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Master's thesis

**Micro-scale Solar Assisted District Heating System for Rural  
Kyrgyzstan: A Feasibility Study for a High-altitude Settlement**

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## DECLARATION

I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, 11.12.2023



Ekaterina Mingaleva

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## ABSTRACT

The present study investigates the viability of implementing a micro-scale district heating system (DHS) powered by solar energy in the elevated rural regions of Kyrgyzstan. The performance assessment of such a system is achieved through modeling and simulation in Polysun software along with a conducted parametric study to find out the optimal volume of the storage tank to the area of the collectors based on the solar fraction.

A parametric study resulted in the possible system configuration with a solar fraction of 19.4%, achieved with 2,000 collectors (4,060 m<sup>2</sup>) and a 400 m<sup>3</sup> storage tank. The follow-up economic evaluation considers total lifecycle costs, comparing the solar-assisted DHS with an electric and a coal boiler as the auxiliary heater, and an individual stove-based system. The DHS with a coal-fired boiler resulted in a slightly lower levelized cost of heat (LCOH) at 10.03 €-ct/kWh compared to the electric boiler at 11.77 €-ct/kWh, while an individual home coal-fired system is 1.13 €-ct/kWh.

However, LCOH-based energy affordability analysis revealed that the proposed DHS would burden typical households, where the man works and the woman manages the household, exceeding income by 74% (with electric boiler) and 48% (with coal-fired boiler).

Therefore, the study underscores the need for careful economic consideration in solar thermal projects, especially in low-income areas. To facilitate successful implementation in such regions, securing subsidies or financial support during the project's implementation stage is essential to maintain the affordability of these systems for the local population.

**Keywords:** Central Asia, rural area, space heating, heat demand, solar thermal, district heating, simulation, Polysun, parametric study, levelized cost of heat, energy affordability

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## ABBREVIATIONS

ASL	Above Sea Level
DH	District Heating
DHN	District Heating Network
DHS	District Heating System
CO <sub>2</sub>	Carbon dioxide
CHP	Combined Heat and Power
IEA	International Energy Agency
InES	Institute of new Energy Systems
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Heat
NPV	Net Present Value
OECD	The Organization for Economic Co-operation and Development
O&M	Operation and Maintenance

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## 1 INTRODUCTION

Central Asia is a landlocked region where the territory of countries (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan) has varied relief from plains and valleys to high mountains. Due to this diverse terrain, countries in Central Asia experience pronounced seasonal changes, ranging from hot summers to harsh winters. In certain areas, the heating season spans up to eight months, and hence, indoor heating is crucial for a comfortable life.

The district heating system (DHS) serves as the primary source for space heating in urban areas of Central Asian countries. These systems were extensively established during the Soviet Union era, in the context of large-scale urban development. If appropriately planned, efficiently managed, and adjusted to local conditions, the DHS is the most convenient way of providing space heating to households. However, the DHS common feature of the examined Central Asia countries is its poor condition due to ageing equipment, resulting in deteriorating service quality.

In contrast to urban areas, rural households use traditional stoves for space heating and rely on solid fuels such as coal, wood, and cow dung, and electric heaters are also an option. However, this study focuses on the high-altitude rural areas where inhabitants depend entirely on solid fuels, which has adverse effects on their health. The remote location from big cities means that there are no heat energy services for households in these areas. However, the severe climate conditions in the mountainous area significantly increase fuel consumption and prolong the heating period compared to lowlands. Consequently, this results in health issues for the locals and also contributes to climate change through air pollution and regional deforestation for heating purposes.

A potential solution is to introduce a district heating system (DHS) in rural areas. A well-designed and efficient micro-scale DHS on a small community level powered by solar thermal energy presents a promising path to improve living conditions, minimizing health problems, and mitigating environmental degradation and the impacts of climate change.

A central question that arises in relation to this solution is: can the implementation of micro-scale solar-assisted DHS in elevated remote rural areas bring about positive changes, and could it be an economically and technically viable solution? This research aims to respond to this question and explore the feasibility and effectiveness of solar-assisted DHS in rural Kyrgyzstan, assessing its environmental and economic viability and population affordability.

## 1.1 Current status of district heating in Central Asia

Kazakhstan, Kyrgyzstan and Tajikistan were selected for a literature review exploring the state of district heating in Central Asia. Kazakhstan and Kyrgyzstan were chosen due to their harsh winter climates in the region. While Tajikistan, Uzbekistan and Turkmenistan typically experience milder temperatures, Tajikistan's mountainous terrain sees more notable seasonal variations.

### 1.1.1 District heating sector in the Kyrgyz Republic

The population density of the Kyrgyz Republic is 34 per km<sup>2</sup> for the data of 2020 (The World Bank, 2020). Statistical data for the same year reveals that only 34% of the country's populace reside in urban areas, while the remaining 66% live in rural regions. Interestingly, nearly half of the urban population lives in Bishkek, the capital city of the country (NatStatCom KG, 2020, p. 19).

Since Kyrgyzstan is a mountainous country, it has an impact on the weather conditions. Figure 1 provides an overview of temperature changes across the country, using data from three cities: Bishkek in the north, Osh in the west, and Naryn in the middle. These cities are situated at altitudes of 800m, 963m, and 2020m above sea level (ASL), respectively. The temperature drops below freezing in the winter throughout the country, but residents of high-altitude regions experience even harsher climates. Heating is an essential requirement for survival. The duration of time when space heating is necessary varies by region but can extend up to 7-8 months.

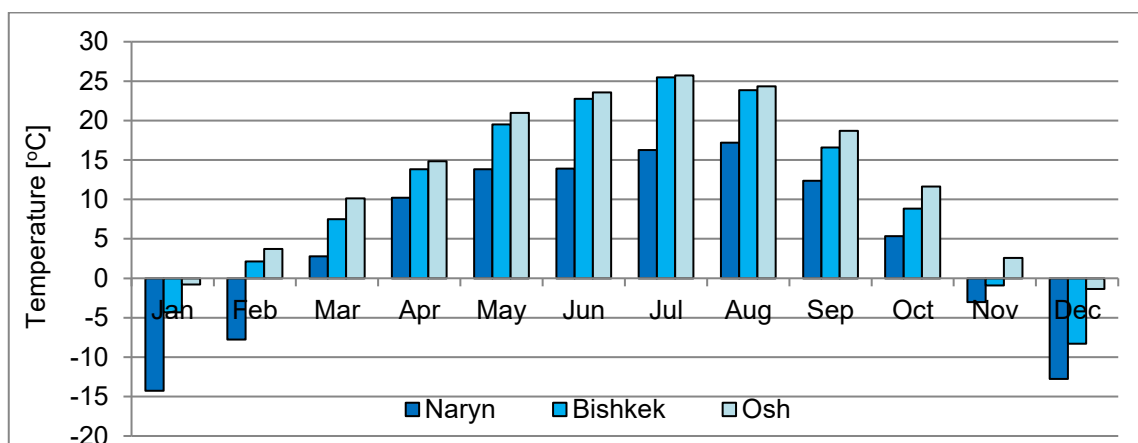


Figure 1. Kyrgyzstan monthly average outdoor temperature in 2020 (based on <https://rp5.ru>)

In terms of the whole country, district heating does not play a significant role in the space heating of houses. It can be observed from Figure 2 that the share of connected urban households to DHS does not exceed even 50% regionally. Here, the Chuy region has the largest share of urban DHS because of the capital city allocation, and it is one of the densely populated regions.

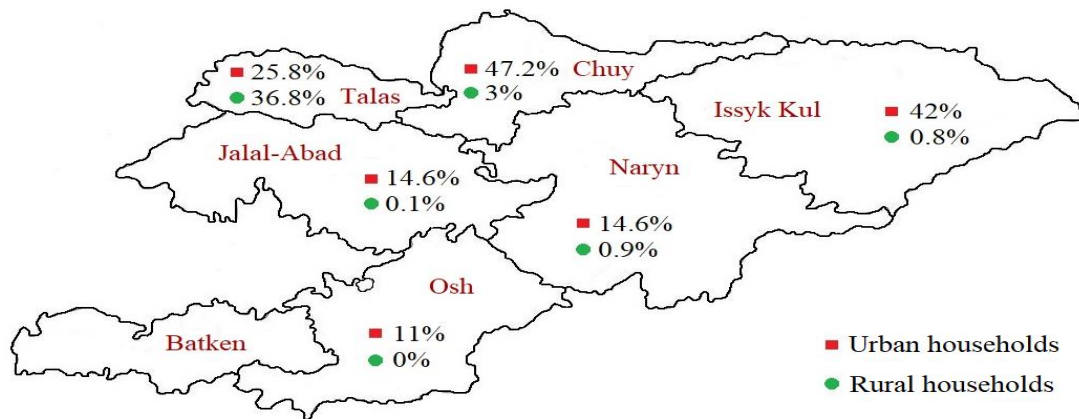


Figure 2. Share of connected households to DHS, Kyrgyzstan (based on NatStatCom KG, 2019)

But if the situation in cities is relatively good people in rural areas have nothing else but to use stoves, rarely electric radiators, and hardly ever electric boilers. The same applies to private houses in urban areas, and in both situations, people commonly use coal, firewood, and cow dung as fuel for heating stoves. The widespread use of solid fuel during the heating season is responsible for air pollution problems, with Bishkek ranking top in the international air pollution rating (Deutsche Welle, 2021).

The scale of need in space heating of households depends on the building's energy efficiency as well. Popular building materials for single-family houses are traditional red bricks and clay-straw mixture which is formed into bricks or formed into a wall by filling and tamping in a detachable formwork. The usual main types of apartment buildings are brick masonry, panel, monolithic concrete buildings, or frame structures with brick filling (The World Bank, 2015, pp. 4–5). Both single-family houses and apartment buildings are not energy efficient. In the first case, not every owner of individual houses can afford the house insulation because of low income. In the second case, most apartment buildings were built in the Soviet period when energy efficiency was not considered in building norms. Moreover, this question was taken into account only in 2011 with the adoption of the law N137 “Energy efficiency of buildings” (Energy efficiency of buildings 2011) and further changes in Building norms and rules in 2013 (SNIP KR 23-01:2013, SP KR 23-101:2013).

This situation with housing stock throughout the country makes households the largest energy consumers. Figure 3 shows the trend of thermal energy balance in Kyrgyzstan for the last twenty years. Since 1999 the share of space heating increased from 66% to 88% of total produced thermal energy. That happens because of the reduction of heat consumption by industries and the agricultural sector. If to believe in statistic the largest rate of losses was in 2014 – 28% of the total production, and then decreased sharply by 4 times and accounts for 6.7% in 2021.

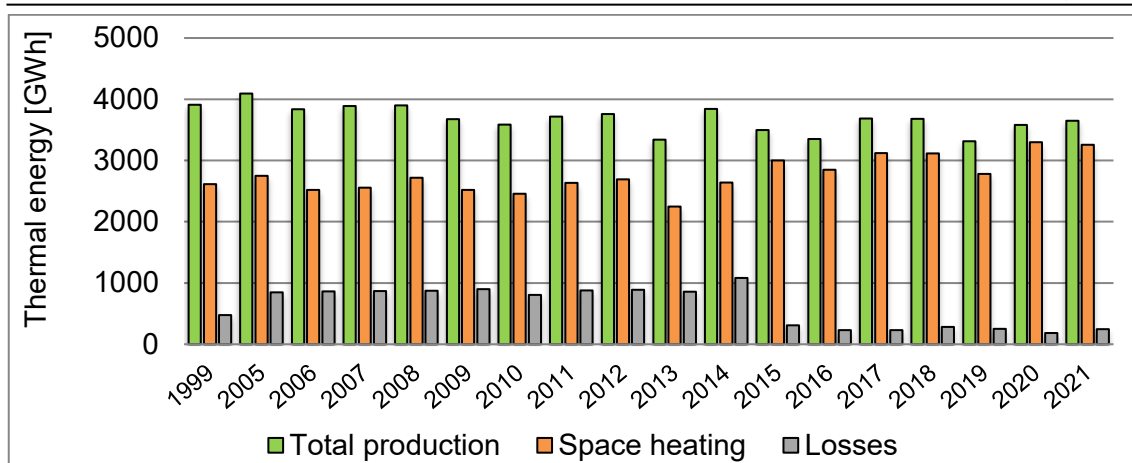


Figure 3. Kyrgyzstan thermal energy balance (NatStatCom KG, 2021, p. 9)

Basically, there are three main thermal power generating companies: “Kyrgyzteploenergo”, “Bishkekteploenergo”, and Osh “Teplosnabzhenie”. Companies “Bishkekteploenergo” and Osh “Teplosnabzhenie” are local producers and distributors in Bishkek and Osh that operate 66 and 83 boiler houses accordingly. The third company “Kyrgyzteploenergo” provides heat supply services throughout the country and has 134 boiler houses. Table 1 provides detailed data on boiler houses amount by the region and on what fuel it operates. So, coal is the most widespread fuel type, and half of the heat units are operated on it. Electricity is also commonly used since it is an easily available option. Broad usage of natural gas is not so common since the country buys it from neighboring countries and there is a low gasification level throughout the country.

Table 1. Amount of boiler houses operated in Kyrgyzstan (Cabinet of Ministers of the Kyrgyz Republic, 2020, annex 11)

Region name	Boiler houses total	In which working on:			
		Natural gas	Fuel oil	Coal	Electricity
Utility company “Bishkekteploenergo”, Bishkek	66	28	-	27	11
Municipal enterprise “Teplosnabzhenie”, Osh	83	1	-	64	18
State enterprise “Kyrgyzteploenergo” in which:	134	20	26	56	32
Talas region	5	-	1	4	-
Chuy region	41	13	15	10	3
Dzhalal-Abad region	27	7	7	11	2
Naryn region	23	-	-	4	19
Issyk-Kul region	32	-	3	21	8

Region name	Boiler houses total	In which working on:			
		Natural gas	Fuel oil	Coal	Electricity
Osh region	6	-	-	6	-
<i>Republic total:</i>	283	49	26	147	61

In addition, in Bishkek and Osh heat supply is also carried out by combined heat and power (CHP) plants, and it operates by OJSC “Elektricheskie stancii”. CHP unit in Osh is operated on natural gas and fuel oil. The main fuel of the CHP plant in Bishkek is coal, but gas and fuel oil are used as fuel for the start of work (OJSC “Elektricheskie stancii”, no date). In 2021 the question was raised about the transfer of Bishkek CHP to natural gas in order to reduce smog during heating season. But this transfer has been suspended because of the high price of natural gas. The authorities could not agree with “Gazprom” company to reduce the price and it was estimated that the use of coal would be nine times cheaper than gas (Roziyev, 2021).

Also, there is a government plan on rehabilitation of the CHP-2 in Bishkek. Its construction began in Soviet times and according to the project natural gas was the main fuel. However, after the collapse of the USSR the project was frozen for many years. Now it is assumed that the power plant will be completed within the next 2-5 years and provide uninterrupted power and heat supply (President of KG website, no date).

Besides the mentioned boiler houses, utility company “Bishkekteploenergo” has experience in renewable energy usage. There are three boiler houses where solar collectors are installed, and it helps to reduce fossil fuel consumption. The first two installations were commissioned in 2017. On the territory of the boiler house on Gagarina Street 364 solar collectors were installed with total power of 0.518 MW (GreenEconomy.kg, 2017). Further, 120 collectors were installed on plant “Orto-Sai” and total capacity of 0.168 MW. So, it was assumed that natural gas consumption in those boiler houses will be reduced by 168.34 thousand m<sup>3</sup> per year and payback period is 5 years (“Vecherniy Bishkek” Publishing House, 2017). The last one’s collectors were installed on “Rotor” boiler house in 2019 with capacity of 0.6 MW. As result of that program in cooperation with Bishkek city hall it was expected to reduce emissions by 236.8 tons per year including 150.5 tons of greenhouse emissions per year (“Kabar” Kyrgyz National News Agency, 2019).

At the same time, there is a problem with the district heating network and equipment because almost all systems are the legacy of the Soviet Union. For example, according to the found article 76% of heating networks of OJSC “Bishkekteploset” have worked out the standard service life (Duishenbaev M., 2018). Here, OJSC “Bishkekteploset” is the company which serves heating networks and pumping stations in Bishkek. So, 76%

of pipes are older than 25 years and it must be changed. Such deterioration creates emergency situations in heating season and increases heat losses. Speaking of the equipment, there was serious accident in CHPP-1 in Bishkek in 2018. On 26 of January one of the old boilers failed and further there was a pipe break on 29th when trying to connect one more boiler. For these days output temperature from CHP plant was considerably reduced and the temperature in the citizen's apartments has dropped. The situation was complicated by the fact that during this period abnormal cold weather came to the country and it was up to minus 30 °C (Kapushenko A., 2018). Hence, the old equipment and heating network are definitely required to be modernized to avoid such situation but there is lack of money for that.

### 1.1.2 District heating sector in the Kazakhstan Republic

Kazakhstan has a low population density, with 7 individuals per km<sup>2</sup> according to 2020 data (The World Bank, 2020). As of the start of 2021, 60% of the population reside in urban areas while the remaining 40% are in rural regions. Within urban populations, 22% are located in the three major cities of the country: Astana, Almaty, and Shykment (NatStat bureau of the KZ, 2021a).

Kazakhstan is predominantly a flatland characterized by plains and lowlands with a small proportion of high mountainous areas. For the temperature evaluation: the capital Astana is located close to the north of the country (347m ASL); Aktau is located on the coast of the Caspian Sea (8m ASL); Almaty is located at the foot of the southeast mountains (600-1,650m ASL). There is large range between winter and summer temperatures in the country, and while the north has long harsh winters and short summers, on the contrary, there are longer summers and smothered wintertime in the south (Figure 4). Nevertheless, there is a need for space heating in all parts of the country.

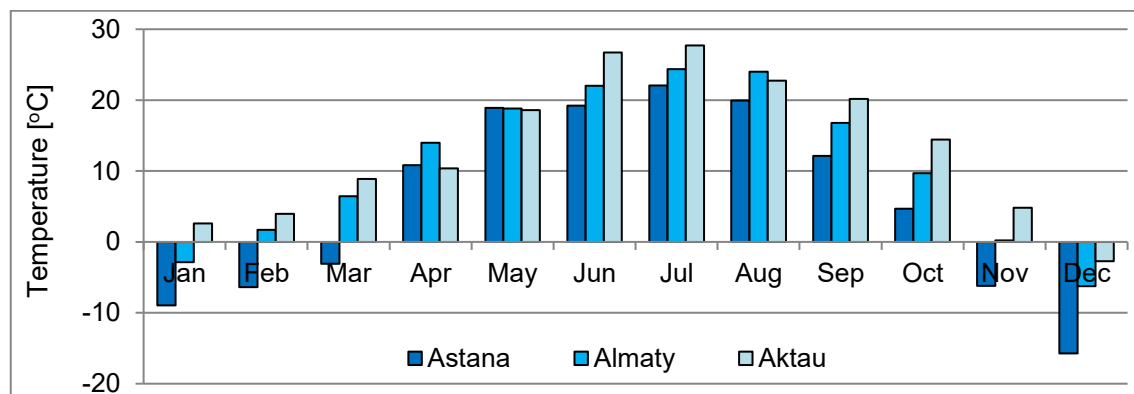


Figure 4. Kazakhstan monthly average outdoor temperature in 2020 (based on <https://rp5.ru>)

Of the total private housing stock in the country, 62% is situated in urban areas and 35% in rural areas. Within urban locales, apartment buildings constitute 13.3% whilst single-family houses represent 86.7%. A comparable situation exists in rural regions, where apartment buildings account for 12.6% and single-family houses for 87.4%. Notably, the majority of the country's residential buildings were built during the Soviet era. So, 60% of houses were commissioned in 1970-1990, a further 25% between 1991-2010, and the rest till 2020 (NatStat bureau of the KZ, 2021b). The situation with popular building materials is the same as in the Kyrgyz Republic. And again, looking at the houses commissioning years, is it obvious that insulation is not considered in most buildings.

