China on the east (Fig. 1). It is a landlocked country with a population of 6.3 million people. The majority of the Kyrgyz population (66 %) lives in rural areas; in the foothills and mountain areas (NSC, 2018b). The Tien Shan mountain range occupies more than 85 % of the Kyrgyz territory and almost 90 % of the Kyrgyz territory is located 1,500 meters above sea level (NSC, 2018b).

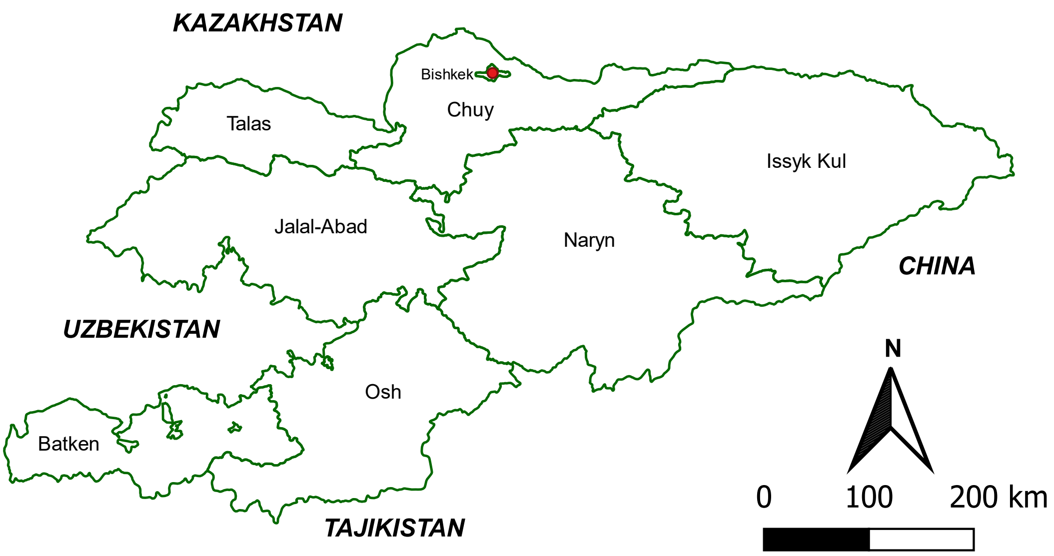


**Fig. 1 Regional map of Kyrgyzstan**


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A large part of the Kyrgyz territory is covered by mountain ranges with extremely cold winters with the temperatures ranging between about -4 °C to -6 °C in the lowlands and -25 °C to -30 °C in the mountainous valleys (Bergström and Johannessen, 2014). The cold climate is responsible for the long heating period of about six to nine months in the country. Hence, domestic heating is an essential need for the Kyrgyz population. The main three climatic zones of Kyrgyzstan are listed in Tab. 1 and are characterized by their approximate length of a heating season.

**Tab. 1 Climatic zones of Kyrgyzstan (data according to Balabanyan (2015))**

| Region of Kyrgyzstan | Average outdoor air temperature during winter | Heating season length [days] | Heating Degree Days |
|---|---|---|---|
| **Osh and Jalalabat** | +1.4 ºC | 135 | 2,240 |
| **Bishkek and Talas, Kara-Balta, Tokmok and cities in the Chui valley** | -1.0 ºC | 160 | 3,040 |
| **Naryn province, south-eastern areas of Issyk-Kul province** | -6.9 ºC | 197 | 4,905 |

The rural settlements in Kyrgyzstan are situated far away from major energy production centers and main economic centers, therefore they are less likely to have access to communal services such as connection to a district heating system, piped water into dwelling and sewage system. Further to this, most of the residential buildings in Kyrgyzstan were constructed during the Soviet era. Typical village houses in Kyrgyzstan are either built with poor insulation or even completely without insulation (Haab, 2017). Hence, residential buildings require a considerable amount of energy for space heating. Commonly, the high domestic heat demand is usually covered by solid fuels. Due to the lack of energy supply, the rural Kyrgyz population is forced to extract the energy they require from their surrounding environment. The cold weather conditions yield higher fuel consumption to meet domestic heat demand in rural areas of Kyrgyzstan.

The heavy reliance on natural resources by local people makes Kyrgyzstan most vulnerable to climate change among Central Asian regions (UNICEF, 2017). Furthermore, overuse of non-sustainable solid fuels is not favorable from both a health and an environmental point of view. On the other hand, the country has significant untapped renewable energy resources (UNDP, 2014). Therefore, this research paper aims to investigate the potential of the various renewable resources as well as how to meet the energy demand for domestic space heating and domestic hot water preparation of single-family houses in rural Kyrgyzstan with the available renewable energy resources.

