Performance comparison of different types of solar thermal collectors on residential space heating demand in high-altitude cold climatic environment: A simulation-based study

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Abstract

On the one hand, high-altitude rural Kyrgyz houses have a high heat demand, especially due to the age of buildings and low temperatures in winter evoked by the cold climate. On the other hand, this continental climate results in a high amount of solar irradiation over the year which is ideal for the application of solar systems and in particular solar thermal systems for heat energy supply. This study investigates the performance of different types of solar thermal collectors by considering the challenges for a solar thermal system in the harsh climate of Kyrgyzstan such as three different flat plate collectors and two evacuated tube collectors. For in-depth assessment, a parametric study on appropriate collector types was performed which helps to select the potentially most techno-economically suitable combination of system components based on energy output, system security and economic feasibility. Unfortunately, under current circumstances, a solar thermal system is not economically feasible in rural Kyrgyzstan. The main two reasons are low energy prices for conventional heat sources and the lack of market for solar thermal applications.

Keywords: cold climate, solar thermal energy, solar thermal collector, high-altitude, domestic space heating, parametric study, techno-economic analysis

1. Introduction

1.1. The climatic situation of Kyrgyzstan

Kyrgyzstan is a former Soviet Union country situated in Central Asia and home to 6.5 million people (National Statistical Committee of the Kyrgyz Republic, 2020). The average altitude of the country is 2,800 m above sea level (CIA, 2021) which leads to cold climatic conditions. For example, in January the average temperature in Naryn, a city 2,000 m above sea level in central Kyrgyzstan, is -14 °C (Mehta et al., 2021). Depending on the region, this cold climate results in an extended winter period up to nine months. Because of the cold climate and extended heating season, domestic space heating is a key energy need for Kyrgyz people.

1.2. Theory and Context: Space Heating in rural Kyrgyzstan

Domestic space heating remains a key challenge for rural Kyrgyzstan where more than 65 % of the Kyrgyz population lives. The majority of the rural Kyrgyz building stock was built from earthen materials without proper building construction techniques during the Soviet era 30-50 years ago (Schweinichen et al., 2010; Mehta et al., 2020a). In addition, typical rural residential homes are one-story buildings built with poor or without insulation material. This results in a high heat flow rate out of the building (through the building envelope) which needs to be compensated by a heat energy supply equal to these losses to maintain the target temperature inside the building. These factors lead to a high domestic space heating demand in rural Kyrgyz households which is significantly higher compared to energy demand for cooking as well as for domestic hot water preparation. This high heat demand is usually covered by burning locally available non-sustainable solid fuels like coal, wood from neighboring forests, and dried cow dung from their livestock (Mehta et al., 2020a). District heating systems do not exist in rural areas, mainly due to too low heat density. Fig. 1 shows a typical rural Kyrgyz house and a traditional stove. Utilizing an excessive amount of solid fuels in low thermal efficient traditional stoves results in significant indoor and outdoor air pollution. Besides, the over usage of firewood leads to a negative impact on the riparian forests in Kyrgyzstan (Lauermann et al., 2020). Hence, there is a necessity to provide an approach that

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helps to reduce solid fuel consumption and deliver sustainable heat for high-altitude house heating. The own comparative assessment indicated that the annual global irradiation of Kyrgyzstan is 60 % higher than a location in Central Europe (Mehta et al., 2020b). Accordingly, the potential of heat generated from solar energy is proportionally higher, which can be used to supply Kyrgyz households with sustainable heat. However, most of the solar energy remains untapped due to the lack of technical knowledge and infrastructure.

Nevertheless, the existing systems (for example a 0.5 MW system for the district heating network in Bishkek (Solar District Heating (Ed.), 2018)) are located in cities and are often used in district heating networks.

Fig. 1: Typical rural residential house in Kyrgyzstan with an open-roof construction (left) as well as a traditional heating stove (right) which is used for cooking and heating up one or two rooms of the building

2. Research objective and methodology

There is a lack of research available that focuses on solar thermal assisted heat supply systems and their usage in Kyrgyzstan, in particular for single-family households which is the most common form of living in rural areas (Schweinichen et al., 2010). Additionally, there is a gap in research regarding suitable collector types, the performance evaluation of solar thermal collectors in high-altitude and the extreme winters of Kyrgyzstan. Considering the lack of a heating concept based on solar thermal energy for households, there is a need to analyze possible concepts. To fill the gap of knowledge, the presented article deals with untapped solar thermal energy to perform the comparative assessment on residential space heating demand of high-altitude single-family rural Kyrgyz houses. The flowchart (c.f. Fig. 2) shows the methodology of this paper to compare the different types of solar thermal collectors and identify the best suitable configuration to tackle this problem. In a first step, the heat demand of residential households in cold-climatic and high-altitude Kyrgyzstan is identified. This results in a heat