Kazakhstan has a well-developed DHS when it comes to cities. Overall, the share of connected urban households to the DHS accounts for 63.6%. The lowest urban rate belongs to the South Kazakhstan region with 12.8% while the highest is the Pavlodar region with 89% (Figure 5). Rural areas and some urban houses do not have such houses improvement and people have to use solid fuel, gas, or electricity. However, there is a large gasification level of households according to the statistic, and it is 81.3% of urban and 97.3% of rural houses (NatStat bureau of the KZ, 2021b). According to the one International Agency (IEA) report, 17% of urban and 55% of rural households use coal and/or firewood. But most households prefer to use fuel in combination: coal, firewood, propane – 51%, coal and propane – 30%, coal and firewood – 8%, coal only – 7% (International Energy Agency, 2020, pp. 11–13).

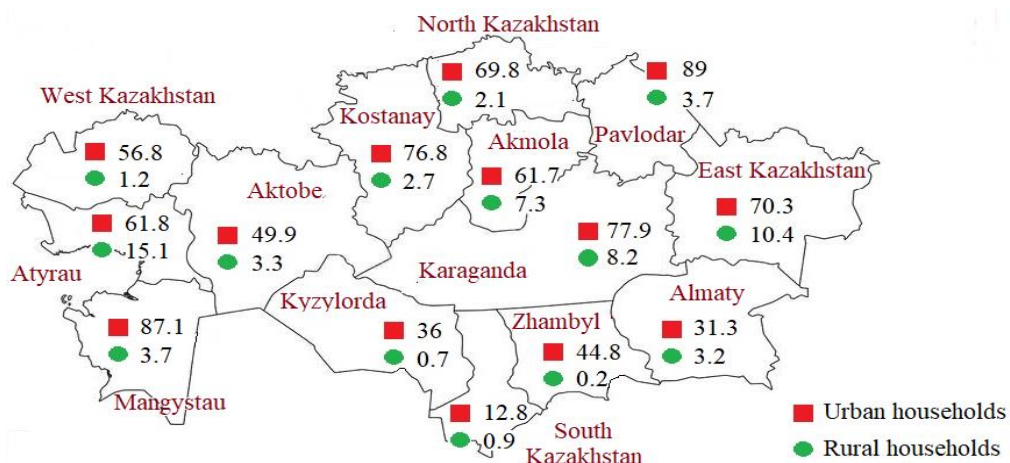


Figure 5. Percentage of connected households to DHS, Kazakhstan (based on NatStat bureau of the KZ, 2021b, pp. 103–104)

In relation to thermal energy consumption, the population does not constitute the largest end user. Nearly half of the energy produced is consumed by industrial and commercial sectors. The supply of thermal energy to the population is only responsible for 30% of the total energy production in the country (Figure 6). Since 2011 losses in the heating network decreased from 11% to 7.8%.



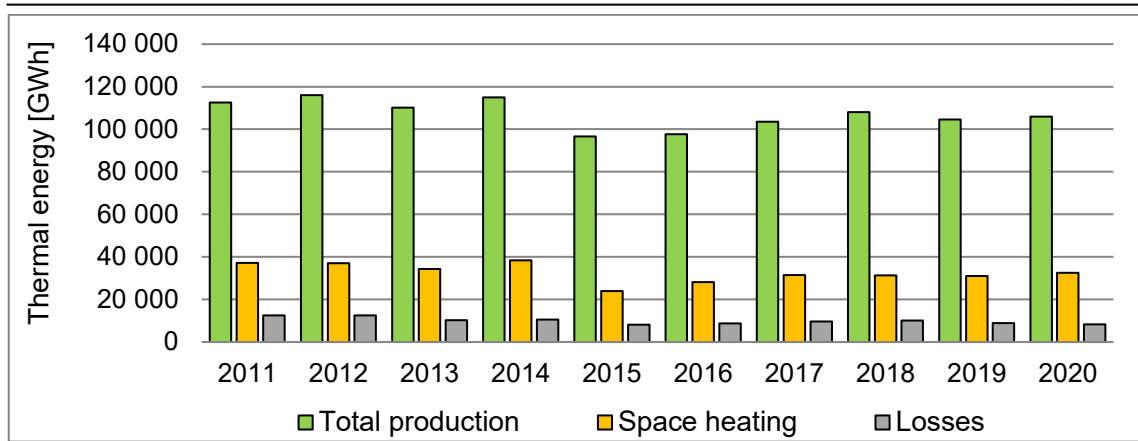


Figure 6. Kazakhstan thermal energy balance (NatStat bureau of the KZ, 2021c, pp. 31–32)

DH systems based on CHP plants are the most developed in Kazakhstan. Hence, heat production throughout the country is summarized as follows: 45% of the total produced thermal energy belongs to CHP plants, 35% - big boiler houses, 20% - small boiler houses. However, CHP plants amount account only for 40 units, and there are 28 big boiler houses, and 5600 small boiler houses. Here, a boiler house with a heat capacity over 100 Gcal/h (116.2 MWh) is considered as big, and hence it is small if less than that. The main fuel type is coal from local coal deposits, for example in CHP plants its usage share is equal to 80%, another 15% and 5% is natural gas and fuel oil accordingly. Boiler houses and heating networks are mainly publicly owned (Concept for the development of the fuel and energy complex of the Republic of Kazakhstan until 2030, 2014).

The Concept for the development of the fuel and energy complex highlights problems of the district heating sector. There is a common problem in post-soviet countries, and it is the aging and wear and tear of equipment and heating network. According to the Concept, the use of low-quality coal and water accelerated equipment wear. Allocated funds for the repair are often spent ineffectively because the availability of new technologies and the feasibility of modernizing the boiler house are not considered.

Regarding the use of renewable energy, Kazakhstan has potential sources of geothermal energy. The Ministry of Energy worked in partnership with the World Bank to investigate energy potential, demonstrating that there is an opportunity to develop heat generation capacity based on geothermal sources in the Almaty and South Kazakhstan regions (Kazinform News agency, 2019). However, there are already some projects in the Almaty region on the base of the Zharkent basin. Geothermal water is used in a balneology resort as well as in space heating of buildings and facilities. It is also used in agriculture for space heating in greenhouses and fish farming pools ("Geotherm' Production company, n.d.).

### 1.1.3 District heating sector in the Tajikistan Republic

The population density of Tajikistan is 69 per km<sup>2</sup> for the data of 2020 (The World Bank, 2020). The rural area of Tajikistan is the most populated and at the beginning of 2019, there lived 73.7% of the total inhabitants. Hence, the urban population amounted to 26.3%, and one third of the urban inhabitants live in the capital Dushanbe (Agency on statistic of the Tajikistan, 2019).

The climate of Tajikistan as a mountainous country is very diverse. Average winter and summer temperatures vary from valleys to high mountainous areas. For the comparison were taken Dushanbe (823m ASL), Kurgan-tyube (430m ASL) and Murgab (3,612m ASL). In this case, Murgab temperature distribution stands out from all the rest (Figure 7). It is located in the East part of the country which is mountainous region named Gorno-Badakhshan region. It has harsh winter temperatures and also during the summer months average temperature is not higher than 20°C. And apparently such hard conditions do not attract people because in statistic data only 2.5% from total population live in this region (Agency on statistic of the Tajikistan, 2019). Low-altitude areas and valleys have smother climate conditions and winter average monthly temperatures in the west part of the country are above zero. But still for several months space heating is required for comfort life.

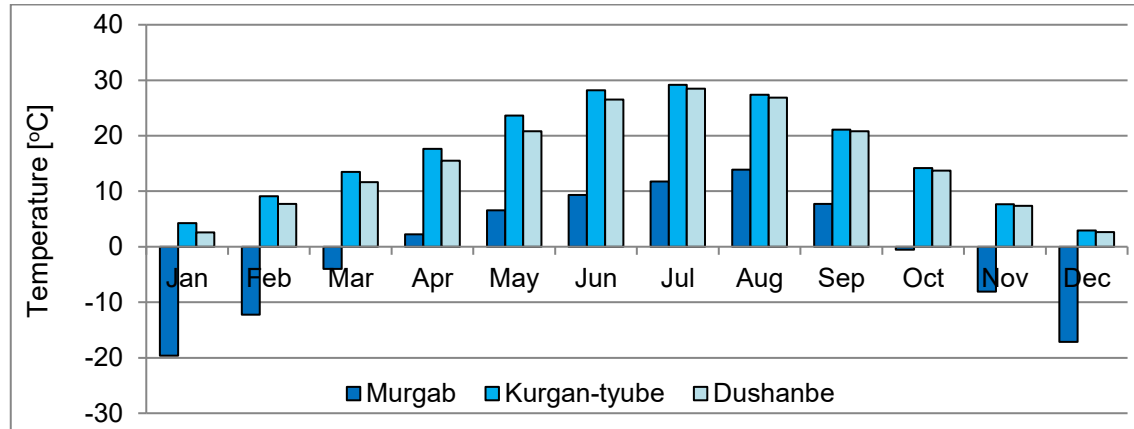


Figure 7. Tajikistan monthly average outdoor temperature in 2020 (based on <https://rp5.ru>)

Regarding housing stock of the country in 2019, 33.4% of the total housing area is located in the urban area and another 66.6% in rural area (Agency on statistic of the Tajikistan, no date). Evaluation of present housing conditions turned out to be difficult because data is limited to the census data of 2010. As a statistic 2010, single-family houses were the most popular way to live where 54% of the urban population and 99.51% of the rural population belonged to. Speaking of quantity, 82.77% of single-family houses were located in the rural area and 17.23% in the urban area. In another

hand, 94.96% of apartment buildings were located in the urban area and 5.54% in the rural area (Agency on statistic of the Tajikistan, 2013, 8-10, 212-215)

The popular building material for single-family houses is clay, so 33.9% of houses are made from raw brick, 47.26% from adobe and clay, and 10% from red bricks. Buildings with walls made of red bricks (50.65%) and concrete blocks or panels (39.36%) are predominant among apartment buildings. Most of the residential buildings were built during the Soviet era, thus 88.36% of total apartment buildings and 57.35% of total single-family houses were constructed and commissioned between 1951 and 1990. Construction of apartment buildings from 1991 to 2010 was not common and accounted for 5.12% of the total share, while 39.24% of single-family houses were built within that period (Agency on statistic of the Tajikistan, 2013, 212, 238-239). Hence, housing stock faces a problem of aging that entails low energy efficiency and high energy demand.

The district heating situation in Tajikistan is poorly developed nowadays. Only 3.48% of urban households have a connection to the DHS (Table 2). A common way to heat flats in apartment buildings is to use electricity. Meanwhile, people living in single-family houses both urban and rural areas use stoves where the prevalent fuel is coal, wood, or dung.

Table 2. The share of households heating methods (Agency on statistic of the Tajikistan, 2013, 75-76, 79-80)

	<b>Urban households</b>	<b>Rural households</b>
District heating	3.48%	-
Individual facilities, boilers	11.71%	4.91%
Stoves	36.66%	88.12%
Electrical radiators and etc.	48.02%	6.87%
No space heating	0.13	0.1%

The country has a problem with winter shortages due to low water levels in rivers since almost all electricity is produced by hydropower plants. Thus, in winter, the country has a significant electricity deficit of 2.2 - 2.5 billion kWh (Ministry of foreign affairs of the Tajikistan Republic, 2019). Especially, in this situation households in rural areas suffer because there is a practice to cut off the power supply. For example, this took a case in 2021 when there was no electricity from 11 pm to 6 am (Yuldashev A., 2021). Such shortages in rural areas happen frequently and not only during the night based on many found news articles. That is one of the reasons why people there rely on stoves.

After the collapse of the USSR situation with district heating got worse and most heat units were disabled. Basically, Dushanbe is the only city in the country that has a

functioning DHS. Here, the CHP-1 plant was the only source before 2014 when the first stage of CHP-2 was commissioned. Its construction started in 2012 and finished in 2016 with the commissioning of the second stage. Both CHP plants use local coal as the main fuel (OSHC "Barki Tojik", no date). In the country, small boiler houses also exist but it supplies heat mainly to public buildings.

After construction of the CHP-2 in the capital, pipes were re-laid to provide heat to the people. It seems the situation has improved, but people dismantled batteries and in-house pipes because of missing heating services during the last 20 years. This brings problems in the implementation of the restoration of heat supply to households. People should restore all in-house systems in an apartment building with their own money and this is expensive for them. Following present legislation, the maintenance of public infrastructure in apartment buildings and its repair is the responsibility of apartment owners (Deynarovich N., 2016).

## 1.2 Countries comparison

All the examined Central Asian countries have similar climate conditions. Long winters with low temperatures create a high energy demand in heating among the population. Energy need in the heating sector of Kazakhstan and Kyrgyzstan is almost the same reaching 5,000 heating degree days (Figure 8). Tajikistan has one of the coldest spots located in the high mountainous region resulting in 7,000 heating degree days. However, this area has the lowest level of population density in the country. Other areas of Tajikistan have smoother weather conditions which significantly decrease energy need for the heating season compared to other countries.

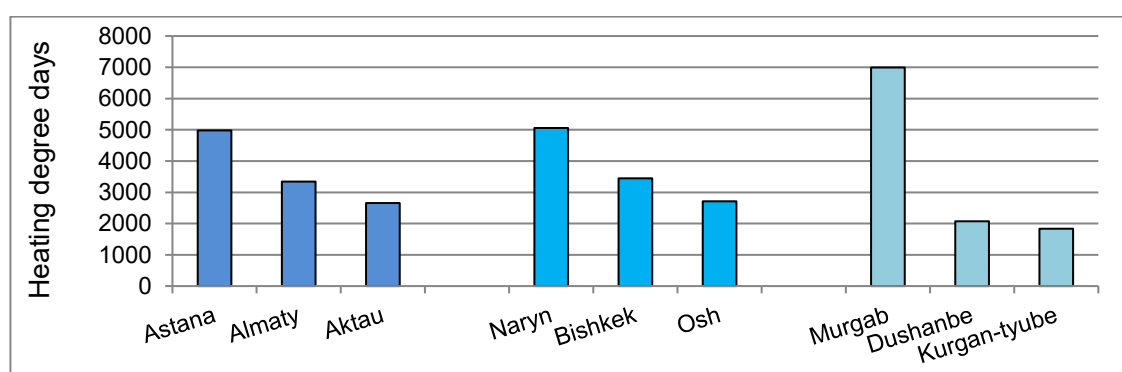


Figure 8. Comparison of the Heating degree days (estimation based on temperature data)

The DH sector of Central Asian countries has common characteristics because these countries have unified history as a part of the Soviet era. Before the collapse of the USSR, these countries had pretty good established DH systems, but after faced an energy crisis. Most CHP plants were designed to work on natural gas as well as boiler houses. Hence, with the loss of constant gas supply, thermal units had to be converted

to coal as an affordable source in the countries. Such transformation resulted in the low energy efficiency of plants and higher air pollution. And in the present days coal is still the main fuel used in the heating sector (Table 3). With the mentioned supply problem, the operation of many units was even suspended, for example in Tajikistan which significantly reduced the number of households connected to DHS. Among reviewed countries, the widespread DHS is retained only in Kazakhstan.

Table 3. The DHS comparison of Central Asian countries

	<b>Kazakhstan</b>	<b>Kyrgyzstan</b>	<b>Tajikistan</b>
Number of plants	<ul style="list-style-type: none"> <li>• 40 CHP plants,</li> <li>• 28 big boiler houses,</li> <li>• 5,600 small boiler houses</li> </ul>	<ul style="list-style-type: none"> <li>• CHP Bishkek,</li> <li>• CHP Osh,</li> <li>• 283 boiler rooms</li> </ul>	<ul style="list-style-type: none"> <li>• CHP-1,</li> <li>• CHP-2 in Dushanbe</li> </ul>
Fuel types	80% on coal, 15% on natural gas, 5% fuel oil	Coal; natural gas; fuel oil	Coal
Percent of connected consumers	63.6% urban area; 3.9% rural area (in 2020)	33.7% urban area; 3.1% rural area; (in 2019)	3.5% urban area (in 2010)
Heat losses	12%	7.6%	9%
Tariff for population	Different in each region: 1,805 – 5,383 KZT/Gcal (3.64 – 10.87 Euro/Gcal)	1,248.0 KGS/Gcal (13.15 Euro/Gcal)	1.18 TJS/m <sup>2</sup> * (0.1 Euro/m <sup>2</sup> )

\* Established measurement is difficult to compare. However, the tariff for population shouldn't be higher than the tariff for the state-financed organization which is 98.67 TJS/Gcal (8.48 Euro/Gcal)

Further, wear and tear of equipment together with pipeline aging is a thing in common among countries. This, in turn, causes frequent accidents and pipeline breaks which noticeably affect the quality of provided services and even put people at risk. These problems are complemented by the problem of the state of the housing stock. All the examined countries have similar housing conditions. More than half of the apartment buildings were commissioned in Soviet times when the pace of construction was most important. At those times, house insulation was not considered in building norms and rules since the country had rich fuel reserves and could cover any demand. Nowadays, these houses require major renovation since it is not energy efficient. Single-family houses also have problem of aging, furthermore, mostly built from adobe material and in general, any insulation is not considered.

Based on previously obtained data from examined countries, the DHS is represented basically only in the urban areas. And even in such densely populated areas the DH is

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unprofitable sector for heat supply companies, and all the mentioned above problems play a role in this situation. Generating units are not operating at full capacity because of old equipment and pipelines. Allocated funds for the repair are often spent ineffectively. Moreover, heat energy cost is often higher than the established tariff for population and it is partially subsidized by the State.

This situation effects on the DHS in rural areas, it is an unattractive sector. A large budget is required to create all the necessary infrastructure, starting with the heating units, and laying pipes, ending with in-house facilities. While the current problems remained unsolved in the cities, no one attaches particular importance to the development of the rural area. Hence, people rely on themselves and use stoves at their houses where coal, wood, and dung are the main fuel. Since the connection to the electricity grid is well-established throughout the countries people also rely on electric heaters.

The biggest part of the population of the examined countries lives in urban areas and people there rely on the environment using solid fuel for heating and cooking. High dependency on solid fuel and its usage in traditional in-house stoves has negative health consequences. Household air pollution is a risk factor for chronic obstructive pulmonary disease. In the Central Asia region, Kyrgyzstan has the highest respiratory mortality rate, and morbidity is most common in high-altitude areas according to the study of Brakema (Brakema et al., 2019). On another side, according to UNICEF, Kyrgyzstan is the most vulnerable to climate change among Central Asia countries (Dzhaparova M., 2017). The power sector of this country depends on water resources and already faces electricity-generating problems in the wintertime because of lower water levels in rivers.

## 2 RESEARCH SCOPE

### 2.1 Thesis objective

The main focus of this study is to investigate the feasibility of implementing a solar-assisted district heating system in the elevated rural regions of Kyrgyzstan. The Kyrgyz Republic is chosen for this study as the country that is most dependent on the environment in the power sector and, accordingly, the most vulnerable to climate change. Health problems due to indoor air pollution from solid fuel play a key role in the selection of the study and its location. Although Kyrgyzstan has good potential in solar energy usage due to high global irradiation (Figure 9), the use of solar energy in any applications, both electrical and thermal, has not been widely adopted.