## 2. Energy landscape of Kyrgyzstan

### 2.1 Current energy situation

The long-range of mountains results in a great number of glaciers and permanent snow in the country. Thus, abundant hydro resources are a keystone profile of Kyrgyzstan. The enormous water resources are used for 80 % of the total electrical power production by different small hydropower plants in Kyrgyzstan (Gassner et al., 2017). Access to electricity through the national grid is nearly universal in Kyrgyzstan, covering 99.8 % of rural and urban households (Gassner et al., 2017). The price of grid-supplied electricity in Kyrgyzstan is approximately 0.01 USD / kWh, which is the lowest electricity price in Central Asia (Gassner et al., 2017).

However, electricity is not a reliable source of energy for heating and is not preferred by the rural population. During winter, the river flow decreases, leading to reduced power production. The users experience frequent interruptions in the supply of electricity as well as fluctuations in voltage because of reduced power production in winter (FAO, 2016; IEC, 2018). Low-income, rural and mountainous households reportedly experience interruptions in electricity services weekly (FAO, 2016). Many rural households, especially in mountainous areas, do not have a permanent source of income because job opportunities are scarce. To increase their energy security, villagers collect heating fuel or purchase and store it whenever they have the financial capacity (Bakashova et al., 2013).

To survive with inconsistent energy supply as well as poverty, rural communities often switch to solid fuels to maintain thermal comfort of their houses. Access to the district heating (DH) networks is limited to urban areas, but even here they supply heat to only about 19 % of the urban population (Balabanyan, 2015). Close to 73 % of rural households are intensively using non-sustainable biomass or coal burned in traditional stoves / boilers for space heating (Balabanyan, 2015).

Rural households use a variety of solid fuels to meet domestic heat demand. Most rural families prefer to use coal or wood and less frequently animal dung. The on-site household survey revealed that during the heating period (October to March), a typical rural Kyrgyz household (with a floor area of ~ 100 $m^2$) consumes 2 to 5 tonnes of coal, 1.5 to 3$m^3$ of firewood and 1 to 2 truck of cow dung to maintain the thermal comfort in the house. People fulfil their primary need for warmth and this induces overuse of firewood, which is one of the major reasons for deforestation. Additionally, non-sustainable solid fuel use contributes to indoor and outdoor air pollution in Kyrgyzstan (World Bank and Factfish, 2015a, 2015b).

2.2 Renewable energy in Kyrgyzstan

Among various renewable energy resources, only hydro energy plays a significant role in the Kyrgyz energy sector. Besides the abundant hydro resources, Kyrgyzstan is blessed with good potential of solar, wind and biomass energy (UNDP, 2014). It is estimated that the country's total renewable energy potential of approximately 270 GW can replace up to 51 % of energy consumption in the country (Asian Development Bank, 2016). Due to the low and non-cost-effective-electricity tariffs and the strength of hydropower, other renewable energy sources are mainly untapped in Kyrgyzstan. Tab. 2 captures the estimated technical potential of renewable energy sources in the Kyrgyz Republic (UNDP, 2014).

**Tab. 2 Technical potential of renewable energy (RE) sources in Kyrgyzstan (data according to UNDP (2014))**

| Type | Solar PV | Wind | Small hydro | Biomass |
|---|---|---|---|---|
| Technical Potential for Installed RE Capacity in MW | 267,000 | 1,500 | 1,800 | 200 |
| Installed renewable electricity capacity 2012 in MW | 0 | 0 | 41.4 | 0 |

Kyrgyzstan is located in the Northern hemisphere between 39° and 43° latitude. Therefore, the high-altitude characteristic is responsible for more than 300 solar days in a year (Kampakis, 2015). The sunshine duration for Kyrgyzstan is between 2,100 to 2,900 hours annually (Kampakis, 2015; Baybagyshov and Degembaeva, 2019). As the altitude of the country is not uniform, the availability of solar irradiation deviates according to the individual location of the region. Though, the annual average solar irradiation of the country ranges between 1,500-1,600 kWh/$m^2$, which is almost 60 % higher as compared to Germany (World Bank, 2017). Fig. 2 illustrates the global horizontal irradiation of the Kyrgyz Republic. Nevertheless, the utilization of solar energy in Kyrgyzstan is barely developed.

