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EXPERIMENTAL STUDY OF A SOLAR TRIGENERATION SYSTEM PROTOTYPE

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A prototype solar trigeneration system was built in a new private single-family residential house for experimental purposes. The prototype system was designed to supply the building with the required thermal energy and cooling to a full extent. In addition, one of the conditions is that the thermal and the electrical energy generated by the solar systems should be used for the needs of the building to a maximum extent. The prototype system provides an opportunity to recover thermal energy both during the heating and the cooling season.

This article describes the prototype configuration, the first results of testing, analysis of the results obtained, and the operational features and shortcomings of the open system, as well as the possibilities for its improvement.

Keywords: *Prototype system, single-family residential houses, solar trigeneration.*

1. INTRODUCTION

The information available on electrically operated solar trigeneration systems (S3G) is limited. International literature mainly provides information on the Building Integrated Management (BIM) system descriptions of large office or factory buildings. However, even in these descriptions, there are only general references to the algorithmic management and operational routines without an in-depth analysis. On the other hand, information on the use of S3G for private houses is scarcely available. Literature describes visions of the potential existence of equivalent systems and the smart management they require. At the start of this study, it has been clear that separately operated heating, cooling and electricity systems are widely used in households, but they have weak connectivity: the separate systems operate completely independently of each other, excluding the possibility to optimize the energy supply. Consequently, the aim of the study is to combine the separate heat supply, cooling, electricity con-

sumption and solar photovoltaic systems into a single S3G system with a common control unit. Solar inverter manufacturers tend to think in terms of taking into account the yield of solar electrical energy and the consumer demand for electricity. It can be assumed that this is mainly about controlling the large power-consuming devices, like switching on the washing machine, or charging electric cars, or switching on electric heaters. An in-depth study of such control systems shows that they function on a fairly primitive level. Producers are aware of this behaviour and are actively working on improvements.

Smart control units are becoming increasingly prevalent, primarily, to make sure that electricity storage accumulators are charged during the off-peak hours when the market prices of electricity are low and that the accumulators are discharged when the prices on electricity are high. Some experimental systems are able to take into account connection to a solar power plant. As shown by experience, the control algorithm of such systems tends not to be openly published, and, unfortunately, these control units are not very widespread globally.

There is, certainly, a lot of interest in S3G systems on the part of solar energy researchers and engineers. This study analyses S3G technology, which uses low-power components to meet the domestic heating, cooling and electricity needs of single family homes by using solar and geothermal energy. The public grid is used to compensate for insufficient electricity and to transport excess electricity. One of the aims of the study is to achieve minimum electricity import for household use.

2. METHODOLOGY

The main sources of energy in this household energy supply system are solar energy and geothermal heat. The main components of the system are: flat vacuum solar collectors with a total capacity of 11.5 kW, a 13kW heat pump, a ventilation installation unit with a recuperator and air conditioning units; two accumulating heat storage tanks: a heat storage tank with an actual volume of 0.788 m^3, and a low temperature (up to 25 ºC) heat storage tank; solar photovoltaic panels 32 pcs. at 405 W each, 12.96 kW in total; and an 11.1 kW inverter, 3 phases, 16A; several control units based on Technea Alternative and additional Siemens components combined in a single control system. The system was equipped with the sensors required for controlling the system itself and additional sensors for the in-depth study of the system operation.

The prototype system was installed in a private residential house. The house was already equipped with a heat pump system. The additional installations were: solar collectors, a free cooling unit, solar panels and and an inverter, and automated control. The prototype system was equipped with numerous performance sensors, providing for the required aggregation of system performance indicators for further analysis.

The private house is a 2-storey building with a heated area of 200 m^2. The building is well insulated: the walls are built from aerated concrete blocks with mineral wool thermal insulation, the attic and the roof are separated from the structure and insulated with mineral wool, the windows have triple glazing, and the entrance door is a double door. Thus, the building has low specific heat consumption amounting to 36.6 kwh/m^2/per year.

The building has warm floor heating

and heat ventilation. Heat accumulation takes place both in the main/basic storage tank (filled with technical water) and in an additional storage tank (filled with a mixture of bioethanol with a freezing point down to -17 °C). The basic storage tank serves as a heat accumulation and distribution unit. The upper part of the storage tank is intended for household hot-water preparation and is maintained at a temperature above +50 °C; the middle part is intended for heating and it is maintained at a temperature that exceeds the temperature required for heating by a few degrees; the bottom part is intended for preheating hot water with the heat generated by solar collectors.

