The application of solar collectors in district heating systems: a case study in Krasnodar Krai

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Abstract. Though renewable energy sources are widely used around the world, the cost of "green" energy in most cases is still uncompetitive with the "traditional" one. This is most pronounced in countries and regions with a developed resource base, including Russia. However, renewable energy sources in some cases can be successfully implemented in district heating systems using natural gas. This paper reports on the effective use of simple design solar collectors in a gasified central heat supply system in the city of Gelendzhik, Krasnodar Krai, with the cost of heat generated does not exceed 0.01 USD/kWh. The conditions for reproduction of this project are defined following the results of its operation.

Key words: solar collector, district heating, cost efficiency

1. Introduction

Renewable energy production is experiencing a sharp rise in the world over the past decade. The growth rate of heat and electricity generation via renewable energy sources is up to 14% per year [1], their contribution to global output varies from 10% to 60% in different countries [2]. The development of renewable energy systems is often supported at the state level around the world. There are projects for the complete transition of economically developed countries from fossil fuels to renewable energy sources by 2050 [3]. The power engineering in the near future will undoubtedly focus on utilizing renewable energy sources and the development of associated environmentally friendly technologies.

Solar energy is one of the most promising branches of renewable energy. This is due to the versatility and ubiquitous availability of the solar resource in contrast to hydrothermal and wind resources. In addition, solar energy causes minimal environmental damage compared to other technologies.

The history of solar energy utilization in Russia dates back more than a century, units of domestic manufacture continue their successful operation, the feasibility of their use is obvious due to attractive quality-price indicator [4-6]. The intensity of solar emission over certain regions of Russia is comparable, and in some places exceeds this indicator for European countries, including Germany and Austria, where facilities for collecting and converting solar irradiation have long been widely implemented [7]. The availability of free space for the equipment of almost any capacity as well as recent developments in the field of highly efficient materials also contributes to the further growth of Russian solar energy sector [8].

Over the past decade, solar energy technologies have moved from the development phase fraught with high costs and low technical and economic indicators to the level of commercial implementation.
Solar energy sector comprises two general concepts: solar collector units, where the solar irradiation is transferred to heat carrier, and photovoltaic panels, where the direct generation of electric energy is carried out. There are also projects combining these two concepts in devices where photovoltaic energy is implemented for generating heat [9, 10]. Herewith, the price of photovoltaic panels for the indicated period has decreased by an order of magnitude, the total surface of devices installed is growing incrementally, the cost of electricity they produce is approaching the market price of that for retail consumers in centralized power systems.

Initially, photovoltaic panels, as a high-tech product, were significantly more expensive than solar collectors. But at the moment, the photovoltaic panels’ production process improvement, intensive support from government agencies, and the transition to mass production have provided a breakthrough in this direction. Results of calculations in published reports show that at present the cost of energy produced by photovoltaic panels and then converted into the heat of water is comparable to the cost of energy directly absorbed by solar collectors for the same application.

This circumstance caused a reduction in the global market for solar collectors. The rate of growth of the global solar collector market decreased from 18% in 2011 to 6% in 2015 and further to 5% in 2016 [11]. Forecasts based on these statistics predict a further drop in their market demand.

However, like any technology, solar collectors have certain specific applications in which they can show efficiency and competitiveness. This study reflects one specific area where solar collectors are successfully used in traditional heat supply systems based on gas boiler plants, even in conditions of relatively low cost of natural gas for Russian consumers.

2. The Gazprom Teploenergo experience in Krasnodar Krai
Krasnodar Krai holds one of the leading positions in introducing renewable energy sources in Russia. These include solar panels, wind generators and geothermal power stations. The construction of solar systems for the domestic hot water supply of residential buildings, resort facilities can save up to 1.5 million tonnes of standard fuel annually, which is approximately equal to 10% of the region’s total consumption of heat and energy resources per year.