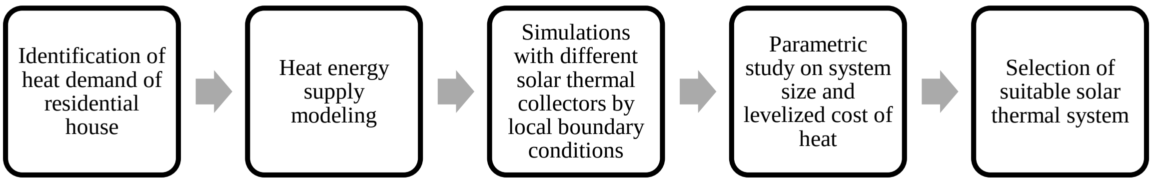

Fig. 2: Methodology to identify the suitable solar thermal system for a residential house in cold-climatic and high-altitude Kyrgyzstan

load profile which will be subsequently used to create a heat supply model in *Polysun* (Vela Solaris AG, 2021). A parametric study with different types of collectors and system sizes will be used to identify suitable system configurations. The aim is to identify the technical suitability as well as the economic practicability of the selected collector types. By varying the type of collector, the surface area of collectors and the size of storage tank within a reasonable range, an optimized system configuration will be examined. As an outcome, this research aims to deliver a technical blueprint for the most suitable solar thermal assisted heat energy supply system from an economic perspective in rural Kyrgyzstan.

3. Simulations with different solar thermal collectors according to local conditions

3.1. Determination of heat demand of residential house

To evaluate the performance of the various configurations of solar thermal collectors and their contribution to the overall domestic space heating demand, the heat demand for a typical rural Kyrgyz house was identified. The simulation study was performed in *Polysun* software (Vela Solaris AG, 2021).

As mentioned previously, most of the high-altitude rural Kyrgyz homes are aged and without any insulation. These measures yield high heat demand. Mehta et al. (2020a) calculated the annual specific heat demand by simulation of a single-family house in rural Kyrgyzstan for space heating. Depending on the exact configuration of the investigated houses, the annual specific heat demand was at least 300 kWh/m^2.

For the presented research, the heat demand of a building is determined by the balance of heat gains (i.e., solar gains and internal gains) and heat losses (i.e., heat losses through building envelope). As radiation from the sun enters the building through the windows the interior of the building heats up. Therefore, the window area on every surface of the building is important. Other sources are people or electric devices, as they emit a small amount of heat. The internal gains of the here used standardized building accumulate up to 4,000 kWh/a (i.e. 1,000 kWh per year and inhabitant). Losses of the building are made up of infiltration and ventilation (involuntary and voluntary exchange of the warm air inside the building with air from outside the building) as well as the losses through the envelope of the building. The losses through the envelope correspond to more than three-quarters of all losses and are in cold climatic zones during winter always higher than the gains. To maintain temperature inside of the building an additional heat source is needed to cover the difference between gains and losses.

Focusing on heat losses through the envelope, a few parameters are necessary to properly determine the losses (in brackets the values used in this study can be found):

- Heating set point of the building (20 °C during the day, 19 °C during night; see also Botpaev et al., 2011)
- Average outdoor temperature (weather profile provided from the integrated Meteonorm Webservice in *Polysun*)
- U-value of the building (calculation based on the proportional U-values and areas according to Mehta et al., 2020a and Botpaev et al., 2008: 1.2 W/m^{2}K for the whole building, in software *Polysun* there is no distinction between U-values of different building components)

The software *Polysun* provides hourly values (or even shorter intervals) for heat demand which is necessary to analyze the dynamic performance of the solar thermal system efficiency. The calculated hourly heat demand and the outdoor temperature are displayed in Fig. 3. In this figure domestic hot water demand (DHW) with around 1950 kWh/a is excluded because it is negligibly small compared to the demand for space heating. There is an inversely proportional correlation between the low temperatures during the winter months and the corresponding heat demand during these months. Due to the temperature difference, the losses through envelope are the main drivers for heat demand in this case. Correspondingly to the outdoor temperature, the heating period lasts at least from October to the beginning of May.

The location of the system is 41°24’47’’ N, 75°03’16’’ E in the Naryn region, Kyrgyzstan. The building size is 10 m x 10 m x 2.5 m. Window-to-wall area ratios are 6 % for the north, 13 % for the west, 25 % for the east, 25 % for the south. Using these parameters (including values for losses) results in a heat demand of 367 kWh/m^{2}a. Compared to German standards where according to Deutsche Energie-Agentur GmbH, 2016, 90 % of the houses have a lower heat demand, this is a high heat demand. To cover such high demand and always guarantee an availability of enough heat, it is necessary to combine a solar thermal system with another heat source like a boiler, stove, or heat pump, as these devices can provide energy independently from solar irradiation. Theoretically, seasonal storages for solar thermal systems can solve this problem. However, they are typically not affordable for the rural population as the necessary investments would be enormous (Yang et al., 2021).