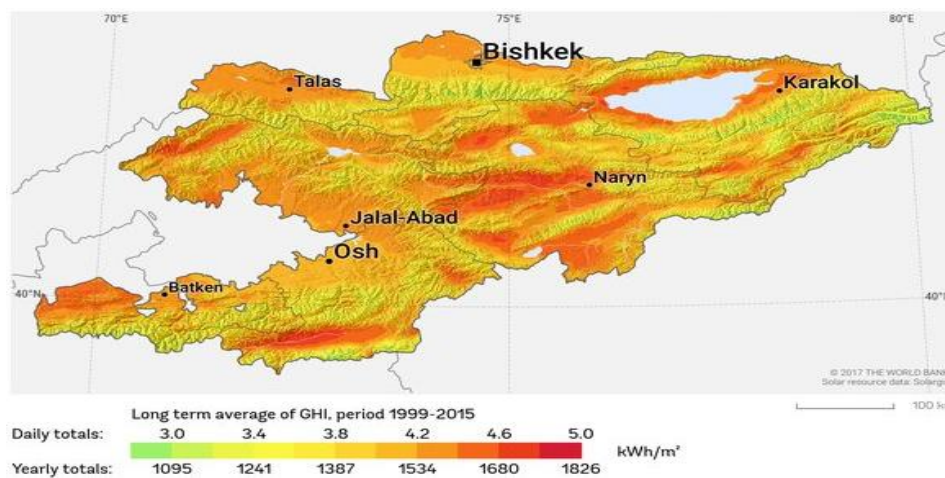


Figure 9. Global Horizontal Irradiation of Kyrgyzstan (solargis.com)

As a study spot for the thesis, the Ak-Tal community, located in the mountainous region of Kyrgyzstan on the bank of the Naryn river, is chosen. With the help of the Ak-Tal community as a case study, this thesis is proposed to:

- Identify how to design the solar-assisted DHS and find out the suitable software program for modeling and simulation;
- Determine the heat losses in the district heating network in the current case study conditions;
- Evaluate the proper tilt angle and the inter-row spacing for the solar collector field;
- Conduct a parametric study and identify the optimum solar fraction for the system;
- Analyze costs of system and evaluate the corresponding LCOH;
- Identify barriers or challenges to solar thermal energy implementation in rural settings.

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## 2.2 Methodology

The work method to achieve study results can be described by the following steps (Figure 10):

### *1. Research process*

Starts with the identification of the problem which explains the need for this thesis work. Further literature review on the state of the district heating sector in Central Asia brings the problem background. Then, the determination of research questions that help to examine the potential problem solution. Furthermore, the research process is applied in every part of this work.

### *2. Identify suitable software*

Determination of software program that contains the necessary tools for designing and simulating solar thermal systems.

### *3. Input data finalizing*

Get the final version of the heat demand profile for the simulation (community heat demand plus the District Heating Network (DHN) losses). The heating network cannot be modeled in Polysun due to its complexity. Calculation of the DHN losses should be done separately.

### *4. Modeling the district heating system*

Model the system in Polysun, as well the control system is developed. Find out the suitable elements for the proper system utilization, and controller options.

### *5. Simulation*

Running multiple simulations to validate the scheme correctness, performance, and functionality of the control system. Further model optimization based on simulation results.

### *6. Parametric study on the solar fraction*

Find out the optimum solar fraction for the system based on the ratio of a solar collector field area to the volume of a storage tank.

### *7. Economic evaluation*

Conduct an economic assessment of the system that takes into account total life cycle costs, including initial investment, operating costs, maintenance, and fuel costs.

### *8. Evaluation of Results*

Evaluation of the results of all previously conducted studies in the current thesis, results of simulations, and results of an economic assessment of the system.



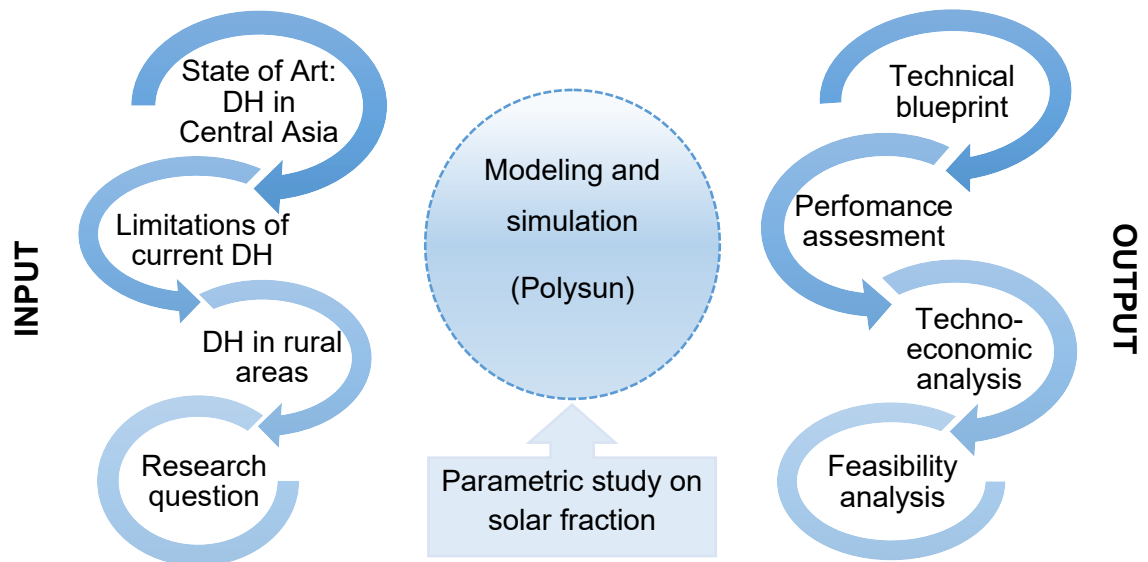


Figure 10. Basic structural outline of the thesis

### 2.3 Case-study community description

Ak-Tal community is located at 41.413°, 75.06°, in the Naryn region of Kyrgyzstan, at an altitude of 1,650 m above sea level. It is situated on one side at the foot of the mountain chain and the other side on the bank of the Naryn river (Figure 11). Due to such a site the houses are built along the main road and the community itself has an elongated location in a length around of 3 km (Figure 12).



Figure 11. Map of Kyrgyzstan



Figure 12. Aerial view of the Ak-Tal community (source: Google Earth)

The climate of this mountainous area is sharply continental with harsh, snowy winters and warm but short summers. Average temperatures during winter months vary between -10 and -20 degrees, however, could be lower and reach -30 °C (Figure 13). Early spring and late autumn have minus temperatures most of the time. Only from May through September minimum temperatures are above zero level. Thus, such climate conditions strongly influence on energy demand of community households.

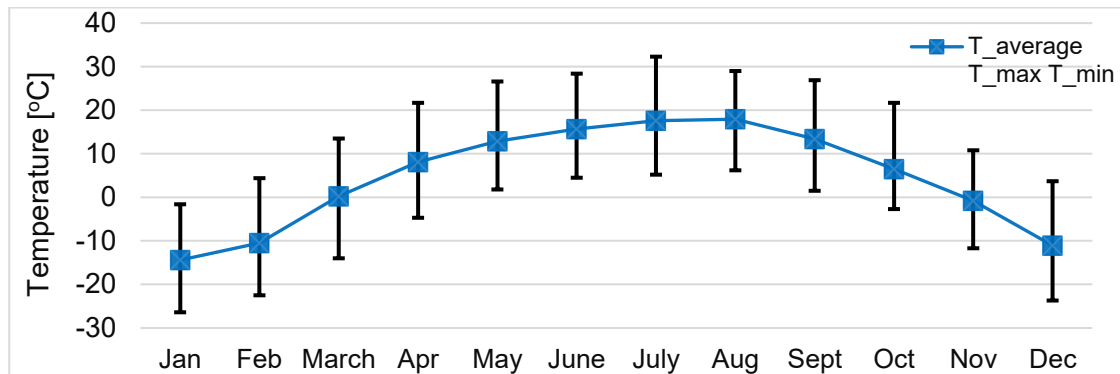


Figure 13. Monthly ambient temperatures of Ak-Tal (based on data from Polysun)

Despite the challenging weather conditions faced by the Ak-Tal community, they have valuable data on solar radiation, thanks to the strategic geographical location of the country. Figure 14 represents the average daily global, direct, and diffuse irradiance in each month. Notably, the community has a constant solar resource throughout the year. This is evidenced by the fact that even during the winter months when weather conditions are less favorable, the global solar irradiance remains at a valuable level of around 2 kW/m<sup>2</sup>. This availability of solar irradiance data, even during the colder months, greatly increases the feasibility and attractiveness of using various solar energy systems in the community.

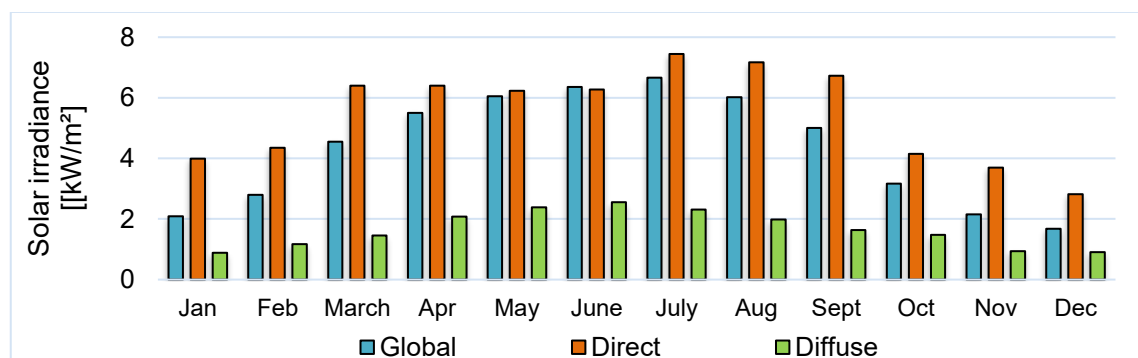


Figure 14. Average daily solar irradiance (based on data from Polysun)

Ak-Tal community is a small rural settlement with a population of about 1,500 people, for a total of 234 households. The residential stock of the area consists of single-family houses, there are no apartment buildings. The main energy needs of the community population are electricity and heat for space heating.

As it was shortly described earlier traditional red bricks and bricks of the clay-straw mixture are widespread materials for the construction of single-family houses in Kyrgyzstan. This situation is also applied to the Ak-Tal community where 80% of private households are constructed of earthen materials (Mehta et al., 2021). The popularity of such material is due to its availability and low cost since there are mostly self-built houses. Households survey in this article determined that the age of more than half of houses exceeds 30 years and almost all respondents answered that any insulation materials are not used.

The heat demand of the Ak-Tal community was estimated in a study within the ÖkoFlussPlan project by Kedar Mehta (researcher from InES) using households modeling and simulation. For the present study the heating season is taken as from October to April when minimum temperatures drop below zero, and during this season the heat demand is equal to 4,296 MWh. December, January, and February are the coldest months here when community heat demand reaches almost 1.6 MW per hour (Figure 15).

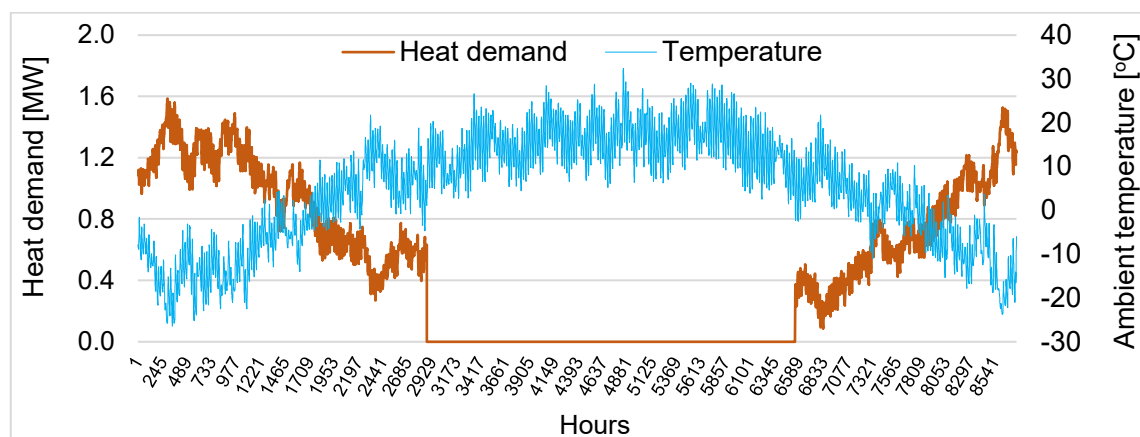


Figure 15. Households heat demand vs ambient temperature

The heat demand of the community households is mostly covered by a traditional heating method such as stoves with the usage of coal, biomass, or cow dung. Rarely do community inhabitants use electric appliances as the main heating source because the final cost of constant use can be too high for them. Hence, electricity for the heating can be used only as support for the stoves. Table 4 illustrate the average fuel demand for one community household per heating season.

Table 4. Household fuel demand and cost per heating season (Mehta et al., 2021)

Commodity	Demand	Cost
Coal	2 – 6 tons	50 – 250 €
Wood	1.5 – 3 m <sup>3</sup>	5 – 30 €
Cow dung	1–2 truckloads	5 – 10 €

Coal is widely used both at city thermal plants and at single-family houses due to its availability in the country. In addition to heating with coal, people also use up to 3 m<sup>3</sup> of firewood and up to 2 truckloads of cow dung during the heating season. The exact numbers of electricity demand for heating purposes are not known, however, in the wintertime monthly consumption increases by around 500 kWh compared to the summer months (Mehta et al., 2021).

### 3 SYSTEM MODELING AND DATA DEFINITION

#### 3.1 Software program

When comparing software programs for solar thermal systems, there are several factors to consider, including ease of use, accuracy, functionality, and cost. Some of these programs are more user-friendly than others, while others may be more accurate in their simulations. However, the main feature in studies with limited time seems to be an intuitive interface of the software meaning it is not required extensive training for the user to use it effectively. But the functionality of the program is no less important when it included the necessary tools for designing and simulating solar thermal systems.

The article of Allegrini et al. (2015) provides a comprehensive review of different tools for the design and simulation of district-scale energy systems. In the Figure 16 a matrix can be seen which provides software programs considering their functionality. The current figure represents only 10 of those presented in the article that has more capabilities.

	External air flow	SW radiation	LW radiation	Building thermal behaviour	Building system	Thermal network	Electrical network	Gas network	District plant	Thermal storage	Wind power	Photovoltaics	Ground source	Spatial	Transportation	Embodied energy		
CitySim	X <sup>1</sup>	D <sup>2</sup>	D	S	D	S	S	X	X	X	S <sup>3</sup>	S	S	S <sup>4</sup>	D	X	X	City energy simulation for groups of buildings / city quarters.
EnergyPlus	S	D	S <sup>1</sup>	D	D	D	S	X	X	S	S	S	S	D	S <sup>5</sup>	X	X	Detailed building simulation, limited interactions.
ESP-r	S	D	S	D	D	D	S	D <sup>6</sup>	X	S	D <sup>7</sup>	S	S	S	X	X	X	Detailed building simulation, thermal and elec networks possible.
IDA ICE	S	D	S	D	D	D	D <sup>8</sup>	X	X	S	S	X	S	D	S	X	X	Detailed building simulation, thermal networks possible.
Polysun	X <sup>9</sup>	D	S	S <sup>10</sup>	D	D	D	S	X	S	D	X	D	D	X	X	X	Detailed solar thermal and hydraulic systems.
TRNSYS	L	D	D	D	D	D	D	S	X	D	D	D	D	D	X	X	X	Detailed simulation tool for systems and single buildings.
Envi-met	S	S	S	S	X	X	X	X	X	X	X	X	X	X	S	X	X	Microclimate model.
KULeuven IDEAS lib	S	D	D	D	D <sup>11</sup>	D	S	D	X	S	S	X	D <sup>12</sup>	D <sup>13</sup>	X	X	X	District-level Modelica library.
LBNL District lib	S	D	D	D	S	D	S	D	X	S	S	S	D	D <sup>14</sup>	X	X	X	District (and building) Modelica libraries.
energyPRO	X	X	X	L	X	D	D	D	X	D	D	D	S	S <sup>15</sup>	X	X	X	Techno-economic simulation of energy systems.

Figure 16. Matrix of software tools with its capabilities (Allegrini et al., 2015)

The further literature review has shown that the most common programs are TRNSYS and Polysun in various articles and studies carried out on the design and simulation of different thermal systems. Figure 16 confirms great thermal modeling features of TRNSYS and Polysun software programs. The main difference is their user interface. TRNSYS has a more complex and technical user interface, and Polysun, on the other hand, has a more user-friendly interface that is easier to use. Also, Polysun has a wide templates library for various thermal systems which simplifies the learning process, and according to Figure 16 it is possible to model a detailed solar thermal and hydraulic systems.

Polysun is a software program that is used for the design and simulation of solar thermal, photovoltaic, and geothermal systems. It is developed by Vela Solaris, a Swiss

company that specializes in solar energy software. The user-friendly graphical interface of the software assists to design different types of systems: domestic hot water, space heating, cooling, and process heat. It includes a variety of features and tools for system design and analysis.

The main feature of the software is its ability to simulate a solar thermal system's performance under various operating conditions. This allows users to optimize the system design for maximum efficiency and performance. Polysun also comes with a comprehensive database of solar thermal components like collectors, pumps, and storage tanks, which can be utilized in system design.

Weather data in Polysun is taken from Meteonorm and the user can assign this data by location either by selecting a city from the database or by selecting a point on the map (latitude, longitude). Moreover, the program allows users to import data, such as weather data or performance data from manufacturers. Polysun also includes tools for economic analysis, such as calculating the payback period and the net present value of a solar thermal system.

### **3.2 System model in Polysun software**

The simplified model of the solar-assisted thermal plant is created in an object-oriented manner in Polysun software. This thesis research system is designed to use solar thermal energy as a source of water preheating. The system consists of solar thermal collectors, a storage tank, an auxiliary heat source, an external heat exchanger, circulation pumps, controllers, a mixing valve, and an energy sink (Figure 17). There are basically three fluid transfer loops: solar loop (heat exchanger – solar collectors), storage tank – heat exchanger transfer circuit, and tank – boiler – consumer circuit. The working fluid of the solar loop is a mixture of water and propylene glycol, and in two other – water. Propylene glycol has a low freezing point, and it is non-toxic and safe for use. Such heat transfer fluid is important in solar collectors that operate in a cold environment, where water-based fluids could freeze and damage the collector.

The heat transfer system circulates a fluid through the solar collector field. The heated fluid is then circulated through an external heat exchanger, where it transfers its heat to water and then goes to a storage tank. The preheated water passes through the boiler where the water is heated to the desired temperature. The hot water is then distributed to the district heating network, where it is used for space heating.