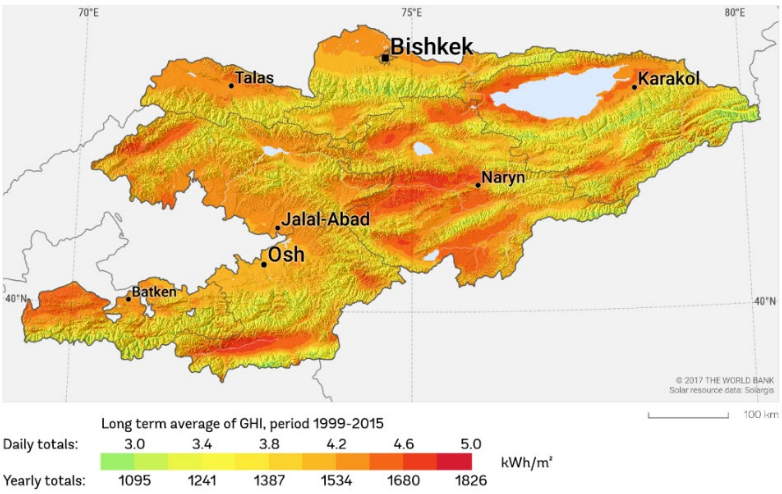



**Fig. 2 Global Horizontal Irradiation of Kyrgyzstan (World Bank, 2017)**

Out of the other available untapped renewable energy resources, solar energy is considered as one of the most promising energy sources. Kelpšaitė et al. (2018) draw attention to the usage of solar photovoltaic (PV) and mentioned that solar PV is more suitable for the public sector or to install mini-grid power plants. Most Kyrgyz households are connected to the national grid. Thus, the application of photovoltaic energy is an option for the service sector where PV panels could be used in public and commercial buildings to reduce the burden on the national grid. Kyrgyzstan has also drawn on its rich resources of silicon to develop PV manufacturing units. To date, solar power deployment in Kyrgyzstan has taken place either in the form of pilot projects or mini off-grid installations.

The high-altitude characteristic, significant solar irradiation and abundant sunshine hours also underline the potential of solar-thermal energy which can be utilized for sustainable heat energy supply (Abidov et al., 2020). However, there are very limited studies available that focus on solar thermal assisted heat supply systems and their usage in Kyrgyzstan. The technical potential and feasibility of a solar-thermal system for the domestic space heating system and domestic hot water preparation remain unclear for the rural regions of Kyrgyzstan. Hence, untapped solar thermal energy is considered in the presented article to provide a sustainable heat supply for domestic space heating and hot water preparation. Naryn, a rural region of Kyrgyzstan is chosen as a location for feasibility study.

## 3. Energy demand modelling

To integrate solar thermal energy for a single-family house heating system in Naryn (Kyrgyzstan), it is necessary to identify an annual heat load of a typical rural house. It is also necessary to identify the characteristics of rural Kyrgyz houses in order to describe the thermal operation of a single-family house.

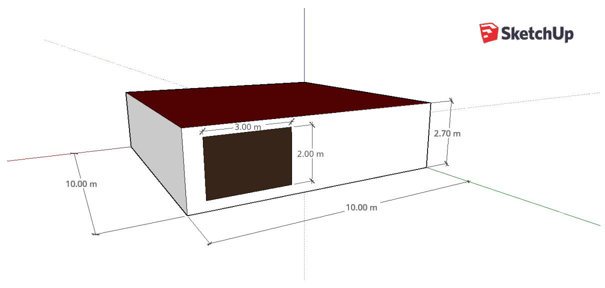
### 3.1 Profile of rural Kyrgyz houses

There are approximately 1.8 million dwellings in Kyrgyzstan. Due to the higher population in rural areas, the number of houses is greater there than in urban areas (NSC, 2018a). Most rural houses are self-built and therefore do not use advanced construction materials with good insulating qualities (Haab, 2017). Because of the self-build construction process, building codes are seldom considered while constructing rural houses. Fig. 3 represents typical residential buildings in rural Kyrgyzstan.

**Fig. 3 Typical rural Kyrgyz houses with natural walls and open gable roof**

The field survey indicates that typical rural houses are built with clay and straw or adobe, which are commonly traditional building construction materials in the Kyrgyz countryside. The self-made bricks for building walls are formed by a mixture of clay and straw. Kyrgyz households are generally large, with more than four people on average and an average living area of 90 $m^2$ – 100 $m^2$. The majority of rural households were built in the Soviet era. The age of the residential buildings, poor housing conditions and the absence of proper thermal insulation result in high heat demand and low thermal comfort in Kyrgyz houses. To save money on heating fuels, rural households usually occupy only one room for heating and close down the rest of the house in winter, which results in indoor air pollution and is responsible for health issues (Balabanyan, 2015).

To determine the annual space heat demand of a rural Kyrgyz house, a building model was developed in *EnergyPlus* (NREL, 2019). *EnergyPlus* calculated the required thermal load of the house by calculating the heat losses through the building envelope considering the local climate. The general building information and building sketch are shown in Fig. 4.




| | |
|---|---|
| Living area | 100 m² |
| Building orientation | North |
| Building location | Naryn, Kyrgyzstan |
| Number of thermal zones | 1 (single zone) |
| Number of windows | 2 (East and West Wall) |
| Dimensions of window | 6 m² (3m x 2m) |
| People occupancy | 4 people |
| Heating set point | 20 °C |
| Lighting level | 1,000 Watt |

**Fig. 4 Building description**

Due to a lack of information about building typology and building codes in Kyrgyzstan, the building model was developed from data found in the literature study. The construction of the opaque elements (walls, floor, and roof) is described in Tab. 3.