Additionally, from this diagram (c.f. Fig. 3) the necessary size of the heat supply system can be derived. This is done by analyzing the peak energy demand over the whole year. In this case, the maximum power is just above 20 kW at around mid of January. As the reference system only uses one heat source, this supply unit should be sized in a way, that it can cover the total heat demand. This is necessary to avoid any deficits as they would lead to the lower temperature inside of the building which relates to less thermal comfort. But as "[…] oversizing does not influence the indoor thermal comfort, but [only] leads to increase of primary energy consumption […]" (Peeters et al., 2007), it may be advisable to select a boiler in the size range around 22 to 25 kW to guarantee to produce enough heat for the building.

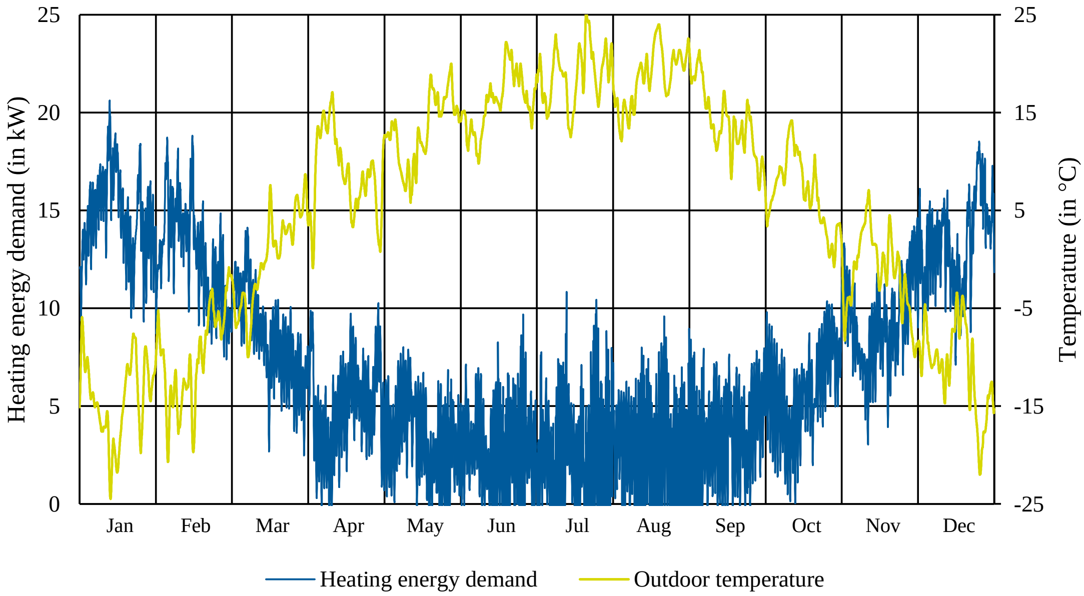

Fig. 3: Simulation results show a typical heat demand profile for the given continental climate conditions in the northern hemisphere (in this case: rural residential house in high-altitude Kyrgyzstan around 1,500 m above sea level which results in a heat demand of 367 kWh/m²a). The location of the system is 41°24'47'' N, 75°03'16'' E in the Naryn region, Kyrgyzstan.

3.2. Overview of different collector technologies

There are various types of collectors available to generate heat for space heating or DHW purposes. In this study, four different technologies are selected (c.f. Tab. 1). The goal is to identify the best-performing collector by selecting the system with the biggest potential in energy savings combined with acceptable economic feasibility. The following information provides a brief overview of the five selected cases (information from Sam, 2011; Kaltschmitt et al., 2014; Evangelisti et al., 2019; Ehrenwirth, 2021).

Case 1 is a simple unglazed flat plate collector. This type of collector is not insulated and does not have a glass cover at the front. They often consist of black plastic material and are used in low-temperature applications. According to Evangelisti et al. this collector has its best performance below a target temperature of 30 °C. Cases 2 and 3 are flat plate collectors (FPC) which are the most common collectors for solar thermal applications and especially DHW preparation as they are suited for target temperatures in the range of 20 to 80 °C (Sam, 2011). In comparison to the unglazed flat plate collectors, heat is trapped at the absorber due to insulation at the back and a front glass pane which allows reaching higher temperature levels.

The evacuated tube collectors (ETC) use additional insulation technologies to optimize heat flow. Case 4 and case 5 fall under this category of collectors as they both have vacuum chambers which increase the insulation of the fluid to the surroundings. So, less heat is lost. Consequently, this relates to a reduced aperture area. Case 5 uses heat pipes, a more complex technology. Within these pipes, a second trapped fluid is heated up. Due to the conditions, steam is generated which starts to circulate in the tube. This steam condenses when it gets in contact with the solar cycle fluid at the top of the collector. During this condensation, heat is conducted to the solar fluid.

