Optimal use of solar collectors in small-scale districts

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Abstract. It is vitally important to choose a sustainable, rational heating system and, in view of the trends of the European Union, as well as a system with lower harmful emissions. This work explores the efficiency of solar collector use in district heating systems. The wide application of solar panels allows to improve it overall efficiency by utilized exceed heat into district heating systems. Especially in small scale systems. Solar collectors are a type of renewable energy that is not only an ecological solution for heat generation but also increases energy independence. Within the framework of the work, a working specifics of district heating system has been studied, where different types of solar collectors are used for partial heat energy supply. By changing the area of solar collectors for constant heat consumption, the results on efficiency and effectiveness of use were obtained and analysed. The TRNSYS energy simulation tool was used for dynamic simulations. Researches, results and conclusions made in this research can be used in the work of engineers and designers to improve the existing centralized heat supply systems and to anticipate possible challenges in the newly built.

1. Introduction
In the European Union as well as in Latvia, a clear target to increase the use of renewable energy resources and decarbonisation in the energy sectors by 2030 was set up. This will reduce the dependency on imported fossil energy resources and significantly minimized CO2 emissions. Although the share of renewable energy sources in heating in Latvia is one of the highest rates in Europe, but the centralized use of solar energy is not sufficient. Central integration of solar energy into district heating system will insure a more environmentally friendly and advanced heating system model.

Due to the climatic conditions of Latvia, the heating season is quite long, approximately 200 days per year. However average outdoor temperature during heating period varies around 0 °C. This make a solar energy more usable and fossil fuels could be needed only to cover peak loads.

Various technical solutions are already available to utilize heat from solar collector by means of different thermal storage technologies, solar cooling systems and integration into existing local and central heating systems.

The aim is to explore the production potential of solar collectors by changing solar collector types and their areas, and to obtain the most efficient performance of the system.

Accordingly, the hypothesis: by integrating solar collectors with an area of 20 m2, 50 m2 and 100 m2 in the heating system, it is economically justified to provide 50% of the heat demand during the year for two apartment buildings with a total surface area of external enclosing structures 920 m2.

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The duration and intensity of solar radiation are directly related to seasons, climatic conditions of the area and geographical location. The duration of Latvia's sunshine ranges from 1700 h to 1900 h and slightly more on the coast of Kurzeme. In Northern Europe, the maximum amount of solar radiation is around 1100 kWh/m². Taking into account the heat transmission and the efficiency of the equipment, it reaches only around 400-450 kWh/m², which varies from one region to another in Latvia [1].

Solar energy is the most widely available energy source in the world with no pollution and can be used in very simple systems. According to many researchers and environmental experts, solar is the key to resolving the crisis associated with greenhouse gas emissions [4].

Solar radiation has been learned by humanity to be used for heat production with solar collectors and generation of electricity with PV panels. Statistics show that the total solar heat output reaches 435 GW and the solar power capacity reaches 227 GW at the end of 2015. Special attention can be paid to the heat output produced by the Sun, as it has increased significantly over the past decade. Solar thermal energy is now widely used around the world to provide heating and cooling. Solar thermal generating plants are also rapidly developing [3].

Solar collectors collect heat by absorbing sunlight and a heat transfer fluid is circulated through the absorber's fluid passageways to remove heat from the solar collector. For further transfer of heat from the heat transfer fluid to a hot water storage tank heat exchanger is used. Flat solar collectors consist of a box, containing heat-insulating material (usually stone wool), a serpent-wrapped tube on stone wool, over which a absorbent, most commonly coated copper plate, covered with an absorbent and dark layer on the top. These layers of the box are covered by a protective glass. This type of collector can be used for a rather wide range of needs, but its effectiveness is rapidly changing depending on the weather [6].

Heat losses in the flat solar collector can be significantly reduced by reducing internal pressure to < 0.5 Pa. Compared to traditional collectors, the expected increase in efficiency is significant in annual production in atmospheric climate conditions with low average solar radiation. [10]

An evacuated tube solar collector is preferable in the event of adverse weather, since the effectiveness of this type of collector is greater than that of a flat solar collector when the experiments were conducted under the same conditions. Based on previous experiments, average output temperature growth for vacuum tubes was 25-40% higher compared with the flat solar collector [12].

Also the solar factor is an important parameter for the assessment of solar heating systems and in many countries, the minimum values of these factors have been set. For the comprehensive assessment of solar systems various factors such as solar intensity, climatic conditions, types of buildings, thermal behaviour, etc. have to be taken into account [5].

Thermal storage plays an increasingly important role in energy supply and improves the overall thermal energy utilisation rate [2].

Among the many forms of heat energy storage, the water heat storage is the cheapest one. Different heat storage techniques are described in [13].

Unevenness of the heat demand in buildings reduces the economic efficiency of the solar thermal systems. Results show that the total operating costs of the system will be reduced by approximately 2% if a storage tank is used compared to a scenario without a tank [9]. One of the beneficial solution is to integrate solar thermal systems in a district heating network as a decentralised feed-in source which ensures full utilisation of produced solar thermal energy.