**Tab. 3 Thermal properties of building envelope (data according to (UNECE, 2010; Botpaev et al., 2013; Haab, 2017))**

| Assembly | Layer | Thickness [m] | Density [kg/m³] | Conductivity [W/(mK)] | Capacity [kJ/(kgK)] | U-value [W/(m²K)] |
|---|---|---|---|---|---|---|
| **Celling and Roof** | Roof tile | 0.02 | 2,200 | 0.96 | 0.92 | 1.6 |
| | Plywood | 0.035 | 300 | 0.081 | 2.50 | |
| **External walls** | Plaster outside | 0.03 | 1,800 | 0.76 | 0.84 | 1.1 |
| | Brick | 0.38 | 1,600 | 0.58 | 0.84 | |
| | Plaster inside | 0.03 | 1,800 | 0.76 | 0.84 | |
| **Floor** | Pinewood | 0.03 | 600 | 0.13 | 1.70 | 1.7 |
| | Plaster | 0.05 | 1,800 | 0.76 | 0.84 | |
| | Concrete slab | 0.22 | 2,500 | 1.92 | 1.13 | |
| **Window** | Glass | 0.006 | - | 0.90 | - | 3.6 |
| | Air | 0.003 | - | - | - | |
| | Glass | 0.006 | - | 0.90 | - | |

The standard schedule of house occupancy and lighting for a single-family house was adopted from the *EnergyPlus* dataset to consider internal gain by the inhabitants and lighting (NREL, 2019). Tab. 4 describes the occupancy and house lighting profile as fractions of present persons.

**Tab. 4 Daily occupancy profile and daily electrical gains in a fraction of present persons (data according to NREL (2019))**

| Time | Until 6:00 | Until 7:00 | Until 8:00 | Until 12:00 | Until 13:00 | Until 16:00 | Until 17:00 | Until 18:00 | Until 24:00 |
|---|---|---|---|---|---|---|---|---|---|
| **Occupancy** | 1 | 0.1 | 0.5 | 1 | 0.5 | 1 | 0.5 | 0.1 | 1 |
| **Lighting** | 0.05 | 0.2 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0.05 |

3.2 Heat demand for space heating and domestic hot water

In order to maintain 20 °C in the living area of the described rural Naryn house, the annual heat demand was determined in *EnergyPlus*. The obtained annual specific heat demand by simulation of a single-family house in rural Kyrgyzstan for space heating is 327.19 kWh/m$^2$. Fig. 5 represents the detailed space heating demand profile of the reference building (simulation results).