Tab. 1: Comparison of collectors and their parameters used for this study based on *Polysun* catalogue/database (type of collector equals name form database; Vela Solaris AG, 2021)

	Case 1	Case 2	Case 3	Case 4	Case 5
Type of collector	Flat plate collector, unglazed	Flat plate collector, inexpensive	Flat plate collector, good quality (FPC)	Evacuated tube collector in u-shape (ETC)	Evacuated tube collector with heat pipe risers
Gross area in m² per collector	1.28	2	2	2	2.42
Aperture area in m² per collector	1.28	1.8	1.8	1.4	1.4
η_0	0.77	0.70	0.80	0.70	0.73
a_1 in W/(m²K)	13.13	4.00	3.50	2.10	1.45
a_2 in W/(m²K²)	0.85	0.03	0.02	0.01	0.02
Yield in kWh per m² gross area and year *	4	400	550	530	580
Costs in € per m² **	100 (Tackmann, 2019)	200 ***	300 (Ehrenwirth, 2021)	600 (Kloth, 2018)	800 ***

* = Yield is calculated by counting the heat energy available at a temperature level of 66 °C (65 °C target temperature for the distribution system and 1 °C cut-in difference necessary for controlling the system). The location of the system is 41°24'47'' N, 75°03'16'' E in the Naryn region, Kyrgyzstan.

** = The costs only include the price for the collector and the necessary components to mount them on the roof of a building (metal sheet roofing). Additional installations costs for storage tank and infrastructure are not part of this.

*** = Own estimations according to literature sources which often state a price range for one collector technology. Here, e.g., cases 2 and 3 are FPCs in two different price ranges according to their given performance parameters.

3.3. Simulation Model in Polysun

In the software *Polysun* (Vela Solaris AG, 2021) a model of the whole heating system was set up (c.f. Fig. 4). This software program helps to analyze the efficiency and performance of the system components. The model includes a building (1) according to the descriptions above in chapter 3.1, representing a heat demand profile. To fulfil this demand, a supply and distribution system is necessary (components 2 to 8). To heat up the building radiators with a constant fluid inlet temperature of 65 °C (2) are used which emit heat to the surrounded area (volume inside the building). This results in a return flow with lower temperature. To ensure that the temperature of the radiator holds its desired level, a mixer (3) is installed which controls the inlet flow. This component mixes the hot water from storage tank (6) with the colder water of the return flow to establish a constant fluid temperature at the inlet of the space heating system. This is necessary as the temperature in the top layer of the storage tank (6) is not constant as this depends on the top layer temperature of the storage tank and the productivity of the two heat generation units (7 and 8). The biggest share of the necessary heat is provided by a boiler (7) which is dimensioned (see also Ch. 3.1) in such a way that the system can be operated with the boiler only. This design allows comparing the heat supply system with a reference layout that does not include the application of solar thermal collectors. In this study, the heater can provide 25 kW for the fluid which is fed to the storage tank. The boiler is running in case the temperature in the upper third of the storage tank drops below the inlet temperature setting for the space heating system (2), in this case, 65 °C. Additionally, to provide DHW (5) the system includes a heat exchanger inside of the storage tank and a mixer to provide hot water at the set temperature of 50 °C for 100 liters/day equally distributed over the day.

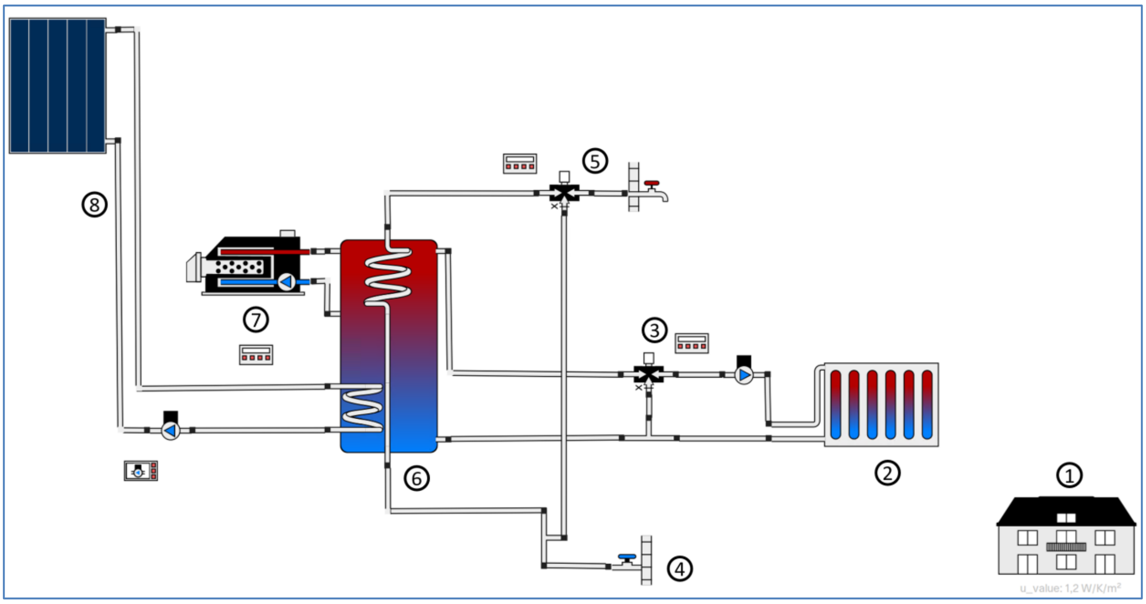

Fig. 4: System layout of the model used for simulations in this study. Main components are the building (1), heat distribution system (2), mixer for space heating (3), cold water source (4), domestic hot water system (5), storage tank (6), boiler/stove (7) and solar thermal system (8).