3. RESULT AND DISCUSSION

At the pre-design stage of the S3G system, the system was modelled with Polysun software, including simulation. The types of the system components, and their basic parameters, and sizes were selected through multiple modelling iterations. In each iteration, one of the basic elements was changed by one step in size with due regard to the sizes of the equipment widely available on the market. The components were optimized with the purpose of minimizing the amount of imported electricity (from the grid). In the next step (re-optimization), the entire optimization process was repeated. In total, we performed one base optimization and three re-optimizations. The difference in the amount of imported electricity as a result of the second and third re-optimization was 0.4 %. This leads to a conclusion that further re-optimization would hardly result in a significant reduction of imported electricity. On the other hand, real-world testing of the prototype and the results obtained showed that there was room for improving the control algorithm.

The prototype system is equipped with flat vacuum solar collectors. Flat vacuum solar collectors do not have mineral thermal insulation, and reduction of heat loss is ensured with air expanded almost to vacuum. Such solar collectors can also operate in a low temperature range without condensation and without corrosion in the solar collectors themselves. With sufficient solar radiation, the solar collectors heat up the storage tank through two snake-shaped solar heat exchangers in the basic storage tank. If the temperature in the solar collectors is higher than the temperature in the upper part of the basic storage tank, a 3-way control valve diverts the heat for heating, initially, through the upper solar heat exchanger and, next, through the lower solar heat exchanger. Thus, the accumulating heat storage tank gets the maximum amount of heat while maintaining the heat stratification in the tank. If the temperature of the solar collectors is lower than the temperature in the upper part of the accumulating heat storage tank but higher than the temperature in the bottom part of the storage tank, the heat transfer fluid from the solar collectors is transferred only to the lower heat exchanger of the basic storage tank. Thus, the upper part of the accumulating tank is not cooled. On the other hand, if there is insufficient solar radiation, the heat produced by the solar collectors is transferred to the additional storage tank. In the solar collector circuit, the heat transfer fluid is monopropylene glycol for solar systems, while in the additional storage tank, the heat transfer fluid is the same as in the ground circuit, i.e., a mixture of bioethanol. Therefore, the transfer of heat from the solar circuit to the additional storage tank

also takes place through a heat exchanger. The heat transfer fluid from the additional storage tank is mixed with the heat transfer fluid from the ground circuit and is transferred to the heat pump.

The heat pump in the building works with variable capacity: the heat capacity is in the range of 2.5 kW to 13 kW. The heat pump produces heat for both heating and hot water preparation. The heat pump, using the heat transfer fluid from the additional storage tank (in the temperature range from 5 °C to 25 °C), brings up the temperature of the heat transfer fluid in the heating circuit (from 30 °C to 55 °C) and goes on to heat the basic storage tank, from where the heat is redirected to be consumed by the building. Due to the installed heat recovery hydrounit, it was possible to use the heat energy obtained from indoor air for hot water preparation by increasing the heat transfer fluid temperature with the help of the heat pump. The free cooling unit, on the other hand, permitted transfer of excess energy into the ground circuit. The heat transferred to the ground circuit is more than sufficient for ensuring the cooling capacity of the building, and no additional cold generation or refrigeration equipment is required. When using the free cooling mode, with energy transferred to the ground, operation of the heat pump is not required. This results in significant energy savings.

The basic heating takes place through the warm floors, and fresh air is fed into the building through the ventilation installation. The ventilation installation is equipped with an air recuperator, a low-temperature heat unit and a cooling unit. Heat is transferred to the ventilation unit from the middle part of the basic storage tank. The cooling unit is connected to the ground circuit through the free cooling unit.



Fig. 1. Solar collectors and photovoltaic panels on the roof of the building.



Fig. 2. Prototype heat generation and heat distribution unit.



Fig. 3. Solar inverter and control unit.

Before handing over the prototype for autonomous operation, the control algorithm was adapted to the energy consumption. The S3G simulation and prototype performance parameters were compared and calibrated. From the very first months of testing, data showed that heat, hot water and electricity consumption depended significantly on a variety of factors, including consumer behaviour.

The lifestyle of the residents of the particular house includes long holidays and events with a large number of guests. Such a lifestyle has a significant impact on energy consumption. In particular, the two heat storage tanks are able to stabilize hot water consumption. On the other hand, fluctuations in electricity consumption had a significant impact on the amount of electricity imported from the grid and transferred to the grid.