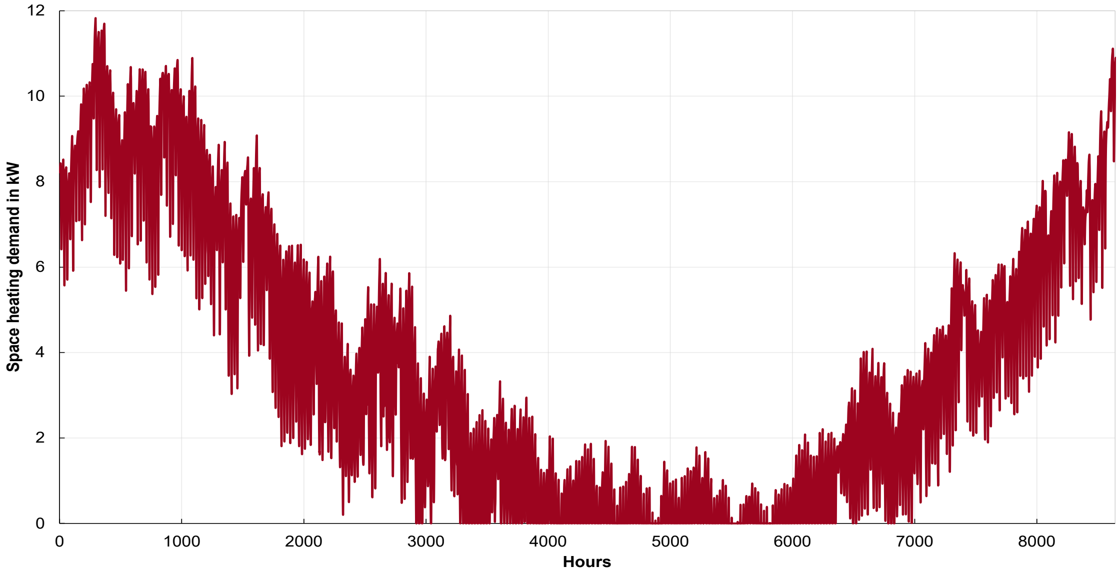



**Fig. 5 Annual space heating load Q_SH of the reference building**

To maintain thermal comfort throughout the heating season, a considerable amount of energy is required for space heating, since the building is uninsulated as well as Naryn region holds the coldest winter among Kyrgyz regions. However, the annual building energy consumption for heating in Kyrgyzstan (and other Central Asian countries) is at 240-360 kWh/m$^2$, which is more than two times higher than average European levels (100-120 kWh/m$^2$ (Bergström and Johannessen, 2014; Kerimray et al., 2017)) due to its climatic patterns.

Despite the abundance of available hydro resources, the water supply structure is not yet fully developed in Kyrgyzstan. Hence, only 15 % of rural households have a connection with piped water. As a result, only 4 % of rural homes have an indoor shower room (FAO, 2016). Therefore, it is difficult to estimate domestic hot water consumption in a single-family rural house. To consider domestic hot water consumption in the investigation, the European tapping standard for domestic hot water demand (Load profile L) was considered for the simulation (EN 13203-2:2015). Fig. 6 represents the tapping cycle to consider the energy demand of domestic hot water preparation. The selected tapping cycle features 24 tappings (draw-offs) for various uses including shower, floor cleaning, household cleaning as well as dishwashing. To maintain a room ambient temperature of 20 °C throughout the heating season, a considerable amount of energy is required. On the other hand, the demand for DHW is constant over the year according to European tapping standard. The daily energy demand for domestic hot water is 11.65 kWh/d.

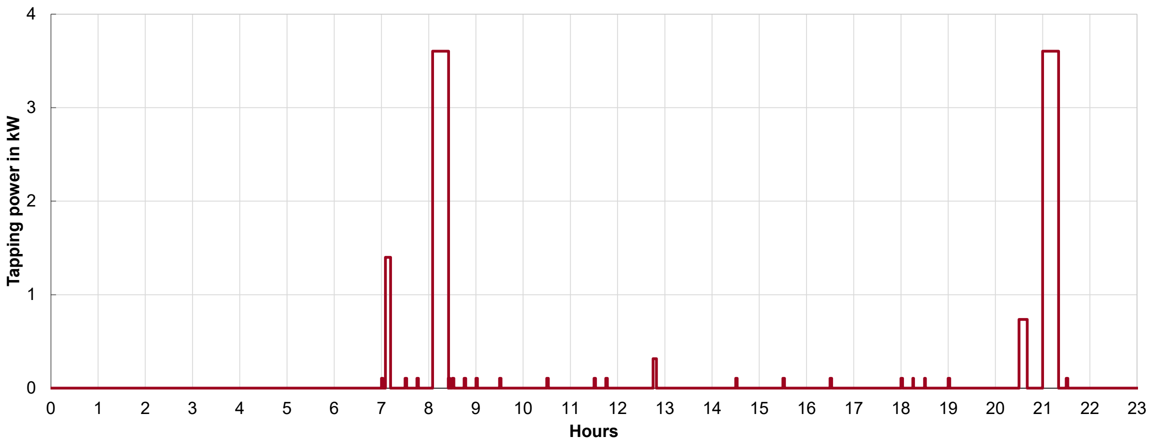



**Fig. 6 Daily constant Domestic Hot Water (DHW) consumption Q_DHW of the reference building (EN 13203-2:2015)**

## 4. Energy supply modeling

To meet the total heat load of the single-family house (space heating & domestic hot water), a suitable solar-thermal heat supply was developed in MATLAB / Simulink using the CARNOT toolbox (CARNOT Toolbox, 2010). The characteristic heat load profile of the house serves as an input to the system simulation model.

4.1 Energy supply on household level

For cold climatic regions (especially in winter), the sunlight period is short compared to summer. Furthermore, losses at the solar collector are higher (Mori and Kawamura, 2014). Therefore, without a large storage, a solar thermal system cannot produce enough energy to satisfy the total heat load of the house. Therefore, the solar thermal operated house heating system must be complemented by an auxiliary back-up heating system.

The key aim of the research paper is to identify the residential energy demand trend in case of space heating DHW demand by considering a worst-case scenario (old and uninsulated building in an extremely cold climate) in Kyrgyzstan and design a sufficiently suitable energy supply model to meet that demand. Fig. 7 represents the energy supply system (i.e. non-ideal / non-optimised solar combi system), which need to be properly designed / optimised before implementation. It has been noted that the reference house is uninsulated and therefore it requires more energy to maintain thermal comfort inside the house. Hence, the space heating demand has a high fraction of the total heat demand. While it was assumed that the house has daily constant hot water energy demand according to the European Tapping cycle which has a negligible portion of total heat demand.