On the left side of the system layout, the solar thermal system (8), is displayed. A simple system configuration with a closed glycol-mixture loop with 40 % glycol and 60 % water together with a heat exchanger inside of the storage tank is used. Heat can be transported into the storage tank in case the collector temperature is higher than the layer temperature at the upper end of the internal heat exchanger. In the presented study, the modules of the solar thermal system are oriented to the south with a tilt angle of 45°.

Own evaluations showed an optimum yield of energy from the solar thermal system when using a tilt angle of a little bit more than 60°. However, according to own assessments, most of the roofs in the rural Kyrgyz region are less steep. This would require a special substructure for elevating the collectors. Then, the tilt angle can be increased compared to the roof angle. This measure would increase the heat output of the solar thermal system but will increase costs. Additionally, the complexity in planning the system will be increased, e.g. due to carefully planning the substructure's ability to resist wind and snow loads. Currently, no such detailed weather data for rural Kyrgyzstan is existing. This makes a case-by-case calculation necessary to guarantee to avoid any problems from the possible extra load on the roof.

The described model was used to perform different simulations of various collector configurations. This includes a parametric study where every case of collector type is selected and simulations with a number of collectors from 1 to 10 are performed. Collector yield and costs are compared in relation to the occupied surface.

4. Techno-economic assessment of parametric study

In a first step, the efficiency of the different solar thermal systems is analyzed. This includes an analysis of the heat production of the solar thermal system (see Fig. 5 left) and an evaluation of fuel consumption of the boiler (c.f. Fig. 5 right). In both diagrams, the green diamond represents the reference system. On the one hand, as this reference model does not have solar thermal included the heat production from this source is 0. On the other hand, this system has the highest fuel consumption with 52.1 MWh.

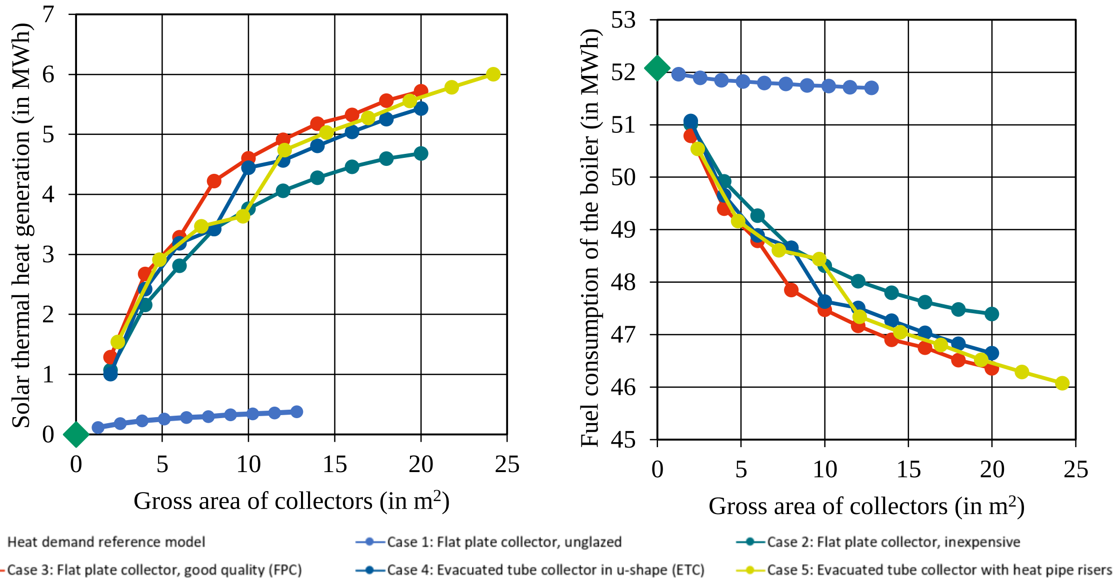

Fig. 5: Trend of solar thermal heat production (left) and the corresponding fuel consumption for different solar thermal system configurations (right)

In comparison with the reference system, the benefits of installing unglazed collectors (case 1) are negligible. The yield of the collector is insufficient as the necessary target temperature to feed the storage tank is only reached for a few hours during the year. This allows only for little savings in fuel consumption of around 300 kWh per year.