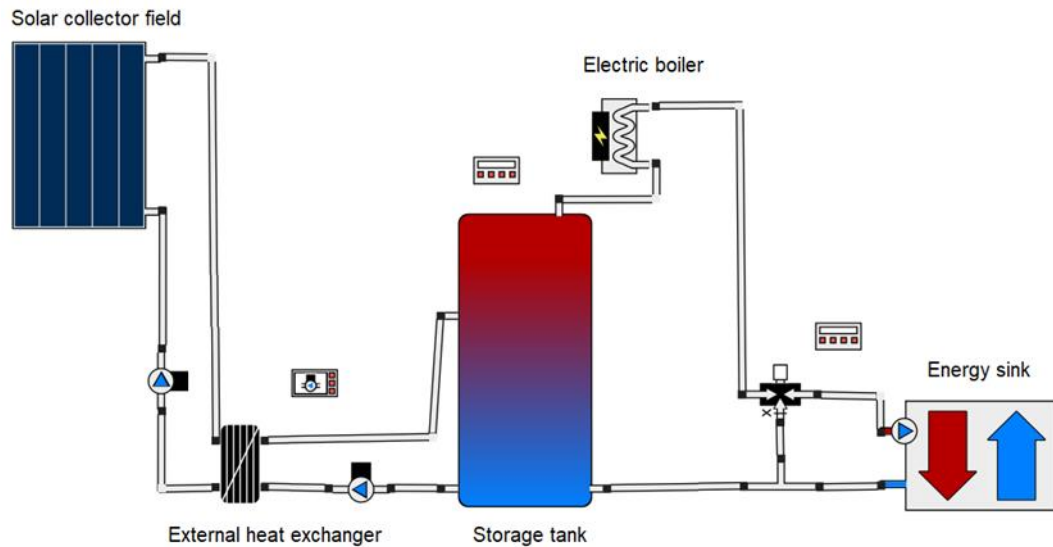


Figure 17. Polysun system model of the heating system for the Ak-Tal community

The main menu of diagram elements is called by a double click on the object where the main parameters can be set. For each system element, there is a data catalog with the range of products from various manufacturers on the market. Hence, the necessary data can be selected in the catalog, or the user can add a new product with specified parameters.

The main parameters for the solar collector data in the catalog are a collector type, an absorber area, efficiency rate parameters, and a specific heat capacity. Further, with the selected collector, other parameters are set up that affect the efficiency of the collector field. There are a number of collectors, an orientation, a tilt angle, a wind speed at the collector array, and also rotation and tracking if it is required.

Regarding the storage tank, there are basically three options based on function and tank volume: domestic hot water tank, tank for hot water and space heating, and seasonal storage tank. Here, the main configurable settings are volume, height, the thickness of walls, top and bottom, the material of the tank, the material of insulation, and its thickness. There is a catalog with a range of possible materials and their properties for the tank and insulation. Storage is divided into twelve isothermal layers in Polysun, and it is possible to select a position of the connecting flanges.

Heat exchangers can be internal and Polysun offers several options for positioning inside the storage tank. In the case of big-scale thermal systems, it is better to use the external heat exchanger as a more efficient model. Length, height, width, number of plates, and heat transfer coefficient are the main parameters for customization.

During the winter auxiliary heater forms the main contribution to heating. In the current scheme, the electric boiler is used since electricity is a cheap and available energy source in the Ak-Tal community. But Polysun offers various types of fuel with relevant

table properties. Here prime parameters of boilers are power, minimum power, efficiency, type of fuel, flow rate, mass, and area.

The best available option to introduce the space heating demand of the community into the Polysun model is to use an element called an energy sink/source. The space heating demand in this study is represented in an hourly manner and it is common for the whole community. In the energy sink element, it is possible to use a personally created profile. For space heating, this profile has data on supply and return temperature, and heat demand in an hourly manner. Based on this data Polysun calculates the required water flow rate to meet the demand.

### 3.3 Control system modeling

The controllers introduced in Polysun are defined in the same way that they are typically used in real-world applications. Polysun currently includes the following types of controllers:

- Solar loop controller,
- Variable speed pump controller,
- Auxiliary heating controller,
- Mixing valve controller,
- Heating circuit controller,
- Temperature controller with AND/OR Operation,
- Flow rate controller,
- Irradiance controller,
- Programmable controller.

Each controller menu has control inputs and outputs based on which it is decided which parameters to control, how, and by what input data. In addition, each controller can be configured with a timer function that determines the availability time at which the controller should operate. In the current scheme (Figure 18) three controllers are used: for the solar loop, for the mixing valve, and a programmable controller for the auxiliary heater.

Controller of solar loop controls on/off status and flow rate of two system pumps based on the temperature difference. The controller menu window for the currently designed system can be seen in the figure. Here, settings are adjusted so that the pumps turn on as soon as the collector outflow temperature is 10 degrees higher than the temperature in the tank on the bottom layer. Such cut-in temperature difference is set to accumulate some useful heat to transfer and reduce pump operation. The flow rate is set as specific at 20 l/h/m<sup>2</sup> of the collector field. According to the Polysun user manual, the specific flow rate is linked to the maximum increase in temperature, and the maximum



is achieved with low-flow which is 10 – 20 l/h/m<sup>2</sup>. Pumps turn off if the maximum collector working temperature is achieved or the maximum tank temperature on the top layer. The controller work during the heating period, October – April, and is available for work 24 hours every day.

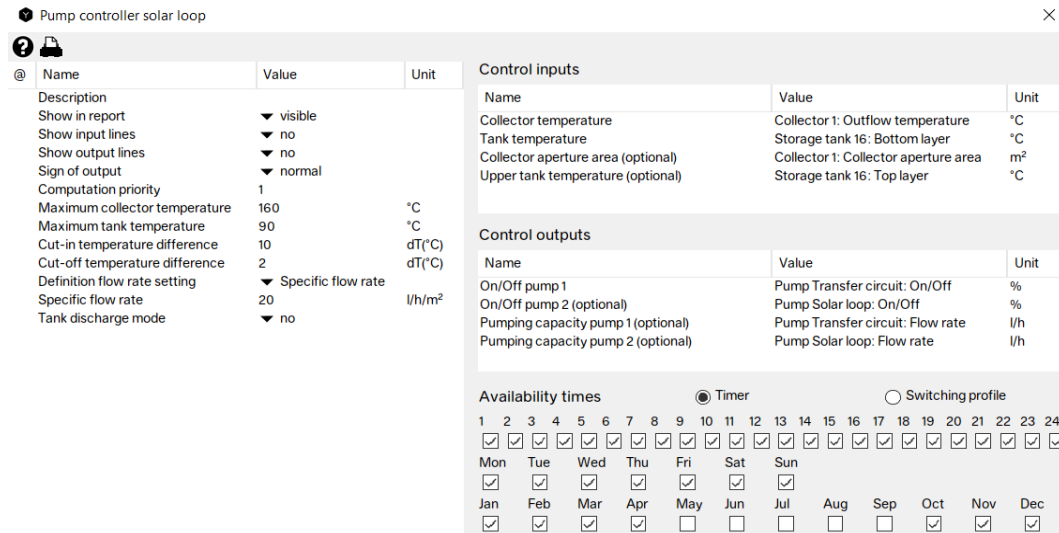


Figure 18. Pump controller solar loop

The mixing valve controller regulates the mixing ratio of two fluids to obtain desired supply temperature to heating network. Here, control inputs are the temperature in pipe from the boiler and return pipe from energy sink. The outflow desired temperature is set constant at 90 degrees.

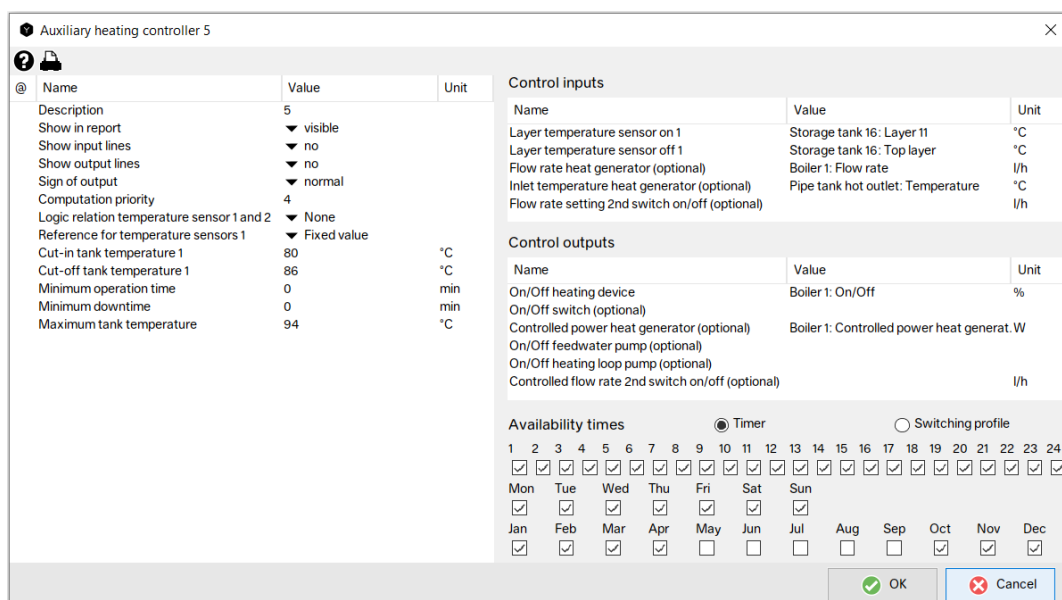


Figure 19. Auxiliary heating controller for the boiler

The auxiliary heating controller for the boiler controls two output parameters: on/off status and controller power of the boiler (Figure 19). The maximum tank temperature is

the boiling temperature at the altitude of the designed system. The boiler switches on when the temperature of layer 11 of the storage tank is lower than 80 degrees. The boiler switches off when the top layer temperature of the storage tank is lower than 86 degrees. Control output “Controlled power heat generator” adjusts the power level according to the set cut-off temperature. This function is represented by the heat transfer formula based on the relationship between the flow rate, the temperature change, and fluid heat capacity.

### 3.4 Losses in the district heating network

For efficient heating of residential buildings, it is necessary to provide a sufficient amount of thermal energy, and for this, it is necessary to take into account heat losses in the pipeline. The community heat demand is the available known data in this study, and it makes sense when planning a heating plant to consider the transportation losses as well. The calculation of heat losses is done separately from the simulation with help of an Excel designed tool (Annexure A). Before the calculation, some parameters are required to define (Figure 20), and it can be mostly based on assumptions.

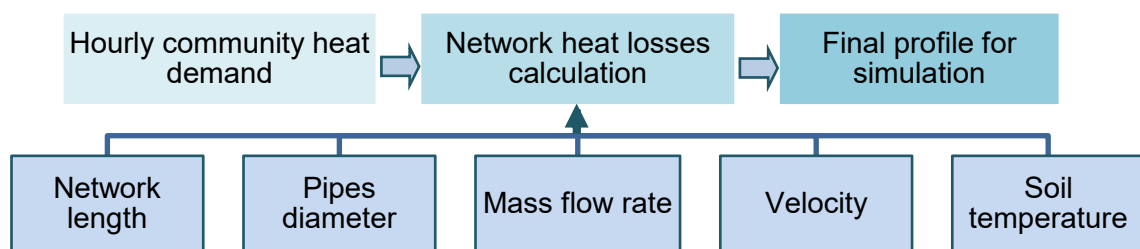


Figure 20. Heat losses determination

Definition of the heating pipeline length can be done with help of Google earth map. A possible scheme of the heating network was outlined (Figure 21), and distances were measured on the map. The measured pipeline length through the Ak-Tal community accounts for around 8.5 km and since there are supply and return pipelines the total length is 17 km.

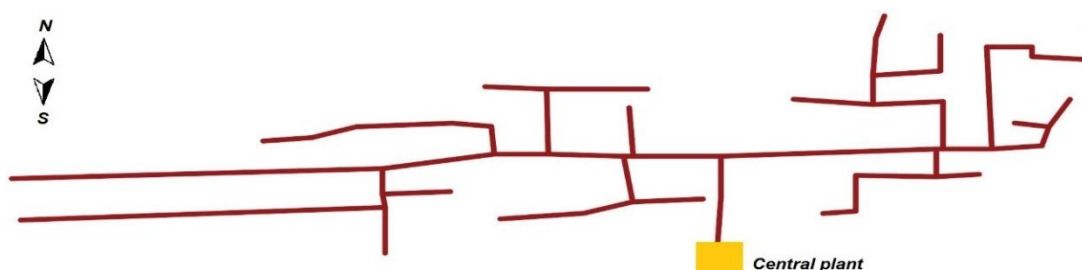


Figure 21. Possible layout of the heating network

One of the main factors of heat losses in the pipeline is pipe size since losses become larger when a pipe diameter increases.

An essential contributor to heat losses within a pipeline is the diameter of the pipe itself. The dependence is such that with an increase in the diameter of the pipe, heat losses also increase. Hence, for the further calculations a rough pipe diameter can be found by the formula of a volumetric flow rate:

$$q = v \cdot A = v \cdot \pi \cdot r^2 = v \cdot \pi \cdot \frac{D^2}{4} \quad \text{Eq.1}$$

where,

q: volume flow rate [m<sup>3</sup>/s];

v: fluid velocity [m/s];

A: cross-sectional area of pipe [m<sup>2</sup>];

r: radius of pipe [m];

D: diameter of pipe [m].

$$D = \sqrt{\frac{4q}{\pi v}} \quad \text{Eq.2}$$

Volume flow rate can be found by the mass flow rate using the formula of the heat transfer:

$$m = \frac{Q}{c\Delta T} = \frac{Q_{\text{max.load}}}{c\Delta T} \quad \text{Eq.3}$$

where,

$Q_{\text{max.load}}$ : the maximum hourly heat demand;

c: specific heat capacity [4,182 J/kg·K]

$\Delta T$ : temperature difference in the pipe.

Pipe sizing is calculated when operating at maximum load. The temperature difference between the inlet and outlet is considered 20 degrees (for one-way). Velocity in the pipe can be only assumed and research gave a number between 2 to 3 m/s as a rule of thumb based on life-cycle cost analysis (Hall, 2021). Hence, the velocity is equal to 2.5 m/s for the further calculations.

So, the mass flow rate is calculated with all defined parameters, and it is equal to 22.74 kg/s which means the volume flow rate is 0.0227 m<sup>3</sup>/s. This result applies to the main pipe from the station, since all the energy goes through it, and the calculated diameter of this pipe is equal to 0.107 m. Production line "Premant" of "A BRUGG group company" (A BRUGG group company, no date) is chosen for the study and the nearest pipe diameter is DN100. There are three pipeline diameters since the energy flow is decreasing further in the network (Figure 22).

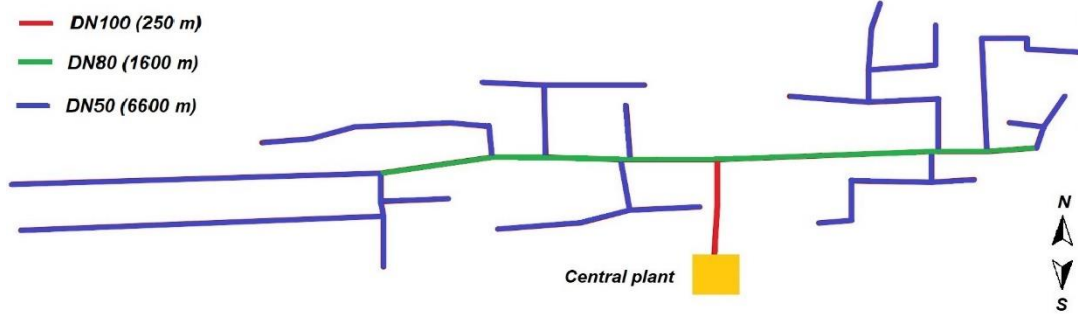


Figure 22. Possible layout of the DHN (pipes diameter and length)

Underground pipe-laying is chosen for the district network because the aboveground pipeline will result in higher losses in the current winter conditions. Additionally, installing pipes above ground is more costly since it must consider the foundation, structural and support elements.

The only data source found for the average monthly temperature of the soil is the handbook “To help a worker in the gas industry” (Volkov et al, 1989). This book contains a table with soil temperatures at various depths for several locations in the former Soviet Union. However, there is no information for Kyrgyzstan, but the table has data on Almaty (Kazakhstan) which is the closest city to the country. In general soil temperature depends on incident solar radiation, rainfall, air temperature, local vegetation cover, soil type, and depth in the earth (Build It Solar, 2005). Hence, these factors can be compared for the case study area. The detailed climate and average weather data for Almaty (Kazakhstan) and Naryn (80 km from Ak-Tal) is collected on the web source Weather Spark (weatherspark.com, no date). On the one hand, both locations have almost similar monthly values of incident solar radiation, comparable precipitation levels, and the same soil type and sparse vegetation cover. On the other hand, due to the high-altitude location air winter temperatures in Naryn are a bit lower than in Almaty, and the snow cover level is slightly higher in Almaty. Hence, it is assumed to adopt the soil temperature of Almaty at a depth of 0.8 m for the study calculation but make it lower by 1 degree due to distinct factors (Figure 23).

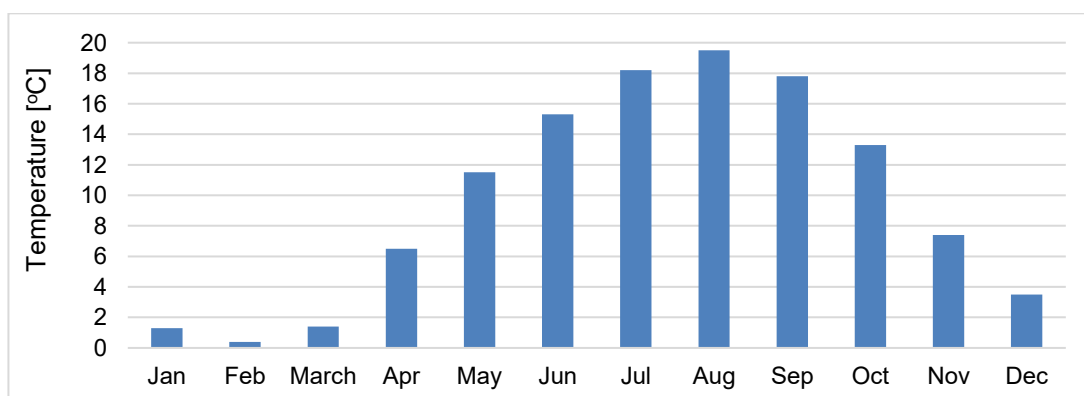


Figure 23. Average soil temperature for the Ak-Tal area

The calculation of heat losses is done in Excel designed tool in hourly manner by the following formula (Kwon, 1998):

$$\text{Heat losses} = \left( \frac{T_{\text{fluid}} - T_{\text{soil}}}{r_{\text{pipe}} + r_{\text{ins}} + r_{\text{soil}}} \right) \cdot L_{\text{pipe}} \quad \text{Eq.4}$$

where,

$T_{\text{fluid}}$ : water temperature in the pipe;

$T_{\text{amb}}$ : soil temperature;

$r_{\text{pipe}}$ : thermal resistance of the pipe wall [K/W];

$r_{\text{ins}}$ : thermal resistance of the pipe insulation [K/W];

$r_{\text{soil}}$ : soil thermal resistance [K/W];

$L_{\text{pipe}}$ : pipeline length [m].

The current calculation of heat losses is done with constant temperature parameters of 80/40 °C (supply/return). This temperature regime is selected based on the analysis of existing solar thermal systems where supply temperatures typically range between 65 and 90 °C, and return temperatures fall within the 35 to 60 °C range (International Energy Agency, 2018). Within this study, the upper limit for the supply temperature is set at 80 °C to prevent boiling within the heating system and network (given that the boiling point is 94 °C at the altitude of the Ak-Tal community). Further reduction in supply temperature is seems impractical, primarily due to the low energy efficiency of the houses. Similarly, the return temperature is fixed at 40 °C and not higher in order to reduce the heat losses in the network and minimize energy consumption for pump operation.