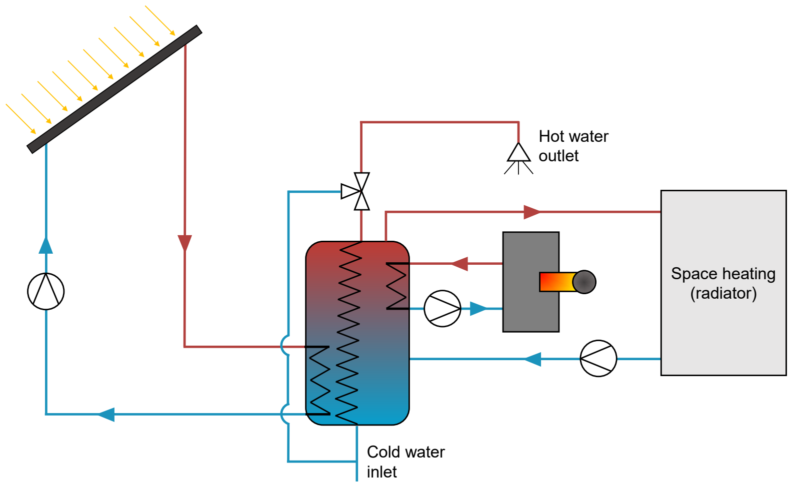



**Fig. 7 Energy system layout**

To assess the technical performance of solar-thermal system design options for heat supply of the single-family house, a parametric study was conducted. The size of the collector array and the size of the thermal storage tank was varied in a parametric study. The volume of storage tank has been varied with a step size of 100 liters from 100 l to 1,000 l. Similarly, the number of collectors (2m² per collector) has been increased in a step size of 2, from 2 to 20 collectors. Thus, for each combination of storage volume and number of collectors, simulations have been performed, in total 100 simulations. The key technical input parameters for the simulation model are mentioned in Tab. 5.

**Tab. 5 Key technical input parameters for the simulation model**

| | |
|---|---|
| Annual global solar irradiation of location | 1,694.5 kWh/m$^2$ |
| Average ambient temperature of location | 4.70 °C |
| Maximum ambient temperature | 32.3 °C |
| Minimum ambient temperature | -26.4 °C |
| Annual space heating demand Q_SH (radiator) | 32,719 kWh |
| Annual domestic hot water demand Q_DHW | 4,554 kWh |
| Area of solar-thermal collector | 2 m$^2$ |
| Initial temperature of collector | 20 °C |
| Collector tilt angle to horizontal | 30 ° |
| Capacity of auxiliary heating | 15 kW |

4.2 Simulation results and technical assessment of parametric study

To evaluate the system size options and identify the suitable combination of storage tank volume and solar collector area the solar heat production fraction was calculated by eq.1. The calculation of heat production ratio characterizes the contribution of solar energy for each combination which is presented in Fig. 8.

$$Heat\ production\ ratio\ r = \frac{Heat\ generation\ by\ solar\ collector\ array\ Q\_sol\ (kWh)}{Heat\ generation\ by\ auxiliary\ heater\ Q\_aux\ (kWh)} \qquad \text{eq.1}$$