The other four collector types show a behavior which is similar among themselves as they all trend comparably. When increasing the system size, it can be recognized that due to the lower efficiency of inexpensive flat plate collectors the solar heat production per gross area of collectors is lower than using more efficient collectors. This result was expected.

The advantages of evacuated tube collectors (case 4 and case 5) are insignificant. The temperature levels required within the system are typical for a standard residential house and far below 80 °C. However, this is the temperature level ETCs are made for (Evangelisti et al., 2019). Additionally, it must be considered, that the solar thermal system feeds the storage tank in its lower third (c.f. Fig. 4). Typically, temperatures are low in the lower part of the storage tank due to layering processes inside the tank (Sterner and Stadler, 2016). So, filling the storage tank with higher temperature differences which is more often the case for ETCs can be less efficient due to circulation related from the mixing processes inside the storage tank. Another small contribution to a worse performance is higher standing losses due to higher temperatures for a longer period of time.

Nevertheless, all systems show a decrease in fuel consumption which is comparatively low to total demand, as even the best configurations can reduce fuel demand by only about 12 %. This is due to the higher heat demand during winter times where the solar thermal system is less effective, so the contribution to a reduction of heat demand is low. Demand for space heating during summer is negligible as temperatures don’t drop to levels below 15 °C for longer periods. DHW demand is nearly fully covered by solar thermal energy.

The inconsistent trend which is particularly evident for both ETCs can be explained by considering the settings for controlling the pump in the solar thermal loop. In this study, all simulations are performed with a flow rate of 40 l/h per m^2 aperture area. Consequently, when changing the gross area of collectors by varying the number of collectors also flow rate changes which again influences temperature level in the collectors and runtime of the system. All factors influence the solar thermal yield. In this study, increasing the gross area relates always to an increase in solar thermal yield (c.f. Fig. 5). The correlation between flow rate and solar thermal yield is more complex. Here for most system configuration the assumption of 40 l/h per m^2 is a suitable approximation to generate a maximum in solar yield. However, for specific system configurations, the ideal flow rate configuration differs from 40 l/h per m^2.

For instance, this situation can be identified when considering a serial system consisting of four ETCs with heat pipe risers (case 5). According to the value of 40 l/h per m^2 aperture area, this system configuration uses a flow rate of around 220 l/h. But when performing a simulation for the identical system with a slightly adjusted flow rate of 200 l/h, the system configuration can manage to provide around 250 kWh more solar yield (which equals around 7 % more yield compared to the system used in this study). Due to the lower flow rate, higher temperatures in the collector can be reached. Especially during summer times it is relevant as the storage tank is often charged and higher temperatures are necessary to transfer heat into the system.

Finding the best settings for each configuration needs to be investigated in further studies.

In a second step, an economic assessment is performed by considering the Levelized cost of heat for the different system configurations. The Levelized cost of heat (LCoH) is a parameter that assesses the costs of heat produced by the various (solar) thermal energy technologies (Ravi Kumar et al., 2021). The LCoH is calculated as following (adaption of calculation according to VDI 6002, 2014 as running costs are not considered here due to a small electricity demand of the system and the low electricity tariffs which sum up to less than 10 € per year):

$$\text{LCoH}\ \left(\text{in}\,\frac{\text{€-ct}}{\text{kWh}}\right) = \frac{[\text{Costs of collectors (in €)}+\text{Installation costs (in €)}]\times f_a}{\text{fuel savings compared to reference system (in kWh)}}\times 100\ \frac{\text{Ct}}{\text{€}} \qquad \text{(eq. 1)}$$

with annuity factor, fa = 6.72 % (considering system operation time of 20 years and capital market rate of 3 %).

The following bullet points will describe the parameters necessary to calculate the LOCH. An example using four collectors of case 3 (Flat plate collector, good quality according to collector name in *Polysun*) is included.

- <u>Costs of collectors</u>

  The prices for different types of collectors (cases) are stated in the Tab. 1. The price is given per gross collector area. This allows comparing the different cases.

  Example: Four collectors of case 3 are used. Specific costs for this collector are 300 €/m^2. As each collector is 2 m^2 in size, the total costs for collectors are

  $$\left(4\times 2\ \text{m}^2\times 300\ \frac{\text{€}}{\text{m}^2}\right)=2400\ \text{€}. \qquad \text{(eq. 2)}$$

- <u>Installation costs</u>

  For installation cost it is assumed that the general installation cost is 2,500 €. When installing a solar thermal system, a part of the installation costs is independent of system size. This includes planning the system, bringing material and workers to the construction site, implementing a storage tank. As this technology only barely exists in Kyrgyzstan, costs for installation are not available. So, assumptions are necessary for this context. The costs for the heat distribution system are not considered in this study.

  Additionally, a small portion of the costs is depending on system size. This includes mounting each collector on the roof and plumbing. So, costs of 75 €/m^2 of collector area are assumed for this process.

  The result for total installation costs equals values from literature (Kasper and Heidler, 2011; Kaltschmitt et al., 2014; Ehrenwirth, 2021).