Thermal resistance calculation of the pipe wall, insulation and soil can be found by the following formulas (Kwon, 1998):

$$r_{\text{pipe}} = \frac{\ln(D_2/D_1)}{2\pi\lambda_{\text{pipe}}}, \quad \text{Eq.5}$$

$$r_{\text{ins}} = \frac{\ln(D_3/D_2)}{2\pi\lambda_{\text{ins}}}, \quad \text{Eq.6}$$

$$r_{\text{soil}} = \frac{\ln\left[\frac{d_h}{r_3} + \sqrt{\left(\frac{d_h}{r_3}\right)^2 - 1}\right]}{2\pi\lambda_{\text{soil}}}, \quad \text{Eq.7}$$

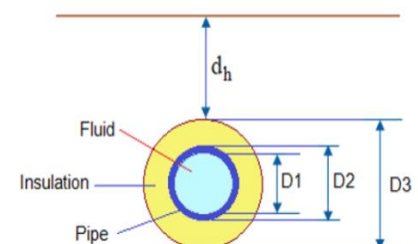
where,

$\lambda_{\text{pipe}}$ : thermal conductivity of the pipe [W/m·K];

$\lambda_{\text{ins}}$ : thermal conductivity of the insulation layer [W/m·K];

$d_h$ : burial depth of the pipe [1 m];

$\lambda_{\text{soil}}$ : thermal conductivity of the soil (1 W/m·K average for sandy clay loam).



Complete characteristics of chosen pipes for the DHS are given in the Table 5 as well as its calculated thermal resistance.

Table 5. Data of district heating pipes

	DN100		DN80		DN50	
	Pipe	Insulation	Pipe	Insulation	Pipe	Insulation
$d_{in}$ [mm]	107.1	114.3	82.5	88.9	54.5	60.3
$d_{out}$ [mm]	114.3	250	88.9	200	60.3	160
Material	P235TR1	Polyurethane	P235TR1	Polyurethane	P235TR1	Polyurethane
Thermal conductivity [W/m·K]	49	0.026	49	0.026	49	0.026
Thermal resistance [K/W]	0.0002113	4.7908	0.0002427	4.9632	0.0003285	5.9735

Due to the proper insulation thickness (10 - 13 cm) of chosen pipes and insignificant temperature fluctuations of the soil, the heat losses value does not change much throughout the year (Figure 24). It is possible to reduce the heat losses in warm months by adjusting the supply temperature depending on the outside air temperature, however, it is required the further work.

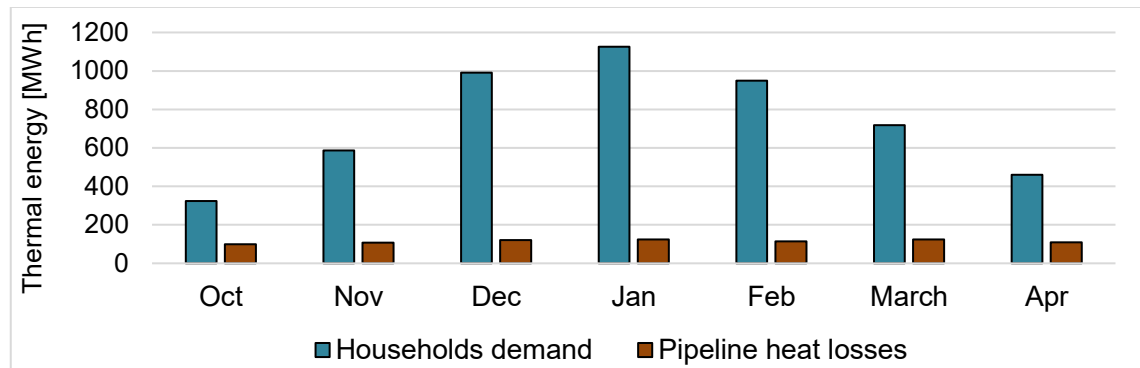


Figure 24. Households heat demand and pipeline heat losses

The months of January and October have the highest and lowest heat losses, amounting to 120 MWh and 99 MWh respectively. Overall yearly losses for the heating period accounts 800 MWh.

### 3.5 Collector field sizing

Here collector field sizing means finding the angle of inclination of the solar collector for the highest thermal energy generation and determining the maximum number of collectors for the parametric study along with finding the inter-row spacing.

The tilt angle refers to the angle at which the solar collector is inclined relative to the horizontal plane. This angle has a significant impact on the amount of solar energy that can be captured and converted into usable heat. Finding the optimal solar collector angle is critical to maximizing the energy efficiency and overall performance of a solar energy system. Additionally, proper tilt angle determination is essential during the current design phase of the solar system since it impacts the arrangement of collectors.

Determination of the optimal tilt angle for solar collector field in the location of Ak-Tal community is done with help of several simulations in Polysun. The simple scheme (collector field, storage tank, boiler) which represented in Polysun templates was taken to evaluate the collector field yield during the heating period (October-April). The size of the collector field and all other input parameters of the system were not changed during the simulations except only tilt angle. The results of this small parametric study on the change in tilt angle and the corresponding output energy can be seen in Figure 25.

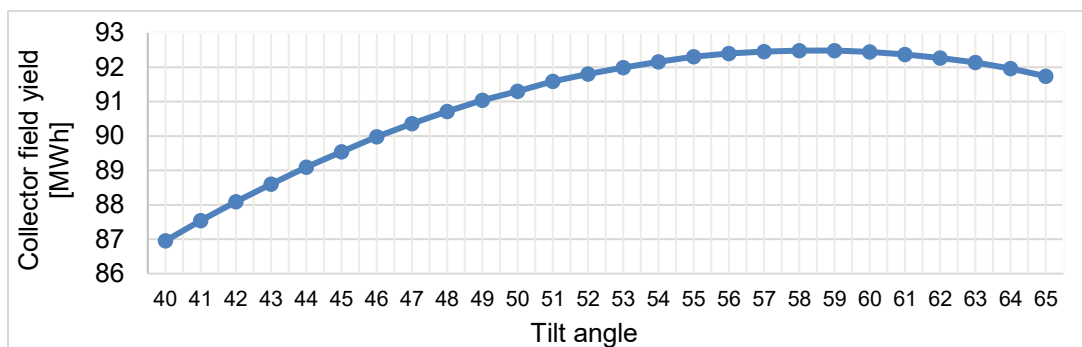


Figure 25. Collector field yield (area of 200m<sup>2</sup>) vs tilt angle

Hence, the collector field yield shows the highest performance at a 59°- tilt angle with equal and non-changeable other system parameters. However, due to the low output difference, it was decided to take a 55° tilt angle to reduce inter-row spacing. It is important that a steeper tilt angle is more effective in capturing sunlight during the winter months when the sun is lower in the sky.

Since the heat demand has the highest values during the winter months it is essential to obtain the maximum available collector's thermal output. For this purpose, it is necessary to know the inter-row spacing, which refers to the distance between rows of solar collectors in an array. It helps mitigate shading which can significantly reduce energy generation by blocking sunlight from reaching the panels.

In the present study, the calculation of inter-row spacing is conducted with a particular focus on the winter solstice period – considered the worst-case scenario for solar energy capture. Figure 26 shows the sun's apparent path in the sky during the year for the Ak-Tal location. On the date of the winter solstice on December 21st, the sun attains its maximum elevation angle of 25° at noon. The specific time window of 10 AM

to 4 PM is selected as the basis for calculations. At this time, the sun's elevation angle is equal to 13 degrees. This elevation angle is key as it affects the distance of the solar collectors for maximum energy absorption.

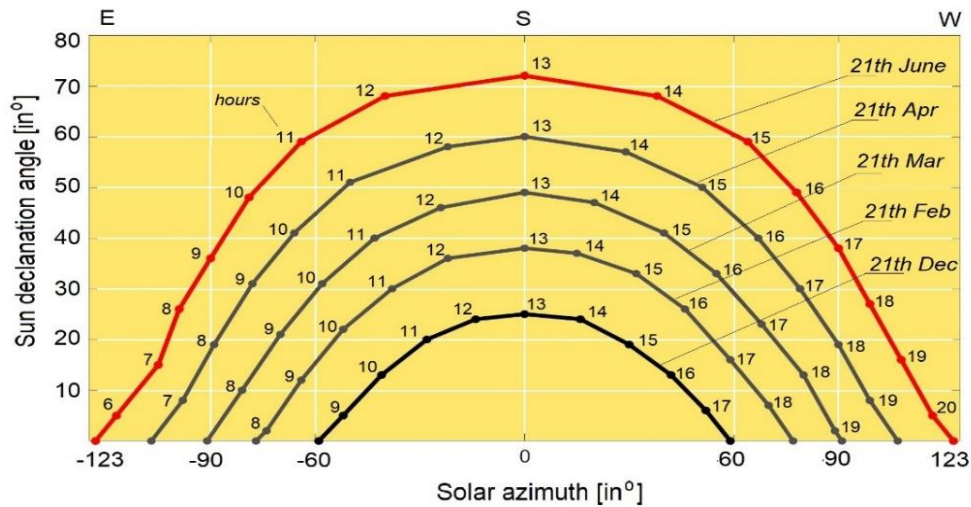


Figure 26. Solar altitude diagram for the Ak-Tal (latitude of 41.413°)

To carry out further calculations of the inter-row spacing the dimensions of the solar collector are required, respectively, it is necessary to decide on the choice of manufacturer and product.

First, the question arises about the type of solar collector and there are three main ones on the market: flat-plate collectors, evacuated tube collectors, and concentrating collectors (Zach Stein, 2023). Evacuated tube collectors have an advanced design with their high efficiency due to vacuum insulation. Concentrating collectors use mirrors or lenses to focus sunlight onto a smaller absorber area, resulting in high efficiency even when sunlight is low. Although these types of collectors have a high efficiency, the technologies used there are more complex in production and therefore the most costly. Flat-plate collectors are characterized by their production simplicity and low maintenance requirements, and consequently are cost-effective. Despite the lower efficiency, these collectors are widely used in various projects for the production of thermal energy. Therefore, the decision on the choice of the type of solar collector stops at a flat-plate collector.

Once the collector type has been decided, the next steps should be taken regarding the selection of the manufacturer and the products they offer. In this regard, it was decided to choose a local manufacturer. This solution is beneficial in supporting local industry and provides the advantage of proximity, potentially simplifying logistical considerations. However, there are no local manufacturers in the Kyrgyz Republic, but within the Central Asia region, one company called “Kuntech” (Kuntech, no date) was



found in Kazakhstan which produces flat-plate solar collectors. The data of the chosen solar collector is given in Table 6.

Table 6. Data of the flat plate collector “Kuntech”

Parameter	Value	Unit
Gross area	$2.04 \times 1.04 = 2.122$	$m^2$
Aperture area	2.03	$m^2$
Absorber area	1.75	$m^2$
Optical efficiency	0.815	-
Volume	1.37	l
Max. flow rate	100	l/h
Max. pressure	6	bar
Max. temperature	170	$^{\circ}C$

After selecting a solar collector with the available dimensional data, the determination of the inter-row spacing is based on the simple mathematics of a right triangle (Adam Diehl, 2020). The calculation steps are given below:

$$\begin{aligned} \text{Height difference} &= \text{collector length} \times \sin(\text{tilt angle}) = && \text{Eq.8} \\ &= 2.04 \times \sin(55^{\circ}) = 1.67 \text{ m.} \end{aligned}$$

$$\begin{aligned} \text{Inter-row space} &= \text{height difference} / \tan(\text{solar elevation angle}) = && \text{Eq.9} \\ &= 1.67 / \tan(13^{\circ}) = 7.233 \text{ m.} \end{aligned}$$

Azimuth Correction:

$$\begin{aligned} \text{Minimum inter-row space} &= \text{Inter-row space} \times \cos(\text{azimuth angle}) = && \text{Eq.10} \\ &= 7.233 \times \cos(40^{\circ}) = 5.55 \text{ m.} \end{aligned}$$

All the results of the calculations can be seen in Figure 27. The calculated minimum required inter-row space is equal to 5.55 m, but it is decided to round it up to 6 m.

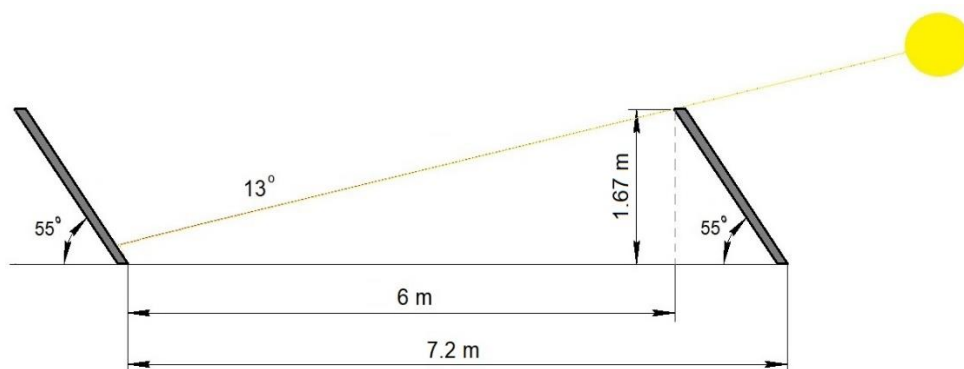


Figure 27. Inter-row space determination

To proceed with the subsequent parametric analysis, the maximum number of collectors is required to know which will serve as the upper limit of the parametric study. Hence, an upper limit can be set based on the available land for station placement. Therefore, the Google Earth is used to determine the optimal land location for the proposed solar collector field. The selected place is not used for agricultural purposes and its dimensions are shown in Figure 28.

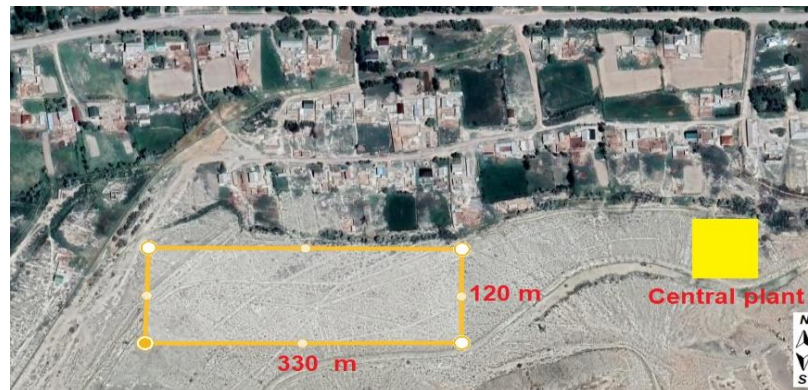


Figure 28. Possible location of the solar collector field

According to the previously calculated data of the distance between the collectors and the required place for the collector itself, it is possible to determine the capacity of the place. In the defined land spot, it is possible to place sixteen rows of 317 collectors, so 5,072 in total. Hence, the result is rounded to thousandths, and it is a maximum collector's number of 5,000 as the upper simulation limit.

## 4. SIMULATION AND RESULTS

### 4.1 Load profile

The load profile for the simulation is based on the heat demand of community households. However, it is decided to increase this heat profile by 20% as a structural shift of the heat plant capacity considering possible future new households' connections and having a reserve in case of worst weather conditions. Hence, the final profile for simulation includes the structural shift of 20% and calculated heat losses in the district heating network (Figure 29). The profile does not include domestic hot water consumption since households do not have appropriate amenities. The simulation considers only the need for heat during the heating period from October to April.

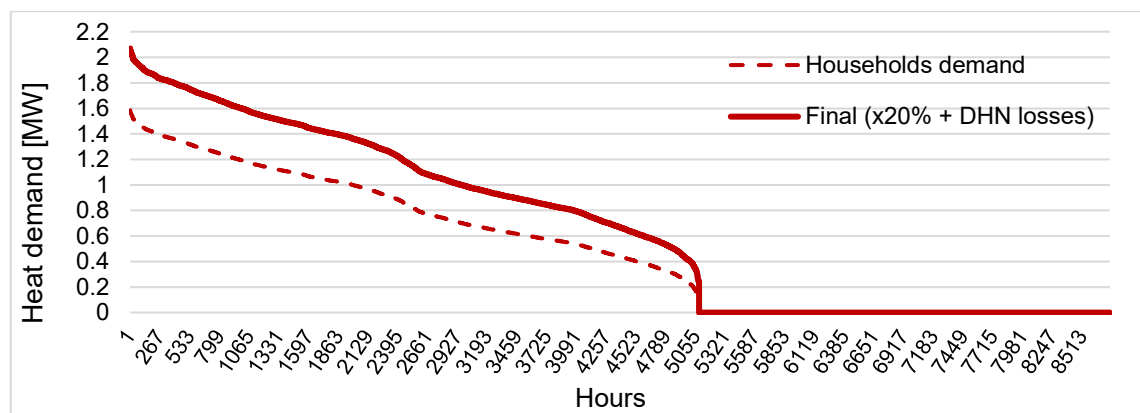


Figure 29. Load duration curve

Figure 29 shows the difference between the two profiles based on the load duration curve. The net heat demand of the households only is equal to 4,295.211 MWh with a peak load of 1.6 MWh. To obtain the final simulation profile this number increases almost by 39%, 20% of energy reserve, and 19% of DHN losses. The final demand accounts for 5,955.061 MWh with a peak load of 2.07 MWh.

The annual peak load is the key quantity that has immense importance in determining the size of the system, as well as the time of the day when it occurs. The peak load in the current simulation profile (2.07 MWh) is a consequence of the low night temperature and reaches a maximum in the morning (Figure 30). At this point in time, there is no solar collector field yield since the sun rises after 8 o'clock in January. For the system, this means that the auxiliary heater must be sized by the peak load to cover the demand.

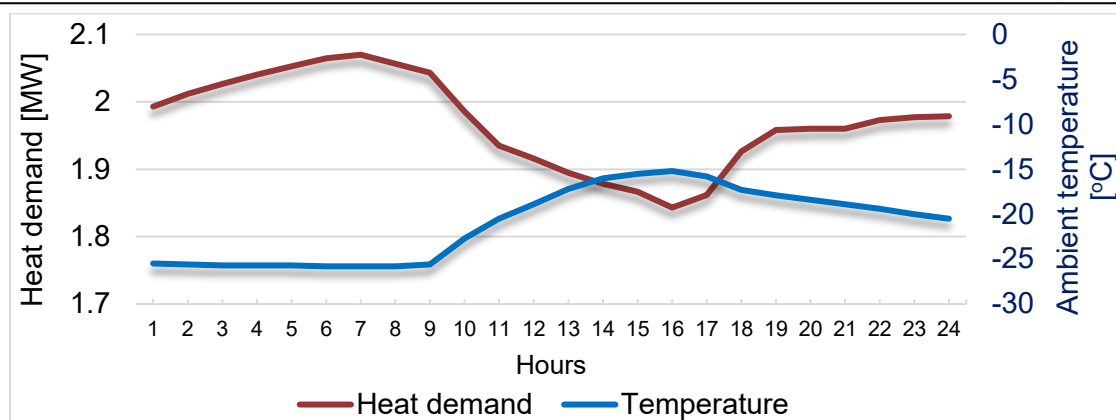


Figure 30. Peak heat demand vs ambient temperature (January)

Thus, the heat load profile including the DHN losses is loaded into the model element “energy sink”. Overall, this profile contains four parameters: time in seconds, supply and return temperature, and required heat (Figure 31).

	A	B	C	D
1	#The first entry has to be the at the simulation time 0.			
2	#Those values are also used for the the flowrate calculations.			
3	#			
4	#Simulationtime[s]	Inlettemp.[C]	Outlettemp.[C]	Power[W]
5	0	80	40	-1087794.062
6	3600	80	40	-1097719.286
7	7200	80	40	-1104225.894
8	10800	80	40	-1109780.764
9	14400	80	40	-1114831.62

Figure 31. Simulation profile of the heat demand

Hence, a specific quantity of heat is required every hour throughout the year, and Polysun will calculate the flow rate based on the given temperature regime during the simulation. The heat demand is equal to zero in the non-heating period.