The prototype system was tested for over a year. This is certainly not long enough for testing prototypes and obtaining in-depth results. Such a study would take several years, but in our case that would exceed the duration of the research project.

The data obtained as a result of the testing were checked, filtered from errors, and aggregated. For easier reading, they were aggregated and reflected in an energy consumption distribution schedule by month and by service types (see Fig. 2).

Since the prototype testing took place in the Baltic region, there is a clear difference in the type and amount of energy consumption during the winter and summer seasons. As a result, the S3G system operates in completely different modes during these seasons.

In the cold winter months, the consumption of thermal energy is significantly higher. The system operates in the heating mode almost without interruptions. Thanks to the heat pump ability to operate with variable capacity, heat production is sufficiently efficient. Thanks to heat storage tanks, which act both for heat stratification and as heat energy buffers, they are generally able to reduce the peaks in heat consumption.

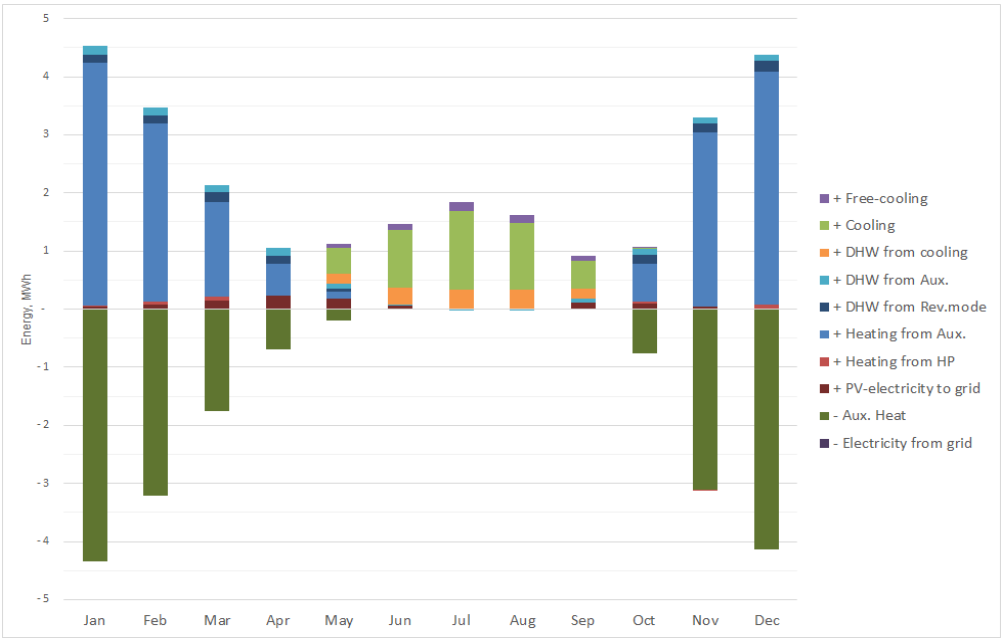


Fig. 4. Distribution of energy consumption in solar trigeneration systems by month.

Running the prototype in real-world conditions showed that hot water consumption peaks could be significant, especially for a family of four who all tend to take their shower on a daily basis during the evening hours. As a result, all the accumulated heat for hot water is spent. At that point, the system switches to high-temperature heating in the nighttime. In this case it is not possible to use solar energy. There are at least three different solutions for optimizing the system. The first option is to use larger accumulating storage tanks for hot water. The disadvantage of such a solution is higher heat loss from a larger storage tank. The second option is to store electricity in batteries, which accumulate the electricity generated by solar PV for later use. There is also the third option – to have a control algorithm for checking and incorporating the weather forecasts for the next day, so that a sunny forecast for the next day would mean the ability to generate enough heat from solar energy for the peak of water consumption on that day. Admittedly, this option is difficult to implement because of the high degree of risk, but this would be a way of maximizing savings in imported energy. If none of the optimization options are implemented, heat can still be produced from cheaper nighttime grid electricity.

4. CONCLUSION

A prototype solar trigeneration system was built in a new private single-family residential house for experimental purposes. The prototype system fully covers needs of house with the required thermal energy and cooling. The thermal and the electrical energy generated by the solar systems is used for the needs of the building to a maximum extent. The prototype system provides an opportunity to recover ther-

mal energy both during the heating and the cooling season. Information about the prototype configuration selection, analysis of the results have been presented in the study. Operational features and shortcomings of the open system, as well as the possibilities for its improvement have been described.

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