  Example: The installation costs for the selected system is

  $$2{,}500\ \text{€}+\left(4\times 2\ \text{m}^2\times 75\ \frac{\text{€}}{\text{m}^2}\right)= 3{,}100\ \text{€}. \qquad \text{(eq. 3)}$$

- <u>Fuel savings compared to the reference system</u>

  The annual yield of the solar thermal system equals not exactly the savings of fuel consumption. This is mainly due to storage tank losses (the storage tank constantly emits heat as it is not perfectly insulated).

By increasing the number of collectors this difference increases as the probability of a full storage increases. In other words: the same storage (considering the volume size) is charged faster with a bigger supply unit. This difference between fuel savings and yield from the solar thermal system in most cases is around 200 kWh. In relation to total demand, this is negligible, but considering the annual yield, it is a not inconsiderable proportion. Nevertheless, from an economical perspective, the fuel savings are relevant as this is the amount of energy difference seen on the bill for fuel. LCoH is calculated accordingly.

Example: According to the simulation results from *Polysun*, this system configuration yields a reduction in fuel consumption of 4,224 kWh/a.

These parameters can now be applied to eq. 1.

Example: For the selected system the result is following:

$$\text{LCoH} = \frac{[2400\,€ + 3100\,€] \times 6.72\,\%}{4{,}224\ \text{kWh}} \times 100\ \frac{\text{ct}}{€} = 8.8\ \frac{\text{ct}}{\text{kWh}} \qquad \text{(eq. 4)}$$

LCoH for all cases and every system size is calculated according to this method. As a result, a graph is drawn (c.f. Fig. 6) which shows the development of the LCoH plotted over the gross area of collectors.

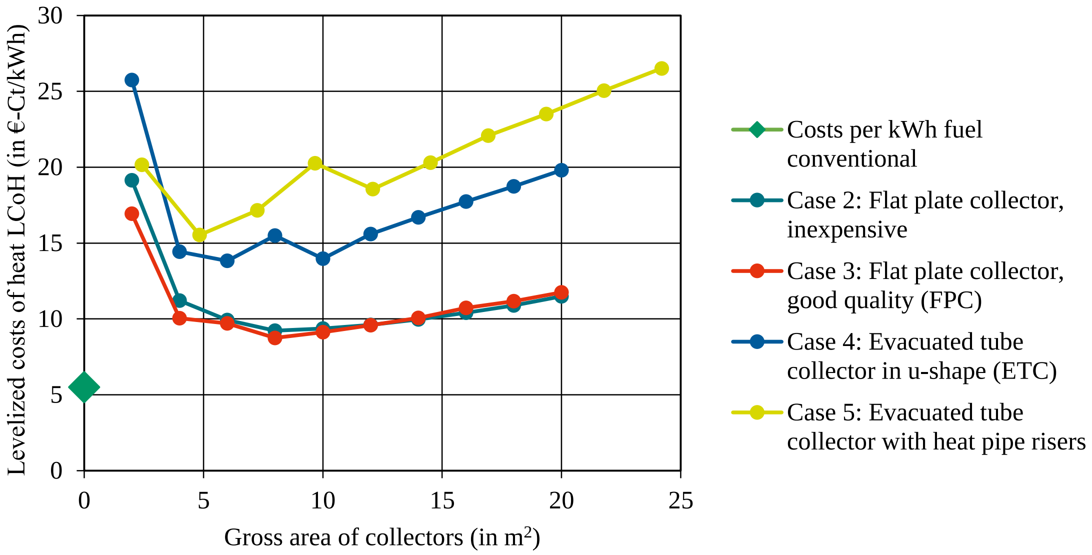

Fig. 6: Trend of Levelized costs of heat for different solar thermal system configurations

As already described above the fuels savings by using unglazed collectors are less than 300 kWh per year, even for the biggest system configuration of this study. This makes the unglazed collector economically not feasible (see also in Tab. 1 in line 4) as LCoH is around 80 €-Ct/kWh or more. Adding graph for case 1 to this graph would strongly distort it.

Focusing now on the four other cases LCoH of heat between 9 and 16 €-Ct/kWh can be reached. The best system configurations from an economic point of view range between 5 to 10 m^2 of gross collector area. As the flat plate collectors are in a similar range of fuel savings compared to the ETCs, their lower specific costs (in €/m^2) become more relevant yielding lower LCoH. Both FPCs do follow the same trend (additional fuel savings from Case 3 collector directly correspond with the higher investment). The inconsistent trend can be seen here too. But as FPCs are the economically more suitable solution the deviation in the curves is not significant.

Unfortunately, estimating costs for one kWh from conventional energy production is difficult, especially for the rural Kyrgyz region due to a lack of information. Nevertheless, for urban areas approximations for the LCoH exist. Around 0.065 US$/kWh$_{th}$ are stated for a house boiler powered with coal for an individual household in the urban environment (Balabanyan et al., 2015). This equals around 5.5 €-Ct/kWh$_{th}$. It is possible that these LCoH are higher compared to rural regions due to the unequally split of wealth in the country (Sultanov et al., 2020). In absence of any more precise data, 5.5 €-Ct/kWh is considered as a price in rural areas (green diamond in Fig. 6).