## 4.2 Weather data

In the Polysun software the weather data for the simulation can be set based on geographic location. Further, based on the location there are several options to access the data: Meteonorm 7.2 or 6, Meteonorm webservice, upload a personal profile and change monthly values.

In the present study, the option of Meteonorm webservice data is used due to the most up-to-date data. The site location is chosen from the map (41.411°, 75.057°), and according to this position Polysun will use all required weather parameters for the simulation.

### 4.3 Simulation parameters

Configuring simulation parameters is an important part of the study to get accurate system performance results. Knowing the real-life parameters of the examined system, it is possible to get precise data on the operation of the system using simulation. However, the system under this thesis study does not exist and all parameters are based on assumptions. But this does not reduce its importance, as it affects the correct operation of the model and the accuracy of the output data. All important parameters of the model used in the simulation are listed in Table 7.

Table 7. Simulation parameters

<b>Simulation parameters</b>	<b>Value, unit</b>
Solar field orientation	South, no tracking
Tilt angle	55 °
Number of collectors	500 – 5,000 (step 500)
Corresponding aperture area	1015 – 10,150 m <sup>2</sup>
Max collector temperature	160°C
Solar loop fluid	Water - propylene glycol, 33%
Pipe to and from solar field:	Underground installation
Pipe and insulation material	Steel, polyurethane foam
Internal / external diameter	54.5 / 60.3 mm
Insulation thickness	60 mm
Depth	0.5 m
Length supply + return	500 + 500 m
Water tank volume	100 – 1,000 m <sup>3</sup> (step 100)
Water tank height	4 m
Number of tank layers	12 (default)
Tank material and thickness	Steel, 2.5 mm
Tank insulation and thickness	Rigid PU foam, 120 mm
Max tank temperature	90°C
Set point temperature (electric boiler)	86 °C
Electric boiler efficiency	99 %
Profile supply / return temperature	80 / 40 °C
Controllers work time	October - April
Simulation time	8,760 hours

Solar collectors are directed to the south at an angle of 55 degrees and do not track the path of the sun. The working fluid in the solar loop is a mixture of water and propylene glycol due to its anti-freezing property. In the simulation, a volumetric percentage of propylene glycol is equal to 33%. This value is recommended by the Polysun user manual as the optimum between the proper thermal capacity of the working fluid and the freezing point.

According to the supply temperature of the heat profile (80 °C), on the one side, it is chosen so that the system does not reach the boiling point due to safety and efficiency reasons (lower losses). The boiling point is around 94 degrees at the height where the Ak-Tal community is located (1,650 m). On the other side, lower supply temperature (for example, low-temperature DHN) may not be as effective as community households are not energy efficient and have heat leakage. In such case with a low temperature, it will be necessary to increase the feed flow rate to meet the required demand.

The set point temperature for the electric boiler is chosen to be 86 °C based on the test simulations. With temperatures below this value, it is not possible to cover the annual heat demand due to heat losses of the system elements.

#### **4.4 Parametric study**

A parametric study helps to understand the impact of several factors on the solar fraction and optimize system design and performance. Here, the main goal of the parametric study is to find out the optimal volume of the storage tank to the area of the collectors.

For the analysis, two parameters were varied while the rest model parameters were kept constant according to Table 7. In this table the parameters to be changed are indicated, this is the number of panels and the volume of the tank.

Since the estimated maximum number of collectors is 5,072, for the analysis it was decided to take the range of variation 500 – 5,000 with step 500. Here the case is in the number of collectors, since this is a configurable parameter in the solar field menu in the Polysun, and the corresponding area is calculated automatically from this number.

Regarding the storage tank volume, various articles and other sources suggest and use a ratio of 50 – 100 liters per square meter of collector area depending on the system purpose. For example, one of the sources contains a system design guide where for a system with short-term storage a ratio 70 – 100 liters per square meter of collector surface is recommended (Planning and installing solar thermal systems, 2010, p. 179). Hence, based on the defined range of collectors and the relevant surface area,

for the analysis it was decided to take the range of variation of the tank volume 100 – 1,000 cubic meters with step 100.

Thus, to find the optimal volume of the tank to the area of the collectors in the parametric study the solar fraction was calculated. The solar fraction is calculated as the heat produced by the solar field divided by the total produced heat (solar field and auxiliary heater). The results of calculations based on the conducted simulations are presented in Figure 32. The lowest solar fraction of 6.7 % is achieved by 500 collectors (area 1,015 m<sup>2</sup>) with the tank volume of 100 m<sup>3</sup>. The highest solar contribution of 25.9% is done by 5,000 collectors (area 10,150 m<sup>2</sup>) with the tank volume of 700 m<sup>3</sup>.

500	<b>0.067</b>	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	1,015
1,000	0.123	<b>0.126</b>	0.126	0.127	0.127	0.126	0.126	0.126	0.126	0.126	2,030
1,500	0.150	0.164	<b>0.166</b>	0.166	0.166	0.166	0.165	0.165	0.165	0.165	3,045
2,000	0.164	0.186	0.193	<b>0.194</b>	0.194	0.194	0.194	0.194	0.194	0.194	4,060
2,500	0.173	0.198	0.210	<b>0.215</b>	0.215	0.215	0.215	0.215	0.215	0.215	5,075
3,000	0.179	0.207	0.222	0.229	<b>0.231</b>	0.231	0.231	0.231	0.231	0.231	6,090
3,500	0.184	0.214	0.230	0.240	<b>0.243</b>	0.243	0.243	0.243	0.243	0.243	7,105
4,000	0.187	0.219	0.235	0.248	<b>0.250</b>	0.250	0.250	0.250	0.250	0.250	8,120
4,500	0.190	0.223	0.238	0.252	<b>0.255</b>	0.255	0.255	0.254	0.254	0.254	9,135
5,000	0.192	0.226	0.239	0.254	0.258	0.258	<b>0.259</b>	0.257	0.257	0.257	10,150
	100	200	300	400	500	600	700	800	900	1000	

Figure 32. Solar fraction of the system (October – April)

Therefore, for each analyzed number of collectors, the optimal volume of the storage tank was determined based on the first highest solar fraction in the row. As it can be seen in Figure 32 these values are highlighted in bold. Thus, the determined values based on the simulation results indicate that for a specific collector area, the tank volume located at the intersection of these values is preferable for the system. This is so, because with a given smallest tank volume and a given area of collectors, the solar collector field can contribute the highest heat production.

Also, by the numbers to the left of the marked cells, it can be distinguished that with the smallest volume, the system cannot accommodate all the produced solar energy. So, in these cases, stagnation of the solar thermal system occurs, which is desirable to avoid during the solar collector's operation. By almost constant values on the right side of the marked cells, it can be understood that the largest volumes of the tank are not effective, but only will oversize the system.

#### 4.5 Preferred solar fraction concept and its analysis

The parametric study conducted with a given range of parameters showed that solar heat production can reach 26% with the maximum available collector area (10,150 m<sup>2</sup>). However, the case-study system is not operational during the “summer” months (May – September) and does not have seasonal storage. In such a case for the system with short-term storage the annual solar fraction lower than 20% is commonly used (International Energy Agency, 2019).

Therefore, as a preferred concept for the heating system design in the Ak-Tal community, it is decided to take the option with a solar fraction of 19.4% which is achieved by 2,000 collectors and the storage tank of 400 m<sup>3</sup>.

Figure 33 represents the annual energy balance of the designed heating system with a solar fraction of 19.4%. All results are obtained from simulation in Polysun software. There is irradiation onto solar collectors (E<sub>sol</sub>), collector field yield (Q<sub>sol</sub>), energy flow through heat exchanger (Q<sub>xfr</sub>), fuel/electricity consumption by the auxiliary heater (E<sub>aux</sub>), heat transferred to the system by the boiler (Q<sub>aux</sub>), total heat transferred to the heating network (Q<sub>use</sub>), and losses.

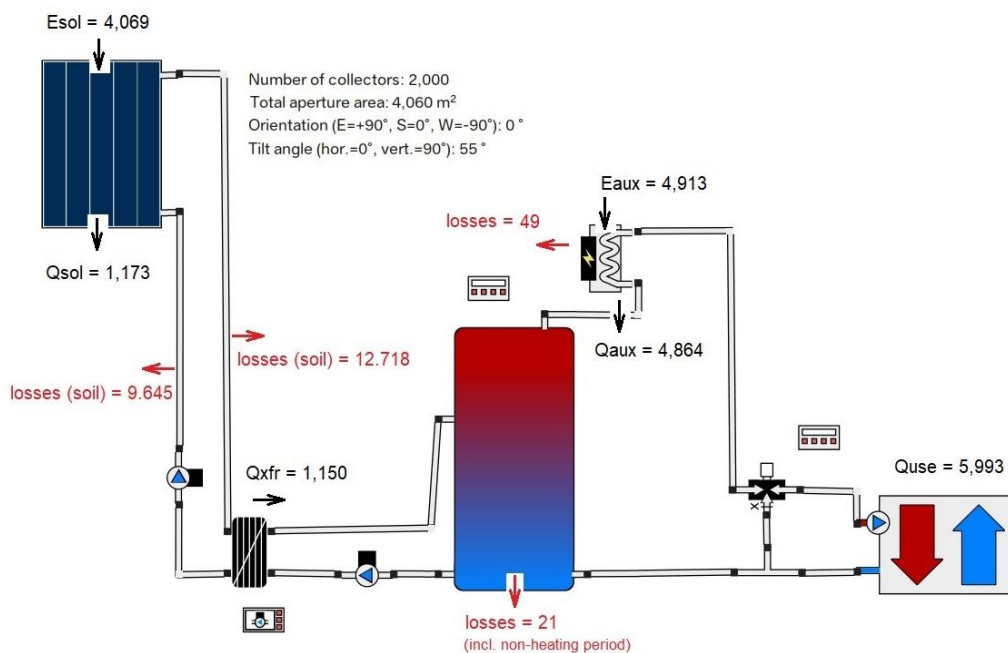


Figure 33. Annual energy balance (units = MWh/year)

The resulting value of the total heat transferred to the heating network is higher than the required heat demand (5,955.061 MWh) because it is impossible to obtain the exact numbers. However, the difference between the simulation result in Q<sub>use</sub> and the heat demand is lower than 1%. Pipes installation to and from the solar field was chosen underground to make the results of the system more realistic and consider the losses in the solar loop as well. According to the simulation results these losses account for a



little over 22 MWh for a total length of 1,000 m at the depth of 0.5 m. Yearly losses of the storage tank account for 21 MWh and it includes losses in the non-heating period (5.5 MWh) because the tank still contains left energy at the time of system shutdown.

Figure 34 illustrates the solar energy received and produced by the solar collector field along with corresponding collector thermal efficiency. Since flat-plate solar collectors are used and the system is located and operates in harsh climate conditions, the efficiency is not so high. The highest efficiency values around 31% occurs in months with warmer ambient temperatures and higher global irradiation.

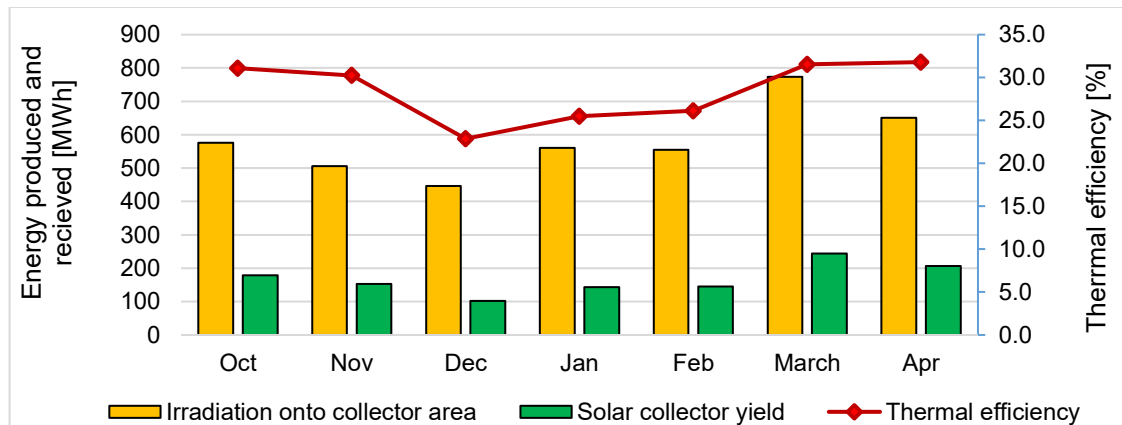


Figure 34. Thermal efficiency of solar collector field

Figure 35 demonstrates more detailed data on heat production by solar collector and auxiliary heater and the corresponding solar fraction in each month of the heating period. The winter months have a low solar fraction and higher reliance on the auxiliary heater because of a combination of reduced solar irradiance and increased heating requirements due to colder weather conditions. The lowest solar fraction of 9% is found in December and the highest with 41.7% in October due to the lowest heat demand.

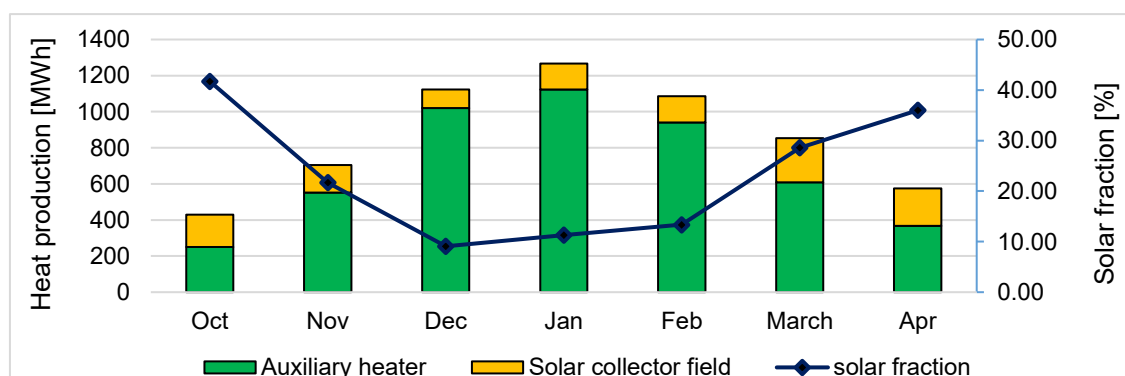


Figure 35. Monthly heat production and solar fraction

Figure 36 clearly indicates that the peak heat demand is solely met by the heat generated from the auxiliary heater. This finding coincides with the previous analysis of heat load (Figure 30), where it was highlighted that the power rating of the auxiliary

heater should be chosen following the peak heat demand of the system. Selecting an auxiliary heater with a capacity matching the peak heat demand becomes essential to ensure reliable and consistent heating performance, especially when solar energy availability is limited.

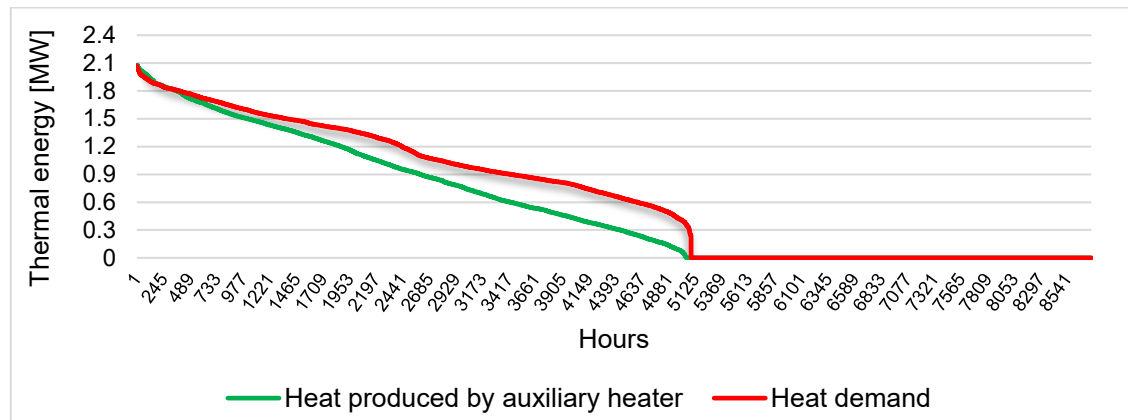


Figure 36. Duration curve of heat demand and heat produced

Figure 37 provides data on the temperature in the bottom layer and the top layer of the storage tank throughout the year. It can be seen from the graph that the temperature in the top layer experiences rapid changes or fluctuations. These fluctuations show that the heat transfer processes of charging and discharging within the storage tank are more dynamic in the upper layer. Such temperature changes in the top layer are influenced by the proximity to the heat input from the solar field, as well as high heat exchange rates when the water flow rate can reach up to 45 m<sup>3</sup>/h at peak heat demand. Also, a gradual drop in the water temperature can be observed after turning off the system for a non-heating period. Part of the tank losses of 5.5 MWh (Figure 33) mentioned earlier relates to this drop in temperature.

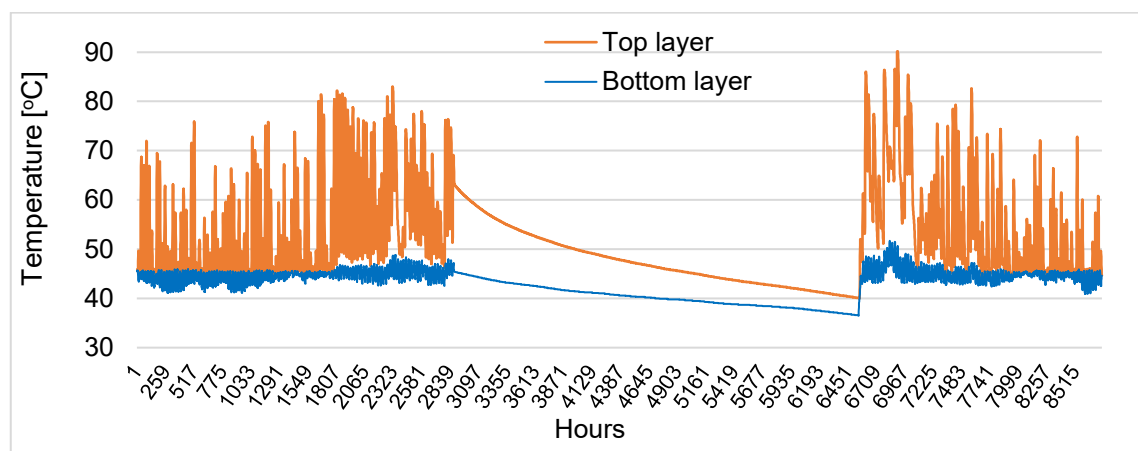


Figure 37. Temperature in the storage tank

The pie chart in Figure 38 provides an overview of the proportionate distribution of energy production, consumption, losses, and energy reserve within the district heating

system with a yearly solar fraction of 19.4%. According to the chart, the production by the auxiliary heater amounts to 81% of the total energy production. This significant share the production by the auxiliary heater indicates its crucial role in meeting the heating demand. Although the percentage of solar thermal energy is relatively small, it highlights the importance of solar thermal technology in reducing dependency on conventional heating methods. The largest portion of energy, 72% of the total, is consumed for space heating purposes. Losses in the distribution network account for 14% of the energy distribution. An additional 14% of the energy is allocated as an energy reserve specifically designed for challenging conditions. This reserve serves as a buffer during periods of extreme cold weather or increased heating demands.