### Nomenclature

- $Q_{\text{DHW}}$: Required heat for district hot water (kWh)
- $V_{\text{DHW}}$: Domestic hot water consumption in period (m³)
- $\rho$: Water density at temperature $\Theta_{\text{DHW}}$ (kg/m³)
- $c_w$: Specific heat capacity of water (J/kg*K)
- $\Theta_{\text{cw}}$: Cold water temperature
- $\Theta_{\text{DHW}}$: Domestic hot water temperature
2. Methods and object

Each building may consume heat for heating, ventilation or hot water preparation. Therefore, in order to find out the required heat load for the building, it is necessary to calculate the thermal energy demand of each engineering system. A well-defined thermal load has an impact on both the total costs and the functioning of the engineering systems.

2.1. Calculation of the required thermal energy for buildings

For projected buildings, the energy consumption in the hot water system shall be evaluated using the formula (1):

\[ Q_{DHW} = V_{DHW} \times \frac{\rho_{DHW} \times c_{w}}{3600} \times (\theta_{DHW} - \theta_{CW}) \]  

(1)

The required energy for heating each area of the building for each calculation period (month or season) shall be determined using the formula (2)

\[ Q_{build} = Q_{loss} - \eta_{gain} \times Q_{gain} \]  

(2)

2.2. Calculation of thermal energy produced by solar collectors

The thermal power of the solar collector depends directly on the area of the absorbent and is determined using the formula (3) [7]:

\[ Q_k = A_{abs} \times I \times \tau \times \alpha \]  

(3)

2.3. Solar fraction factor

The solar fraction factor can be calculated according to the formula (4) [8]:
2.4. Calculation of storage tank volume

If the heat storage material is water, the formula (5) shall be used to calculate the tank volume [14]:

\[ V_{ST} = \frac{Q_{ST}}{c_w \cdot \rho \cdot \Delta \theta} \]  

(5)

2.5. Calculation of boiler capacity

In a dark period of time, a solar collector is unable to work in full capacity, a backup heat source is required. Boiler power depends on fuel quality and can be seen in the formula (6) [11]:

\[ E_{fuel} = V_{fuel} \cdot H_u \]  

(6)

As for renewable energy sources, the heating boiler also needs to ensure district heat-load demand. Heat capacity heating the heat carrier, expressed in a formula (7) [11]:

\[ Q = m \cdot c_p \cdot (t_{out} - t_{in}) \]  

(7)

2.6. Description of models for TRNSYS simulations

TRNSYS is a modular simulation program in which a user can create a model of a system in different industries. You can select system components from a wide library and enter the required parameters and input data. The program shall allow for the adaptation of the established system to the relevant climatic conditions. With only more TRNSYS is used in research activities.

For Model number 1, the diagram created in the TRNSYS program can be viewed in Figure 1.

![Figure 1](image_url)  

Figure 1. Scheme of Model number 1 with evacuated tube solar collector created in TRNSYS.

This model includes buildings for which radiators are used as heating units. For hot water preparation during the month, the model building consumes 244.21 kWh.

The average outdoor temperature Latvian meteorological data over the past five years was taken to ensure that the model is developed in accordance with Latvia's requirements and in line with Latvia's climatic conditions.

The climatic conditions for the model are determined by the built-in TRNSYS element Type 15, to which the average outdoor conditions in Riga are attached.
A heat transfer factor for the whole envelope is defined 0.25 W/(m² * K). The outer surface area of one medium two-story building shall be 460 m² and a capacity of 550 m³. Heat losses are compensated by radiators and the indoor calculation temperature + 25 °C.

The natural gas boiler is planned to be operated with a supply temperature of 90 °C and a maximum power of 15 kW.

The vacuum tube solar collector Type 538 is selected as an alternative energy resource. Solar collectors are installed in 4 rows south oriented on a 45° slope to ensure better overall efficiency.

The comfort temperature of the rooms is controlled by a thermostatic controller, which stops the pumps and interrupt heat supply if sufficient temperature is reached.

Model number 2 is with flat plate solar collector. The characteristics of the element are taken in the same way as in Model 1, so that the results can be assessed when performing simulations. The parameters and input data of the flat plate solar collector Type 539 correspond to those in the evacuated tube solar collector (Model 1), so that the simulations can compare the results. Solar collector is orientated on south and the slope - 45°. The area of the solar collector will change depending on the simulation.

2.7. Description of simulations

Scenario 1
Model 1 buildings will be heated by an evacuated tube solar collector and boiler. The installed area of solar collector shall be 20 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

Scenario 2
Model 1 buildings will be heated by an evacuated tube solar collector and boiler. The installed area of solar collector shall be 50 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

Scenario 3
Model 1 buildings will be heated by an evacuated tube solar collector and boiler. The installed area of solar collector shall be 100 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

Scenario 4
Model 2 buildings will be heated by a flat plate solar collector and boiler. The installed area of solar collector shall be 20 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

Scenario 5
Model 2 buildings will be heated by a flat plate solar collector and boiler. The installed area of solar collector shall be 50 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

Scenario 6
Model 2 buildings will be heated by a flat plate solar collector and boiler. The installed area of solar collector shall be 100 m². The simulation will be carried out during the year at the average temperatures taken in the territory of Latvia over the past five years.