As a proactive experiment held in 2017 and 2018, the Gelendzhik branch of OOO Gazprom Teploenergo Krasnodar equipped several boiler plants in the city of Gelendzhik with a solar collector system. Unlike most previously implemented projects, where the cost efficiency of operational solutions is not high enough and requires significant subsidies and other measures of government support, this project, based on cheap solar collectors, showed sufficient energy and economic efficiency, since it required minimum investment and operating costs.

The city of Gelendzhik is a popular resort center in Krasnodar Krai: the population is 76 thousand people, while the flow of tourists reaches 2-3 million people per year. The climate is mild, close to the Mediterranean, but in winter the temperature drops to $-10^\circ C$, and strong winds are usual, so there is a seasonal need for full-fledged heating systems. The city is fully gasified, there are 3 block boiler plants with a capacity of more than 30 MW, several dozens of municipal and private boiler plants of lesser capacity, as well as individual heat sources. The city’s construction is dense, there is a significant number of apartment buildings, generally located in the district heating zone. Resorts, spas and the private sector are mainly equipped with individual heat sources.

Two district heating substations, that were equipped with solar collectors, are located in a range of boiler plant #3. They carry loads of district heating systems and domestic hot water supply of blocks located in the Severny building estate. The design of the system downstream from district heating substation is four-pipe (2 pipes for heating, 2 pipes for hot water), the domestic hot water load connection is closed-type, it is fed through heat exchangers, the value of hot water load is 110 kW. The boiler plant #3 utilizes trunk natural gas as a fuel; there is a reserve fuel oil facility, but it is out of operation.

The flow diagram of the solar collector is shown in figure 1.
Figure 1. Flow diagram of the solar collector.

T1 — heat supply delivery pipeline; T2 — heat supply return pipeline; T3 — hot water delivery pipeline; T4 — hot water system circulation pipeline; B1 — cold water pipeline; B1.1 — cold water pipeline after the first stage of heating from a solar collector; 1 — hot water system heat exchanger in the district heating substation; 2 — solar collector; 3 — solar collector mount; 4 — cold water system booster pump; 5 — hot water system circulation pump; 6 — district heating substation building.

Solar collectors of a simple design were installed on the roof of the central heat substation; they are fed with cold water where its preliminary heating is carried out, then it enters a hot water system heat exchanger, in which additional heating is performed up to the standard temperature of + 65°C.

The design of solar collectors under this case is based on black polyethylene pipes with an outer diameter of 20 mm, their length within one district heating substation is 1 km (10 loops of 100 m each, connected to a single manifold in accordance with overhead piping flow layout, which eliminates the need for hydraulic adjustment of individual loops). The collector pipes are installed on the roof of the district heating substation openly, so the energy efficiency of the system can be increased by adding shields for preventing wind blowing over solar-heated pipes. In the cold season — from November to March — the system is taken out of operation and drained, so the use of antifreeze is not required. All these features facilitated mitigation of the project capital costs: the total cost of materials and equipment used was about 1,300 USD, the construction and installation work was done by the company's own staff without the involvement of contractors.

It is assumed that, provided the work is performed by a third-party organization, given the equipping collectors with protective steel shields, the cost of a system of this size will not exceed 5,500 USD.

The proposed design of solar collectors has the following advantages compared to existing analogs:

1. The water fed to collector initially has a relatively low temperature, which enables you to utilize not only direct solar radiation but also the heat of the surrounding air. Therefore, the solar collector also acts as a heat exchanger with a temperature drop of up to 30°C.

2. In the collector system implemented, the water undergoes only the preheating procedure, and the final heating is carried out in the heat exchange unit of the district heating substation. This scheme provides for complete utilization of the heat received by the collector during its period of operation with predicted performance and does not require the use of storage tanks as well as control valves or any automation.

The above advantages allowed to reduce the capital cost of the project by almost an order of magnitude toward the comparables, and at the same time achieve high energy efficiency. That's why,
as will be shown below, even at a low cost of heat generated using natural gas, solar collectors can work effectively in district heating systems.