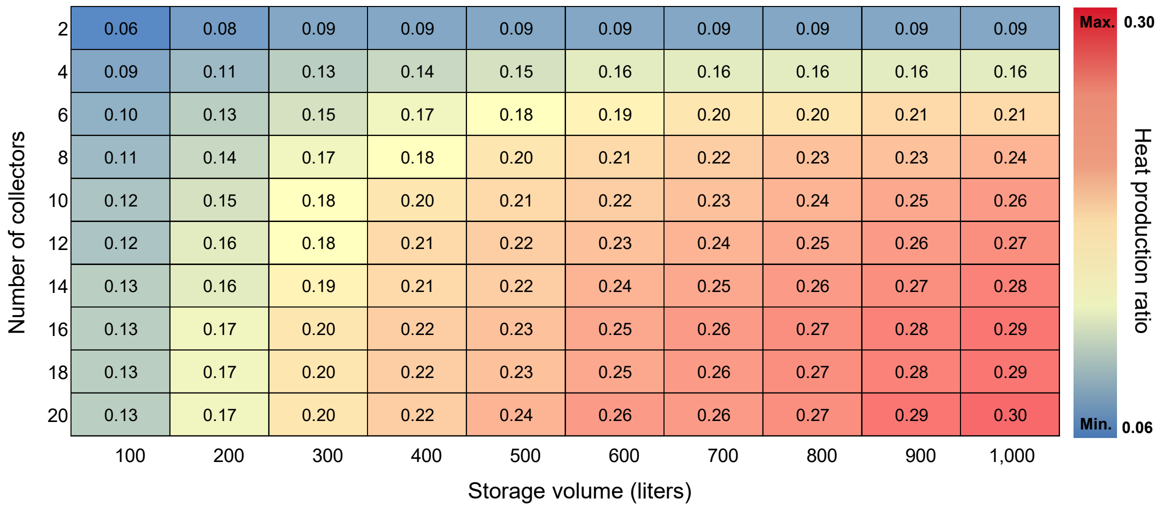



**Fig. 8 Heat production ratio by solar collector array**

It can be evaluated from Fig. 8 that the minimum heat production ratio by solar energy is 0.06 and a maximum heat production contribution by solar is 0.30, thus the evaluated system designs can contribute between 6 % to a maximum of 30 % total heat production. For suitable size selection, three cases were selected and analyzed:

- Case 1: 15 % heat production by solar
- Case 2: 20 % heat production by solar
- Case 3: 25 % heat production by solar

To evaluate the possible solutions for the selected three cases, several combinations of the number of solar collectors and respective storage volume are available which is presented in Fig. 9.

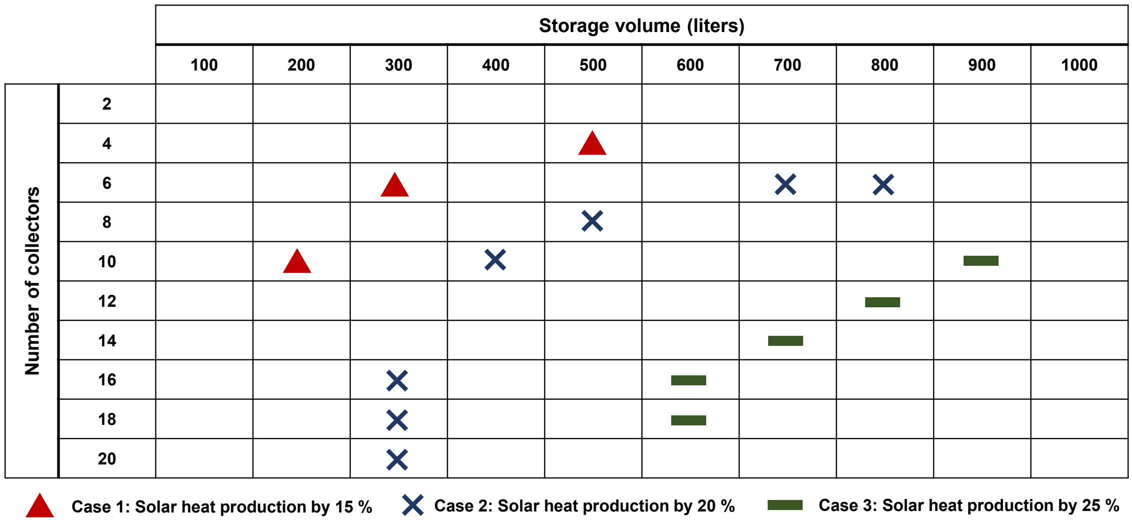



**Fig. 9 Characterization of selected three cases with respect to storage volume and number of collectors**

It can be examined from Fig. 9 for 15 %, 20 % and 25 % share of solar heat production, comparatively reliable options are available. Naturally, a larger storage tank contains a higher capacity to store more thermal energy. However, the increment of storage size results in higher heat loss through a storage tank (Li et al., 2015; Sarbu and

Sebarchievici, 2018). Generally, the volume of hot water storage systems ranges between 200 l to 500 l especially for single-family house energy supply systems (Çomaklı et al., 2012; Cygas and Tollazzi, 2014). Larger hot water storage tanks are commonly used for seasonal storage of solar thermal heat in combination with small district heating (Sarbu and Sebarchievici, 2018). In addition, greater collector area causes a high investment cost.

Therefore, in terms of reducing the usage of non-sustainable solid fuels for house heating, the parametric study results to select the energy system which can generate 20 % solar heat. It is examined from Fig. 9 that with the selection of moderate storage volume (500 l) and 8 solar thermal collectors, 20 % of solar heat production can be achieved, and Fig. 10 represented the detailed simulation results for that combination.