3. Results and discussion

Model buildings are of the same characteristics, so the annual consumption of thermal energy in simulations is the same for both buildings. Annual consumption of the one building is 12,215 kWh of thermal energy. Both buildings consume 24,430 kWh.

Table of results for the six simulations carried out at work. The maximum achieved solar fraction is 42%, 100 m² for a vacuum solar collector as it is shown in table 1.
Table 1. Results of simulations in the annual cut.

| Model No.1 | Model No.2 |
|------------|------------|
| Produced thermal energy by evacuated solar collector, MWh | Produced thermal energy by boiler, MWh |
| Produced thermal energy by flat plate solar collector, MWh | Produced thermal energy by boiler, MWh |
| 20 m² Solar fraction, % | 7,3 | 22,1 | 6,8 | 22,1 |
| 50 m² Solar fraction, % | 11,8 | 18,9 | 10,6 | 19,4 |
| 100 m² Solar fraction, % | 14,9 | 16,7 | 13,3 | 17,6 |

The simulation program TRNSYS also takes into account heat losses from storage tanks, so all generated thermal energy is not delivered directly to the buildings. During summer months, excess heat is partly stored in a storage tank. Figure 2 shows that a 100 m² evacuated tube solar collector is able to provide two model buildings with heat from April to October. Also, it can be seen that due to low thermal energy consumption, the potential of the solar collector is not fully exploited during the summer months. So there is observable stagnation of solar collectors as leftover energy during summer months buildings are unable to consume. Stagnation was observed in all simulations. In the coldest winter months, when there is the lowest intensity of sun radiation, the action of the heating boiler, to ensure the comfort temperature of buildings also is needed.

Figure 2. Comparison of heating energy produced by a 100 m² evacuated solar collector and consumed by both buildings

According to the thermal energy produced by the solar collector during the year, it can be concluded that one square metre of the vacuum tube solar collector produced an average of 149 kWh during the year, which is very few. As in previous two simulations, it appears that in summer months, due to relatively low thermal energy consumption, the solar collector is unable to deliver all the potential. In summer months, due to the relatively low heat consumption, the solar collector isn't able to provide all the potential.
3.1. Economic analysis
Following simulations, the results of the heating energy produced by the buildings, the heating boiler and solar collectors were obtained. These results were analysed. As a result, it is concluded that the increase in the area of solar collectors increases the heat produced and that the solar collector of 100 m² of vacuum tubes is able to cover up to 42% of the thermal energy consumption of the model buildings, but the hypothesis put forward was not confirmed. The economic analysis for solar collectors used in simulations showed that there was no economic justification for further increases in the area of solar collectors under the simulated model. In order to identify the optimal variant of the study model, an existing model was simulated for which the area of the solar collector was reduced to 10 m² and a storage tank of 1 m³ was installed. The use of such a solar collector in the heating system of the investigational model pays off over a period of 12 years.

4. Conclusions
1. The use of solar collectors for heating in Europe is gaining increasing popularity. Improvements are increasingly being sought for solar collectors and heating systems in order to ensure more efficient operation of the system and to reduce harmful emissions in the atmosphere.
2. The setting of precise parameters and in-depth experience of the use of solar collectors in heating systems elsewhere, in the TRNSYS simulation program, enabled the development of a heating system model that is as close as possible to realistic conditions.
3. The use of renewable energy sources in the heating system is capable of significantly reducing the life of the heating boiler and the thermal energy needed. 20 m² of solar collectors were able to reduce the thermal energy required by the boiler by 2.38 MWh. 50 m² of solar collectors reduced the heat output of the boiler by 5.62 MWh and 100 m² of solar collectors reduced the heating boiler's required production by 7.75 MWh.
4. By increasing the area of solar collectors to 100 m², it is possible to reach the solar fraction up to 42% of the thermal energy consumed by the model buildings. However, as the fraction increases in this pattern of experiment, the use of large-area solar collectors for buildings of such thermal energy consumption does not pay off. For the purposes of this experiment, the optimum area for solar collectors would be 10 m² for which the repayment period is 12 years.
5. During the summer period, the vacuum solar collector has, depending on the area, the following heat surplus: 20 m² – 1.67 MWh, 50 m² – 3.3 MWh and 100 m² – 4.67 MWh. On the other hand, for the flat solar collector during the summer period, depending on the area, the heat surplus shall be: 20 m² – 1.31 MWh, 50 m² – 2.63 MWh and 100 m² – 3.41 MWh. With the amount of excess heat, it would be partly possible to ensure the thermal energy consumption of an adjacent kindergarten or school.
6. The establishment of a heating system where it would be possible to redirect unused heat to a district heating system would have the potential to improve not only the overall efficiency of the system but also to obtain financial benefits and to reduce the recovery time of solar collectors.

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