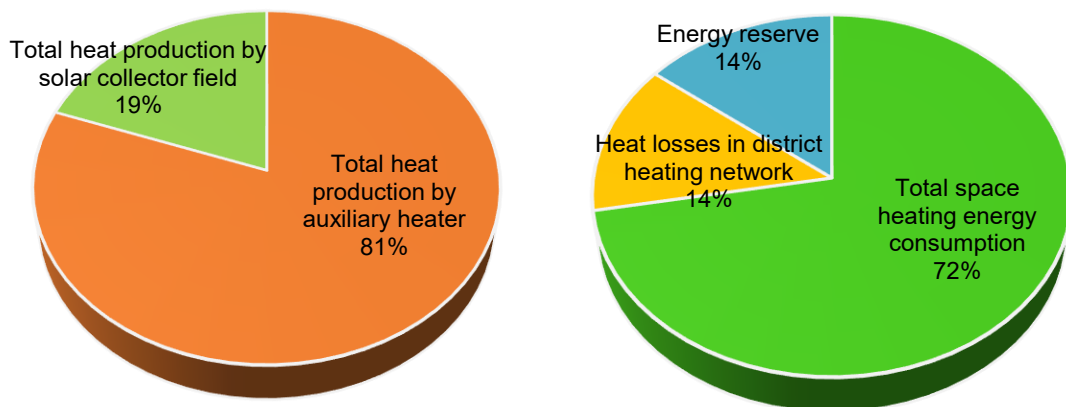


Figure 38. Energy distribution in the analyzed heating system

Overall, to achieve the solar fraction of 19.4% in the analyzed heating system, 2,000 solar collectors and a storage tank with a volume of 400 m<sup>3</sup> are required in the Polysun simulation. The solar thermal system helps to reduce consumption from non-sustainable sources of heat and contributes 1,173 MWh of energy to the system during the heating period. The solar system shows good performance in March with the highest energy production of 244 MWh while the lowest is in December with 102 MWh.

## 5. TECHNO-ECONOMIC ANALYSIS

This section presents the economic evaluation of the solar DHS, providing an analysis of the full-cost accounting. The analysis takes into account the total lifecycle costs, including initial investment, operational expenses, maintenance, and fuel costs, to provide a comprehensive view of the financial implications associated with different heating options. Based on these costs the assessment compares the solar assisted DHS with two alternative auxiliary heaters: an electric boiler and a coal boiler, as well as an individual household system with a stove.

The Ak-Tal community as a remote area has access only to the electric grid, hence the option with an electric boiler as an auxiliary heater is considered. However, the Kyrgyz Republic faces energy insecurity due to reliability only on hydropower energy sector and outdated infrastructure (Mehta et al., 2022). Thus, the second option with a coal-fired boiler is examined since coal is an available and widely used source of heat. For the comparison the third option is added with an individual household system with a stove using coal basically how it exists now. But the household system is improved to enhance the efficiency and effectiveness meaning the addition of distribution system with radiators and a modern stove.

The economic assessment is based on the data from an early analyzed system concept with a solar fraction of 19.4%. Based on the simulation results and analysis of the boiler energy production data and the heat demand (Figure 36), it is required to select the nominal capacity of the auxiliary heater according to the peak heat demand. All general data of the solar assisted DHS for economic evaluation are presented in the Table 8.

Table 8. General data for the economic assessment

Number of solar collectors	2,000
Storage tank volume	400 m <sup>3</sup>
Nominal capacity of the auxiliary heater	2.1 MW (thermal energy production)
Length of district heating network	16,900 m (supply and return)
Thermal energy by the solar field	1,173 MWh
Thermal energy by the auxiliary heater	4,864 MWh
Pumps electricity consumption	3.5 MWh
Electricity price	0.0298 €/kWh (2.87 KGS/kWh) (Decree of the Cabinet of Ministers dated 06.04.23 No. 199 2023)
Coal price	41.6 €/t (4000 KGS/t) (Kadyrbekov T., 2022)(Kadyrbekov T., 2022)

Discount rate	7.5 % p.a
Analysis period	25 a

The economic evaluation of energy projects is mainly based on the assessment of the levelized cost of energy (LCOE). The calculation of the levelized cost of heat (LCOH) further in the present work is done by the formula represented in the IEA report (International Energy Agency, 2016) and it is given below (eq.10).

$$LCoH = \frac{I_0 + \frac{\sum_{t=1}^n O\&M_t}{(1+r)^t}}{\frac{\sum_{t=1}^n E_t}{(1+r)^t}}, \quad \text{Eq.11}$$

where,

n: lifetime of the system;

$I_0$ : investment expenditure in year zero;

O&M: operation and maintenance expenditure;

E: annual heat generation [kWh/a];

r: discount rate.

The lifetime of the system and discount rate is taken from the report on renewable power generation costs (IRENA, 2021). According to this report the evaluation is done for the 25-year economic life and the discount rate for countries besides The Organization for Economic Co-operation and Development (OECD) countries and China is assumed to be 7.5%.

## 5.1 Solar thermal and electric boiler

Here the economic assessment is done for the solar-assisted DHS with an electric boiler as the auxiliary heater.

The price of a solar collector is indicated by the manufacturer per piece (Kuntech, no date), respectively, it is calculated according to the required number of collectors. According to the price list of the company with prices for typical systems, related equipment for the solar system (mounting frame, pipes, pumps, controllers, expansion tank, heat transfer fluid) is around 40% of the cost of collectors. The cost of installing the system is also indicated there and is equal to 20-30% of the total cost, and this figure is taken for present calculations along with an installation.

Since it is required to provide a maximum of 2.1 MW of thermal energy per hour then the industrial-scale electric boiler needs to be installed. A manufacturer of boilers of such a capacity was found with published prices that sells and delivers products in Central Asia (Nevsky LLC, no date). However, the maximum available capacity is 1

MW, respectively, there are two boilers of 1 MW and one 250 kW in the calculations (Annexure B).

The cost of the storage tank is evaluated based on the IEA report (International Energy Agency, 2016). The Agency presented the tank cost as a cost function formula for pressurized carbon steel tanks for volumes of 0.5 m<sup>3</sup> – 500 m<sup>3</sup>:

$$C_{TTES}(V_{storage}) = 403.5 \cdot V_{storage}^{-0.4676} + 750. \quad \text{Eq.12}$$

The cost estimation for heating pipes relies on assumptions due to the absence of a price list on the official website. Instead, the prices of BRUGG pipes were found in one online shop (WOLF-ONLINE-SHOP, no date), and an average price per meter was assumed based on these available prices.

Engineering consulting for projects varies from 5% to 15% based on the obtained data, hence on average, 10% is taken for the present calculations.

Table 9 provides a comprehensive overview of the costs associated with the project's implementation and ongoing operation and maintenance expenses.

Table 9. Investment for solar thermal system with electric boiler (based on the mentioned sources)

<i>Initial investment</i>		<b>Cost [€]</b>
Solar collector	2,000	560,000
Solar field piping and etc.	40% of collectors	224,000
Electric boiler ( $\eta=99\%$ )	2 x 1,000 kW	54,865
	250 kW	7,566
Storage tank	400 m <sup>3</sup>	309,799
Energy center	100 m <sup>2</sup>	20,800
Heating network pipes	150 €/m	2,535,000
Engineering consulting	10% of equipment	371,203
Shipping and Installation	40% of equipment	1,476,492
		<b>5,559,725</b>
<i>Yearly O&amp;M cost</i>		<b>Cost [€]</b>
Electric power (pumps)		104
Electric power (boiler)	4,913.13 MWh	146,647
O&M cost	1% of Investment	55,597
		<b>202,244</b>

The following Figure 39 shows the results of the detailed economic assessment as a breakdown of investments.

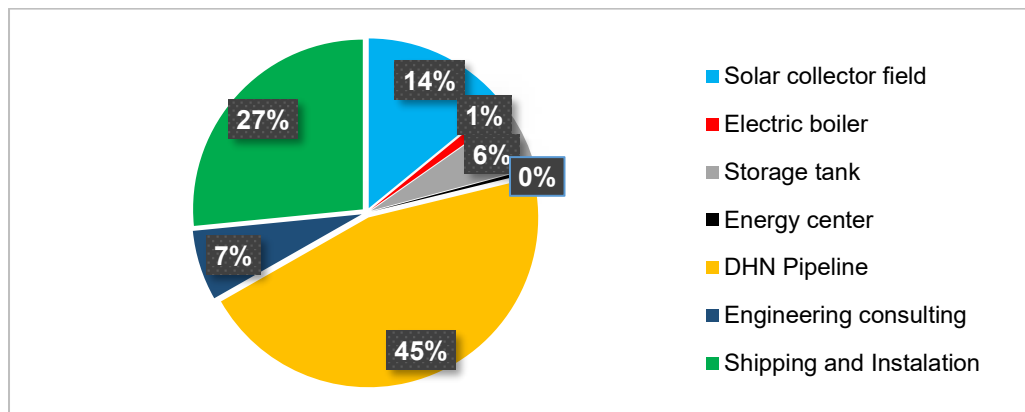


Figure 39. The breakdown of the investment (solar thermal with electric boiler)

The analysis highlights three key components that account for the most significant costs: the DH pipes (45%), the solar collector field (14%), and expenses on the shipping of all equipment and its installation including the DH pipeline (27%). Against the backdrop of previous high expenses, the cost of a storage tank, an electric boiler, an energy center, and the cost of engineering consulting is relatively small and amounts to 14%.

## 5.2 Solar thermal and coal-fired boiler

Here the economic assessment is done for the solar-assisted DHS with a coal-fired boiler as the auxiliary heater.

The economic evaluation is conducted similar to the assessment of the system with electric boiler. The number of solar collectors and the storage tank volume do not change. The area of the energy center should be increased as a large capacity coal fired boiler requires more space than electric boilers.

The manufacturer of industrial-scale coal-fired boilers who delivers products to Central Asia was found with established prices and technical datasheets (Energia-Spb LLC, no date). The nominal capacity of the chosen coal-fired boiler is equal to 2,500 kW with an efficiency of 85% (Annexure C). The fuel consumption of such a boiler amounts to 585 kg/h according to the technical datasheet. Hence, the coal consumption to produce 1 kWh is equal to 0.234 kg. Therefore, to produce thermal energy of 4,864 MWh from the side of the auxiliary heater, it is necessary to consume 1,138.176 tons of coal during the year.

The costs associated with the project's implementation and ongoing operation and maintenance expenses are represented in Table 10.

Table 10. Investment for solar thermal system with coal-fired boiler (based on the mentioned sources)

<i>Initial investment</i>		<b>Cost [€]</b>
Solar collector	2,000	560,000
Solar field piping and etc.	40% of collectors	224,000
Coal boiler	2,500 kW ( $\eta=85\%$ )	18,400
Storage tank	400 m <sup>3</sup>	309,799
Energy center	200 m <sup>2</sup>	41,600
Heating network pipes	150 €/m	2,535,000
Engineering consulting	10% of equipment	368,880
Shipping and Installation	40% of equipment	1,458,880
		<b>5,516,558</b>
<i>Yearly O&amp;M cost</i>		<b>Cost [€]</b>
Electric power (pumps)		104
Coal consumption	1,138.176 t	47,348
O&M cost	1% of Investment	55,166
		<b>102,429</b>

Figure 40 shows the results of the detailed economic assessment as a breakdown of investments.

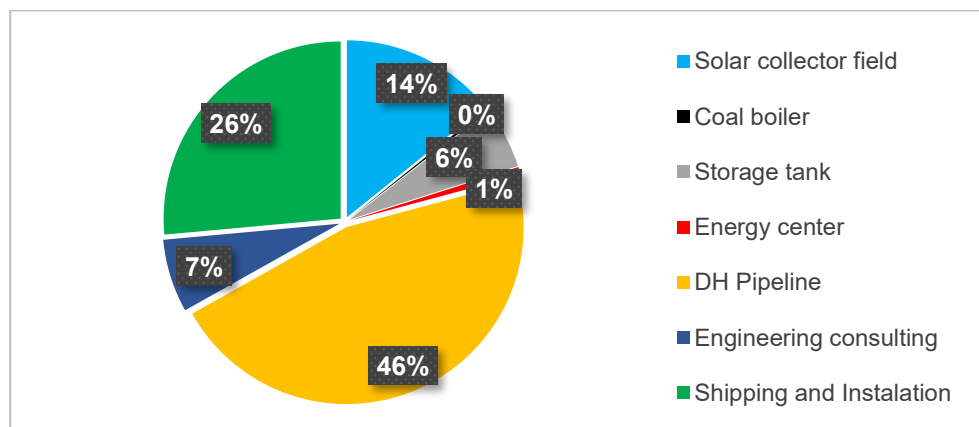


Figure 40. The breakdown of the investment (solar thermal with coal-fired boiler)

In general, the investments pie chart looks similar to the chart of the system with an electric boiler since the difference is only in the cost of the auxiliary heater. The price of the coal-fired boiler is lower than the electric one with the same capacity, and even on the chart it amounts around to 0% due to other higher expenses.



### 5.3 Individual home system with coal-fired boiler

In this chapter, the individual home system with a coal-fired boiler is considered for a house with an area of 100 m<sup>2</sup>. According to the results of the simulation obtained in the EnergyPlus by Kedar Mehta the annual heat demand of such a house in the Ak-Tal community amounts to 32,719 kWh (including the summer period) with peak heat demand of almost 12 kW (Mehta, 2020).

According to known data, the required nominal capacity of a coal-fired boiler is 15 kW if the boiler efficiency is usually 80 – 85%. Based on accessibility for the population, a local manufacturer producing heating boilers for domestic use in the Kyrgyz Republic was taken for an assessment (Thermogradus Ltd, no date).

Regarding the hydraulic system in the house, radiators are found on one of the online marketplaces (VALTEC Engineering plumbing, no date). The heat transfer of one section of one of the selected bimetallic radiators is 187 W, therefore, 64 sections need to be installed to cover the peak heat demand of 12 kW.

The chosen coal-fired boiler does not have any data on coal consumption hence it is calculated based on the coal calorific value. Net calorific value is taken for the coal from one of the biggest coal deposits which is located in the Naryn region and it is equal to 5.5 kW/kg according to one article in the local journal of Kyrgyz-Russian Slavic University (Karabaev S.O. et al., 2010). Hence, based on this data the yearly coal consumption amounts to around 6 tons. However, the heat demand of 32,719 kWh includes also the summer period so when the heating is essential in the heating period (October – April) the demand seems to be lower somewhere by 5,000 kWh (Mehta, 2020). But considering boiler efficiency of 80 – 85% as well it can be assumed that the coal consumption is the previously calculated 6 tons.

Table 11 presents the data on estimated investments for an individual home system with a coal-fired boiler.

Table 11. Investment for an individual home system with a coal-fired boiler (based on mentioned sources)

<i>Initial investment</i>		<b>Cost [€]</b>
Coal-fired boiler	15 kW	312
Radiators, pipes	64 sections	624
Shipping and Installation	30% of equipment	281
		<b>1,217</b>
<i>Yearly O&amp;M cost</i>		<b>Cost [€]</b>
Coal consumption	6 t	<b>250</b>

## 5.4 Comparison of system options

The economic assessment is done for the DHS with an electric boiler and the one with coal-fired boiler, and for an individual home system with a coal-fired boiler.

Overall, in the present study, the calculation for the DHS does not yet include the land price since the chosen land spot is not used for agricultural or any other purposes. The prices found and presented here may be higher in a real-life project due to the remoteness of the case study location but are unlikely to be lower.

The economic evaluation of the three system options is represented by the calculation of the levelized cost of heat (Table 12) based on the previously estimated investments and operation and maintenance expenses. The period of analyzation for the both of DH systems is 25 years as standard for such projects but for an individual home system is 10 years as a lifespan of water-heating boilers is around 10 years. However, the replacement of both electric and coal-fired boilers does not really affect the LCOH due to the low costs relative to the capital investments.

Table 12. LCOH of the estimated system options

	DHS with electric boiler	DHS with coal-fired boiler	Individual home system with a coal-fired boiler
LCOH, €-ct/kWh	11.77	10.03	1.13

From Table 12 it can be seen that the difference in LCOH between the DHS with an electric boiler and the one with coal-fired boiler is around 2 cents. This difference is primarily due to the difference in operating costs associated with the two heating sources. The annual costs associated with the use of coal as a fuel source are about three times lower than those associated with the use of electricity for heating. At the same time, capital investments in a coal-fired boiler are also three times less than in an electric one, but if the price were equal, the LCOH would still not change.

The most costly part of a project for the DH systems is the construction of a heating distribution network. With the exclusion of expenses for this field from capital investments, the LCOH is reduced by 2 times.

A significant contrast is seen when comparing the LCOH for an individual domestic coal-fired boiler system and DH systems. The LCOH for an individual home system is significantly lower, about 9 to 10 times less than the LCOH for a DHS. The cost savings in this scenario are primarily due to the localized nature of the individual home system. As a result, the operating costs associated with heat transportation and distribution are markedly reduced compared to the more complex network in a DHS.

Figure 41 offers an overview of the cumulative cash flow for both the DHS with an electric boiler and the DHS with a coal-fired boiler. This representation includes financial inflows and outflows throughout the life cycle of the project, such as thermal energy sold (heat demand x20%) at the calculated LCOH and annual operating and maintenance costs.

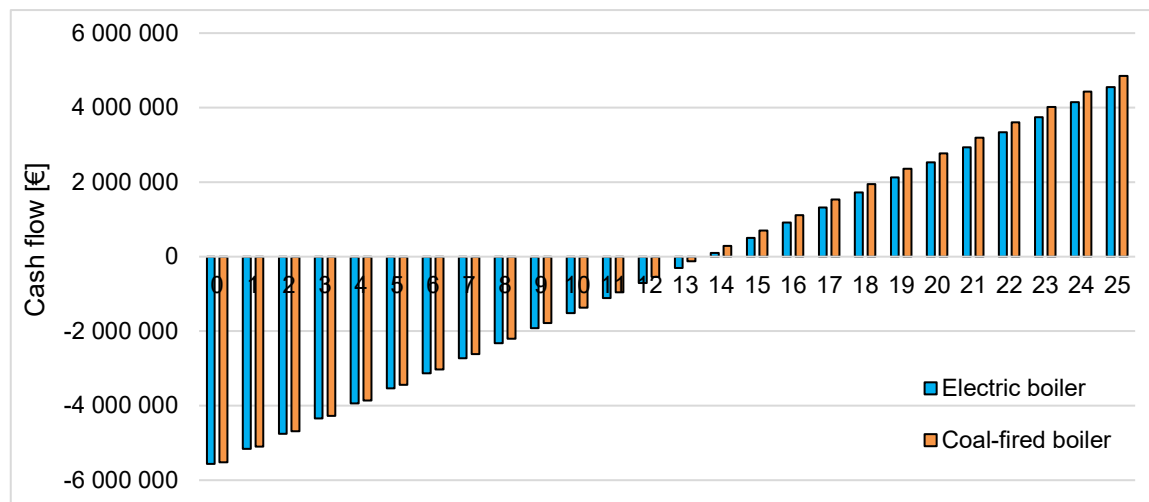


Figure 41. Cumulative cash flow for the DHS with electric and coal-fired boiler

An important metric derived from this analysis is the payback period, which is determined to be about 14 years for both systems in this case. The payback period represents the duration required for the cumulative cash inflows to match the initial investment. However, the final value of the diagram and the initial one gives the negative Net Present Value (NPV). For investors, such a value of the projects usually indicates risks and uncertainties and means that the investment is not financially viable or is likely to result in a loss.

## 5.5 Carbon dioxide emissions

As part of the comparison of systems, an effective evaluation should also include an assessment of their environmental impact, particularly in terms of carbon dioxide (CO<sub>2</sub>) emissions, although the Kyrgyz Republic does not currently have a CO<sub>2</sub> emissions policy. The obtained results of emissions are presented in Table 13.

Among the systems under examination, the DHS with an electric boiler appears to be the most environmentally friendly choice. This is due to the fact that electricity generation within the country relies on hydropower plants. However, due to the growing lack of energy generation, the country is forced to import it from neighboring countries. And in this case, it is impossible to accurately calculate emissions because the sources are unknown. Assuming the usage of coal and gas, an average intensity of 100 g/kWh can be taken, and so total emissions can increase by 4 times.