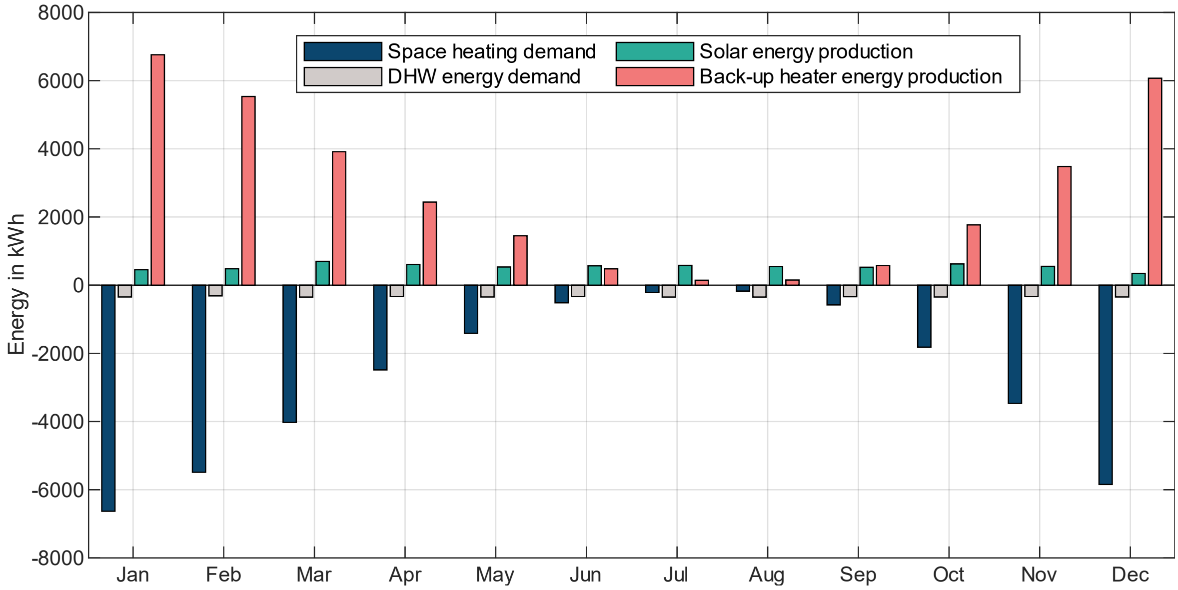



**Fig. 10 Monthly energy production and consumption**

To produce 20 % renewable heat, eight solar flat-plate collectors each with an area of two square meters are considered in the simulation system. The highest monthly energy production from solar is around 700 kWh in March and the lowest energy production is around 345 kWh in December (Fig. 10). As solar energy is not prominent and the production of solar energy could not meet the desired heat load for space heating and domestic hot water, auxiliary heating system works as a back-up heating system. To identify that energy-saving, a house heating energy system solely based on fossil fuel has been simulated. It is calculated that a 20 % contribution of solar heat production in the energy system helps to reduce around 6,000 kWh annual secondary energy demand generated by non-sustainable solid fuels.

## 5. Conclusion

The extremely cold winters of Kyrgyzstan are translated into high heat demand to maintain thermal comfort in the house. Especially in rural Kyrgyzstan, the high demand is typically covered by crude and inefficient heating systems that use non–sustainable solid fuels. The usage of such fuels is not favorable in terms of health and environmental concerns. Hence, there is a substantial need to provide sustainable and adequate heating services for residential buildings, particularly for the rural population. The presented research article deals with the identification of available solar-thermal resources to cover the energy demand for space heating and hot water preparation for a single-family house in rural Kyrgyzstan.

The presented research article offers a wide range of solar-thermal system sizes options by performing a parametric study by considering the different number of solar collectors and sizes of the thermal storage tank. The results indicate that the integration of 20 % solar heat production to the modeled house can be helpful to reduce around 6,000 kWh of heat energy annually, which is produced by non-sustainable solid fuels. The lack of information about rural building construction, Kyrgyz building code as well as occupant behavior, the presented research considered several assumptions for hot water consumption profile, a few building assemblies based on available literature. Further to this, the energy supply system was designed to evaluate the preliminary feasibility of the involvement of solar thermal collectors. The energy system should be optimised and improved as a future scope of research as this article adopted a non-ideal / non-optimised technical setup for the feasibility study.

The investigation identified that in reality, other than the cold climatic conditions of the country, the poor thermal insulation of houses is majorly responsible for high heat demand. Improved thermal insulation could have a significant positive effect on reducing overall heat energy consumption, living conditions and the indoor air temperature. Further to this, some of the major obstacles to use solar thermal-energy in Kyrgyzstan are lack of basic information, lack of skills / training to operate the energy system, as well as extreme poverty in rural Kyrgyzstan.

In general, the assessment shows that from a technical point of view, solar-thermal energy is a suitable solution for space heating and domestic hot water preparation under the given climatic and building infrastructure conditions. The presented information in the research articles reveals the technical potential of solar-thermal energy in Kyrgyzstan which opens the doors for investors to invest in the field of renewable heating and can bring solar-thermal energy in Kyrgyzstan.

## 6. Acknowledgments

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