Bringing the trends of LCoH for solar thermal systems now in context with the costs per kWh using the conventional heating system, it needs to be stated that over a runtime period of 20 years the solar thermal systems are not competitive from an economic point of view as LCoH is always higher than the price for existing reference systems.

5. Discussion

5.1. Best system configuration from this parametric study

This parametric study showed the economic potential of solar thermal systems for rural Kyrgyz residential houses. Using system sizes which are common for single residential houses (up to 20 m^2) fuel demand can be reduced by up to 12 % compared to a reference design based on conventional heat generation. As heat demand during the summer month is negligible and irradiation during winter is less, small systems are more effective as most of the heat produced can be used in the system. As a result, with small systems 500-650 kWh/m^2 (gross collector area) and for bigger systems around 300 kWh/m^2 fuel can be saved. In this study, the economically most feasible system uses four collectors from case 3. LCoH for this system is 8.8 €-ct/kWh. With this solar thermal system, the annual fuel consumption can be reduced by 4,224 kWh which equals a decrease of fuel demand of 8.1 %.

All configurations show no problems regarding stagnation, even though the remaining capacity of the storage tank often is quite small. As there is still a small daily amount of DHW and the maximum stagnation temperature the collectors can withstand is (except for the case 1 – unglazed collector) above 200 °C, an overheating of the pressurized system with potential damage (Quiles et al., 2014) can be avoided. During the nighttime, the colder ambient temperature allows the collectors to cool down that far that on the following day overheating issues can be avoided.

Currently, no system analyzed in the framework of this study is economically feasible compared to the costs for an individual heating system based on conventional fuels which are about 5.5 €-Ct/kWh. Considering a runtime of 20 years, LCoH is always above the value for the conventional heat supply system. Even in case of neglecting interest rates, the cheapest system only reaches 6.5 €-Ct/kWh considering the assumptions for costs made in this study[1]. But there are several ideas to make a solar thermal system more suitable from an economic point of view, especially as the difference of LCoH to the conventional system is small.

First, in this study, typical standard system configurations were analyzed. A heat distribution system is used based on a fluid cycle. As currently no market and know-how for such a solar thermal system exists in Kyrgyzstan, prices for such a system are high. Alternative systems which are less complex should be identified. Systems which are simpler and easier to install can be part of a solution. Systems like solar air collectors or direct heat exchangers without any storage tank do not require that much technical understanding during installation process, especially regarding setup of the piping and control units. These might be more appropriate solutions for the conditions prevailing on site and need to be investigated in the future.

Secondly, components and installation of them such as storage tank and distributions system are included in the LCoH for the solar thermal system. These measures, especially the distribution system, will drastically increase thermal comfort and living conditions. This point of view might relativize the strict economic analysis.

Third, there are political ideas to increase the economic potential of this technology whose technical potential is enormous (Mehta et al., 2020b). Possible measures are described consequently.

[1] In this study, the costs for importing the components and bringing the specialists from foreign countries to the construction site have not even been considered.

5.2. Hurdles that need to be overcome to implement solar heating technology on a large scale

To make solar thermal technology widely acceptable, it is necessary to gear up the solar market in Kyrgyzstan. Such an opportunity will allow manufacturing of solar thermal products within the country with the available resources. Further to this, with the capacity building and knowledge dissemination, skilled manpower will be available who can install typical solar thermal heating technology in Kyrgyzstan. Such factors are the key drivers and can substantially reduce the capital cost of solar thermal-assisted heating technology. As a result, Levelized Costs for solar thermal applications will shrink too.

In addition to that, subsidies can help to make this technology more competitive and widespread. For example, the installation itself can be funded (e.g., by paying bonuses to the house owner when deciding to put solar thermal collectors onto their roof). This measure will happen very unlikely due to the politically and economically instable situation (Ismailov et al., 2021).

From an environmental point of view, it needs to be stated, that reducing heat demand from the building by optimizing the outer shell is more effective and economically feasible after shorter time periods. Previous research showed that insulation can reduce fuel consumption more efficiently as a lower investment is necessary (Beringer et al., 2021). Although, insulating a house is more relevant in case a new building or a big renovation is planned, whereas collectors can be installed on the roof of a finished house in case a heat distribution system is existing.

Finally, the financial situation, the existing heating situation in most of the households, and the lack of knowledge about the availability of such technologies currently don’t allow the installation of solar thermal systems. Solving these issues is a complex task. But creating the awareness and ability to use renewable energy can help residents in aspects like healthcare and energy security by using local fuels and renewables. As a benefit, this is also contributing to a reduction of greenhouse gases globally. This helps to preserve Kyrgyzstan as a habitat for many different peoples and cultures.

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