Table 13. CO2 emissions

	DHS with electric boiler	DHS with coal-fired boiler	Individual home system with a coal-fired boiler
CO2 emissions intensity	24 g/kWh (hydropower) (International Hydropower Association, no date)	363.6 g/kWh (lignite) (Our World In Data, no date)	
Yearly emissions	117.914 tons	1,768.55 tons	10.18 tons

Conversely, the coal-fired boiler in the DHS demonstrates markedly higher emissions, exceeding those of the electric boiler by approximately 15 times in the case of electricity generation by hydropower plants. This large disparity underscores the environmental consequences associated with coal combustion, a process that releases substantial amounts of CO<sub>2</sub> and other pollutants into the atmosphere.

In the case of an individual home system with a coal-fired, the total emissions of the community may exceed those of the DHS with a coal-fired boiler since there are currently 240 households.

## 5.6 Impact on energy affordability

Introducing a new heating system into a community raises important considerations regarding energy affordability for the local population, especially if the proposed heat tariff is set at a relatively high level. The potential impact on residents' financial well-being and access to heating services must be thoroughly assessed.

Unfortunately, it is not possible to collect comprehensive data from the examined Ak-Tal community, such as demographic data encompassing household income, employment status, and number of people per household. Such data could provide a more detailed understanding of the income distribution and socio-economic status of residents allowing for an evaluation of the estimated heat tariff aligns with their financial capacity. However, it is valuable to conduct such an energy affordability assessment in order to understand the feasibility of the system from this point of view. This can be done on the basis of the state statistics and a survey conducted in the one article on energy profiling of the Ak-Tal community by Mehta (Mehta et al., 2021).

First, take a look at the previously mentioned study, specifically the part of it that was done to identify occupant behavior. This part of the article has a description of a local household which usually consists of four to six people. There is a family of two adults, and their children, and usually grandparents live together with one of their children. Usually, the situation is that women are responsible for running the household and men go to work. Accordingly, the situation is such that, on average, a household has an

income from one person, and if the aging parents live together, then it is possible that their pension is added.

Then, examine the state statistics data concerning average wages throughout the country which is 270.72 € (26,031 KGS) per month (NatStatCom KG, 2022a), and average pensions which is 84.39 € (8,114.3 KGS) per month (NatStatCom KG, 2022b). Such data, however, affects accuracy for an examined population since statistics have average data for the Naryn region in terms of salaries, and pensions are average for the country.

The assessment of household expenses for heating services (Table 14) is done for the three cases of households: the first has income from only one working person; the second has also one working person but two aging parents living together; the third has income from two working people. Since the monthly consumption per household is unknown, the analysis is made for the heating period specified here with a mentioned earlier consumption of 28,000 kWh. The total income for three cases is also calculated as funds available within the heating period of seven months. The household expenses on heating are also calculated for three options: individual system where cost only for coal; DHS with electric boiler and coal-fired boiler where total heating cost is defined by the heat tariff estimated earlier (LCOH).

Table 14. Household expenses for heating services per heating season

	Household №1 (One working person)	Household №2 (One working person plus two pensioners)	Household №3 (Two working people)
Total income per 7 months (Oct – Apr)	1,895.04 €	3,076.5 €	3,790.08 €
Percent from total income for heating services:			
individual system (250 €)	13.2 %	8.1 %	6.6 %
DHS with electric boiler (3,295.6 €)	173.9 %	107.1 %	86.9 %
DHS with coal-fired boiler (2,808.4 €)	148.2 %	91.3 %	74.1 %

The outcomes of the energy affordability assessment present an unfavorable picture, clear from the data provided in the table. The situation regarding a household utilizing an individual heating system is manageable, heating expenses constitute approximately 13% of their total income, even when there's a single income earner. However, under the envisioned solar-assisted DHS, the same households find it challenging to meet the expenses, as the bills exceed their financial means by a significant 74% (with an electric boiler) and 48% (with a coal-fired boiler). The issue remains relevant even in families with dual earners, where heating costs make up a significant part of the total income.

## 6. DISCUSSION, CONCLUSION AND FUTURE WORK

### 6.1 Limitations

During this work some assumptions have been made to perform calculations and modelling that affect the results obtained.

In order to estimate heat losses in the distribution network the supply/return temperature is assumed to be 80/40 °C. This temperature mode is also applied in the Polysun model for the hourly heating load profile. This temperature regime is selected based on the analysis of existing solar thermal systems where supply temperatures typically range between 65 and 90 °C, and return temperatures fall within the 35 to 60 °C range (International Energy Agency, 2018). Within this study, the upper limit for the supply temperature is set at 80 °C to prevent boiling within the heating system and network (given that the boiling point is 94 °C at the altitude of the Ak-Tal community). Further reduction in supply temperature seems impractical, primarily due to the low energy efficiency of the houses. Similarly, the return temperature is fixed at 40 °C and not higher to reduce the heat losses in the network and minimize energy consumption for pump operation.

The initial community heating demand estimated within the ÖkoFlussPlan project by Kedar Mehta was decided to increase by 20%. This is justified as a structural shift of the heat plant capacity considering possible future new households' connections and having a reserve in case of the worst weather conditions. Hence, the final profile for simulation includes the structural shift of 20% and calculated heat losses in the district heating network.

### 6.2 Discussion

It is important to emphasize that the key findings are obtained within the techno-economic analysis. Estimation of the LCOH is a key indicator in understanding the economic feasibility of the system. Subsequently, an energy availability analysis was carried out on this basis, considering the implications for the local population who would rely on this system for their heating needs.

The energy affordability assessment reveals disappointing results based on the data found. The proposed solar-assisted DHS poses financial challenges, with bills exceeding means by 74% (electric boiler) and 48% (coal-fired boiler) with single-income earner. This issue persists even in dual-earner households, where heating costs remain a significant financial burden.

The substantial heating expenses can, in part, be attributed to elevated household energy demand. This is primarily due to the absence of thermal insulation in the

majority of houses as well as their age, as findings have revealed. Nonetheless, even if to assume that energy efficiency improvements could halve energy consumption, we are still left with a heating bill that nearly equals the income of a single worker.

Consequently, the issue is further compounded by the notably high tariffs for central heating for the locals. One of the factors contributing to the elevated LCOH is the discount rate, set at 7.5% in the present study, whereas for Europe is typically around 3%. The high discount rate reflects the risk associated with investments in Kyrgyzstan, which is considered relatively high, compounded by a high inflation rate. The second factor is that the Ak-Tal community's low-density development pattern has resulted in considerable distances between houses. Therefore, this has necessitated the establishment of an extensive distribution network, consequently driving up construction costs. In fact, nearly half of the budget is allocated to this infrastructure development. For reference, the calculated LCOH is reduced by half if excludes the construction of the heating network. However, it's essential to emphasize that the heating network is an indispensable component of the district heating project.

In general, in cities of the Kyrgyz Republic with central heating, the heating tariff for the population was subsidized by the state. This means that the tariff was the same for everyone (Table 3), and the losses of companies in the difference between sales to the population and the real production cost were reimbursed by the state. However, this situation remained until 2020, namely, until the adoption of the "Medium-term tariff policy of the Kyrgyz Republic for thermal energy for 2020-2022", which was subsequently extended until 2025 (On approval of the Medium-term tariff policy of the Kyrgyz Republic for heat energy and hot water supply for 2021-2025, 2021). This resolution was aimed to help develop private sector enterprises and reduce the financial burden on the republican and local budgets. And with its adoption, private boiler houses began to sell thermal energy to the population at real production cost, but this is for newly commissioned apartment buildings, the heat supply of which is carried out by local private heating boiler houses. For the population receiving thermal energy from the boiler enterprises "Bishkekteploenergo", "Kyrgyzteploenergo" and "Bishkekteploset", the tariffs remain the same, i.e. subsidized by the state.

Therefore, in the context of a district heating project such as the one discussed in this thesis, the implications of this policy change are that if a private company decides to implement such a project, the tariff will not be subsidized, and locals must buy thermal energy at prime cost.

Thus, securing subsidies or financial support at the stage of project implementation becomes imperative for the successful functioning of such a system. In the global landscape of solar thermal systems, there exists a notably successful system situated at a high altitude of 4,600 meters in Langkazi, Tibet, within China. This pioneering

system employs a pit storage, with solar energy accounting for a remarkable 90% of the total energy production, while the remaining 10% is supplemented by an electric boiler. It is worth noting that this remarkable project was entirely financed by the Chinese government (International Energy Agency, 2019).

On the other hand, the situation in the country should be favorable for the implementation of solar thermal projects. For example, Denmark is the leading country in the world for district solar heating capacity in operation. Here, solar thermal systems are a competitive heat source for central heating due to the low LCOH which was equal to 0.045 USD/kWh in 2019 (IRENA, 2021). This success of Denmark has developed for several reasons: high heat density of existing DH networks; considerable summer load; low DH temperature levels; high energy taxes on fossil fuels; availability of market-based subsidies; and non-profit orientation (Tschopp et al., 2020).

## **6.2 Conclusion**

The presented thesis aimed to study the feasibility of installing a district heating system using solar energy in the high-altitude rural areas of Kyrgyzstan through modeling, simulation, and further analysis.

The literature review of the countries of Central Asia showed a low level of penetration of district heating in rural areas. However, the population of rural areas relies mainly on coal as a source of heat and therefore they have health issues arising from indoor air pollution. The choice of the Kyrgyz Republic as the focus of this study is due to its exceptional dependence on environmental factors in its energy sector, which makes it particularly susceptible to the effects of climate change. Subsequently, the Ak-Tal community was chosen as a case-study location which is located at an altitude of 1,650m ASL in the Naryn region of Kyrgyzstan, with a population of 1,500.

To figure out how the solar-assisted heating system would perform within the given climatic conditions of the chosen area, the capabilities of the Polysun software were used. This software was chosen among others based on the literature research due to its user-friendly interface, object-oriented manner of modeling, an availability of templates for fast learning.

The model of the examined system consists of solar thermal collectors, a storage tank, an auxiliary heat source, an external heat exchanger, circulation pumps, controllers, a mixing valve, and an energy sink. The system operates through three fluid transfer loops: the solar loop with water–propylene glycol mixture (heat exchanger to solar collectors), the storage tank to heat exchanger transfer circuit, and the tank to the boiler to consumer circuit.



Due to the complexity of the possible heating network, it was decided to not include it in the model and therefore calculate the heat losses separately in an Excel-designed tool. The heat losses assessment was done based on several parameters: network length, pipe diameter, mass flow rate, velocity, and soil temperature. Hence, with a temperature regime of 80/40°C the heat network losses during the heating period (October – April) account for 800 MWh while the heat demand is equal to 5,155 MWh.

Further, the Polysun software aided in comprehending system operations by running simulations based on weather data and predefined load profile which include heat demand and estimated distribution losses. Several simulations were conducted to implement the parametric study to find out the optimal volume of the storage tank to the area of the collectors based on the solar fraction. The range for the storage tank is from 100l to 1000l, for solar collector field – 1,015 m<sup>2</sup> to 10,150 m<sup>2</sup> (500 – 5,000 collectors).

Subsequently, the solar fraction of 19.4 % was taken as a preferred concept for the heating system, and it is achieved by 2,000 collectors (4,060 m<sup>2</sup>) and a storage tank of 400 m<sup>3</sup>. In this concept, solar thermal system helps to reduce consumption from non-sustainable sources of heat by 1,173 MWh. The lowest solar fraction of 9% was found in December and the highest with 41.7% in October. The simulation result of this system showed that the peak heat demand is solely met by the heat generated from the auxiliary heater.

The follow-up economic evaluation of the chosen system configuration took into account the total lifecycle costs, including initial investment, operational expenses, maintenance, and fuel costs. Based on these costs the assessment compares the solar-assisted district heating system with two alternative auxiliary heaters: an electric boiler and a coal boiler, as well as an individual household system with a stove. The calculated levelized cost of heating (LCOH) showed that the DH system with the coal-fired boiler is slightly cheaper than the system with an electric boiler, 10.03 €-ct/kWh to 11.77 €-ct/kWh, while an individual home system with a coal-fired boiler is 1.13 €-ct/kWh. However, the coal-fired boiler in the DH system exhibits significantly greater emissions, exceeding the emissions of an electric boiler by approximately 15 times.

Provided further an energy affordability analysis for the local population based on the evaluated LCOH brought disappointing results. The typical local household, with the man working and the woman managing the household, cannot afford to use the option with the proposed district heating system since the heating bills surpass the available income by 74% (electric boiler) and 48% (coal-fired boiler).

Overall, based on the obtained information within the current study, the solar-assisted district heating system could be a good heating option for people living in remote areas instead of coal usage. It can help to reduce carbon dioxide emissions and improve the

quality of life and health by eliminating indoor air pollution. However, based on the findings of the present study, it's evident that careful consideration must be given to the economic aspects of solar thermal projects, particularly in areas with low income. To address this issue and pave the way for the successful implementation of solar thermal projects, it is crucial to secure subsidies or financial support at the project implementation stage. This step is paramount to ensure that such systems remain accessible and affordable to the local population.

## **6.2 Future work**

Future research recommendations serve as limitations of the present study meaning what could be done within this study to improve the performance of the system and the central heating project in general.

Investigating the implementation of variable supply temperatures based on outside conditions could be explored. This approach has the potential to reduce heat losses in the distribution network, which subsequently leads to a decrease in overall energy production. Operating at lower temperatures, when possible, may lead to decreased fuel consumption and operational expenses, consequently elevating the solar fraction.

As the solar collectors do not cover the entire heating load, the use of solar panels can be considered. In winter, the auxiliary heater consumes a considerable amount of energy, and if an electric boiler is used, some of the electricity can be provided by solar panels during the daytime. Here it is a worth examining the option of using a thermal and solar collector together, or a photovoltaic-thermal hybrid solar collector, and comparing the efficiency of the two options, as well as the economic impact.

Another possibility for enhancement is the utilization of seasonal storage. The introduction of seasonal storage systems could increase the efficiency of the system by storing excess heat during the summer months for later use in the winter. This would result in lower operational costs for auxiliary heaters, better energy balancing, and a reduction in peak energy demand.

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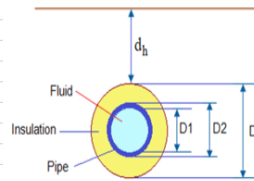
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## Annexure A: Heat losses calculation in MS Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	<b>INPUT</b>												
3	Pipe Roughness, $\epsilon$	mm	0.05										
4	Inlet Temperature	[°C]	80										
5	Pipe Length one way	[m]	8450										
6	Pipe Depth	[mm]	1000										
7	Mass Flow Rate, $\dot{m}$	[kg/s]	22.00										
8	Velocity	[m/s]	2.5										
9													
10	<b>PIPE SIZING</b>												
11	volume mass flow_max	[m3/s]	0.0227										
12	pipe diameter_in	[mm]	0.1077										
13													
14	<b>THERMAL RESISTANCE - PIPE MATERIAL</b>												
15		Pipe	Insulation	Casing		Pipe	Insulation	Casing		Pipe	Insulation	Casing	
16	pipe length	[m]	250			1600				6600			
17	din [mm]	[mm]	107.1	114.3	250	82.5	88.9	200		54.5	60.3	160	
18	dout [mm]	[mm]	114.3	250	250	88.9	200	200		60.3	160	160	
19	Thermal Conductivity, $\lambda$ [W/mK]		49	0.026	0.44	49	0.026	0.44		49	0.026	0.44	
20	Material	-	P235TR1	Polyurethane	Polyethylene (HD)	P235TR1	Polyurethane	olyethylene (HD)		P235TR1	Polyurethane	polyethylene (HD)	
21													
22		$R_{pipe}$	$R_{insulation}$	$R_{casing}$		$R_{pipe}$	$R_{insulation}$	$R_{casing}$		$R_{pipe}$	$R_{insulation}$	$R_{casing}$	
23	Thermal Resistance	[K/W]	0.00021133	4.790774037	0	0.0002427	4.963217665	0		0.000328481	5.973462772	0	
24													
25	<b>THERMAL RESISTANCE - SOIL</b>												
26	$T_{soil}$	[°C]	0										
27	Thermal Conductivity, $\lambda$ [W/mK]		1	$d100$	$d80$	$d50$							
28	$R_{soil}$	[K/W]		0.440645827	0.476386212	0.512045							
29													
30	Soil temp	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
31		1.3	0.4	1.4	6.5	11.5	15.3	18.2	19.5	17.8	13.3	7.4	3.5



$$r_{pipe} = \frac{\ln(D_2/D_1)}{2\pi\lambda_{pipe}}$$

$$r_{ins} = \frac{\ln(D_3/D_2)}{2\pi\lambda_{ins}}$$

$$r_{soil} = \frac{\ln\left[\left(d_h/r_3\right) + \sqrt{\left(d_h/r_3\right)^2 - 1}\right]}{2\pi\lambda_{soil}}$$

	A	B	C	D	E	F	G	H	I	J
1										
2							Heat losses = $\left(\frac{T_{fluid} - T_{soil}}{r_{pipe} + r_{ins} + r_{soil}}\right) \cdot L_{pipe}$			
3	Month	Day	Hour	$T_{amb}$ [C]	$T_{ground}$ [C]	Heat demand [MW]	Heat loss d100 [MW]	Heat loss d80 [MW]	Heat loss d50 [MW]	Heat loss [MW]
4	Jan	1	1	-7.9	1.3	1.087794062	0.003760777	0.023147712	0.080085281	0.10699377
5	Jan	1	2	-8.1	1.3	1.097719286	0.003760777	0.023147712	0.080085281	0.10699377
6	Jan	1	3	-8.4	1.3	1.104225894	0.003760777	0.023147712	0.080085281	0.10699377
7	Jan	1	4	-8.5	1.3	1.109780764	0.003760777	0.023147712	0.080085281	0.10699377
8	Jan	1	5	-8.6	1.3	1.11483162	0.003760777	0.023147712	0.080085281	0.10699377
9	Jan	1	6	-8.7	1.3	1.119639816	0.003760777	0.023147712	0.080085281	0.10699377
10	Jan	1	7	-8.8	1.3	1.11966937	0.003760777	0.023147712	0.080085281	0.10699377
11	Jan	1	8	-8.9	1.3	1.105567577	0.003760777	0.023147712	0.080085281	0.10699377

## Annexure B: Flow-through electric water heater data



<b>Capacity:</b>		<b>250 kW</b>	<b>1,000 kW</b>
Rated voltage +5%/-10%		400 V	400 V
Maximum pressure		0.6 MPa	0.6 MPa
Number of heating groups		6	12
Maximum power of one group		50 kW	100 kW
Coolant temperature control range		50-80 °C	50-80 °C
Rated current of circuit breaker		420 A	1667 A
Nominal performance (x1000 l/h)	$\Delta t$ 30°C	7.1	28.6
	$\Delta t$ 35°C	6.1	24.5
	$\Delta t$ 60°C	3.3	13.2
Volume of the tank		500 l	140 l
Weight		800 kg	163 kg

## Annexure C: Coal-fired water heater data



Power	2500 kW
Fuel type	Coal
Lower heating value of fuel	5230 kcal/kg
Boiler efficiency, not less	85%
Fuel consumption	585 kg/h
Flue gas temperature	200 °C
Coolant flow rate	86 m <sup>3</sup> /h
Water temperature	70-95 °C
Working medium pressure	0.3-0.6 MPa
Hydraulic resistance of the boiler at a temperature difference of 25°C	0.07 MPa
Aerodynamic resistance	400 Pa