3. Calculation of the solar collectors’ efficiency

The flow rate of cold water through within one district heating substation is 100 m$^3$/day, the average temperature of cold water during the non-heating period at the inlet of the station is +20°C. Measurements showed that solar collector increases water temperature by 7°C on the average, the period of collectors operation is 214 days per year. Based on these features of the system, heat supply from the collector to the network is estimated at 174 thousand kWh/year.

With the boiler plant (the general heat source of a district heating substation) fuel efficiency of 0.83, the natural gas economy reaches 26 thousand n.m$^3$/year, which in monetary value would be 1,960 USD/year, given the natural gas price of 0.07 USD/m$^3$.

The forecasted payback period of collectors at their cost of 5,500 USD is 2.8 years. This value is considered attractive in the field of projects for rehabilitation of district heating systems.

Key project performance parameters are listed in table 1.

Table 1. Technical and economic indicators of the solar collector application project in the Krasnodar Krai.

| Indicator | Unit   | Value |
|-----------|--------|-------|
| Solar collector surface area | m$^2$ | 60    |
| Investments | USD   | 5,500 |
| Annual benefits | USD/year | 1,960 |
| Pay back period | years | 2.8   |
| Substitute cost of heat | USD/kWh | 0.01  |
| Specific daily heat output | kWh/m$^2$ | 13.5  |
| Specific annual heat output | kWh/(m$^2$·year) | 2,900 |
| Specific capital cost for the construction of collectors | USD/m$^2$ | 107   |
| Levelized cost of heat transferred from collectors | USD/kWh | 0.005 |
| Proportion of domestic hot water load substituted by solar collector | % | 7     |

The Gelendzhik branch of OOO Gazprom Teploenergo Krasnodar operates 24 boiler plants and 9 district heating substations. The total roof area of facilities with a domestic hot water load (all central heat substations and some boiler plants) is estimated at 2.4 thous. m$^2$. The enterprise’s total heat generation potential via solar collectors can be estimated at 7 thous. MWh annually, and the annual fuel economy — 827 thousand n.m$^3$/year of natural gas, which is about 1% of the enterprise’s consumption.

The economic efficiency of the solar collector under the study can be even 3-4 times higher at non-gasified facilities, for example, at boiler plants using fuel oil, diesel fuel, or electricity.

In the above example, cold water is fed to the district heating substation through the Troitsky group water supply system from a reservoir located more than 100 km away, which ensures its relatively high temperature due to natural heating during transportation. Greater efficiency of solar collectors will be achieved at lower temperatures of cold water fed to them, e.g. if it is extracted from the wells located not far from the place of solar collector operation. In this case, the temperature drop in the water heating process, and, consequently, heat generation, maybe even more significant.

It should also be noted that the warm climate of Gelendzhik is a favorable factor that contributed to the efficiency of the implemented solar collector scheme. This provides an acceptable temperature drop between the environment and the water heating system. And considering that the period of negative temperatures in this region is short, it is feasible to operate solar collectors for more than 7 months a year.
4. Conclusions

- In general, the usage of solar collectors for generating heat becomes impractical, fading for photovoltaic panels.
- The application of solar collectors for domestic hot water pre-heating in district heating systems can be effective even when the fuel price is relatively low.
- The Gelendzhik project turned out cost-effective yet technically simple. It does not require any sophisticated gear or automation equipment. The cost of generated heat is 0.005 USD/kWh while the leveled cost of heat transferred from collectors is 107 USD/m², which provides for less than 3 years payback period.
- The system under research can contribute up to 7% of the heat required for domestic hot water supply purposes; the potential fuel economy for the heat supply organization in total is estimated at 827 thousand m³ annually.
- The implementation of solar collectors of the proposed design will be most effective under the following conditions: the high cost of fuel for the district heating system, low temperature of cold water fed to the collector, warm climate at the collector location.

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