Comparison of Solar Systems with Seasonal Storage for Renewable Heat Production for District Heating

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Abstract

The use of solar energy for renewable heat production for supply to a low-temperature district heating system is compared for two solar system concepts: solar thermal system with photothermal collectors and system combining photovoltaic modules and air source heat pumps. Both systems are operated with identical seasonal heat storage within the borehole field. Renewable heat production and efficiency of seasonal heat storage are compared. The analysis shows that for the same area of collectors a system based on heat pumps powered only by electricity from photovoltaics has about 10 to 20 % higher production and supply of heat than solar thermal system depending on sizing.

Keywords: solar thermal collector, photovoltaic module, heat pump, seasonal heat storage

1. Introduction

Heat accounts for approximately half of the world's total energy consumption. Of this, approximately 46 % is consumed in buildings for space heating and hot water preparation (IEA, 2019). Decarbonisation of the heating sector is expected to play a key role in the transformation to future 100% renewable energy systems. In Europe, the transformation of district heating (DH) systems can significantly enable the application of renewable and waste-heat utilization technologies such as solar thermal systems, heat pumps, geothermal heat, excess heat from processes in industry and commercial buildings (e.g. supermarkets).

The temperature in modern or retrofitted DH systems usually ranges from 30 to 60 °C thanks to low temperature space heating systems in newbuilt buildings, however in the case of existing buildings this means a necessary reduction in energy demand through insulation, replacement of windows and energy-saving ventilation systems with heat recovery. Furthermore, 5th generation DH systems can also be encountered, where the concept of the DH system prefers the distribution of low-potential heat with a temperature level between 15 and 30 °C throughout the district to individual buildings, where decentralized “heat transformers” are installed, usually heat pumps, which on the one hand can take heat from the distribution system (cooling) or transfer it to the distribution system (heating) depending on the type of building or the time of year. The centralized supply of heat and cold is connected into one complex system of thermal energy shared within the cluster of buildings. In addition to the easy integration of renewable sources and waste heat, the advantages of such low temperatures are mainly the elimination of heat losses, a reduction in the level of thermal insulation of the distribution system, the possibility of using cheaper plastic pipes or significant use of seasonal storage of renewable heat (Lund et al. 2021).

2. SYNERGYS project

A unique infrastructure focused on research and testing of renewable energy sources is being realized within the SYNERGYS project (under Just Transition Fund) in city of Litoměřice in Czech Republic, including pilot systems for the production, storage and supply of renewable heat for district heating purpose. The SYNERGYS project combines the topic of using a deep geothermal source of energy and above-ground technologies using seasonal heat storage in the underground. The research infrastructure will be created to show possible ways of transforming Czech cities towards a carbon-free future in the field of building energy supply.

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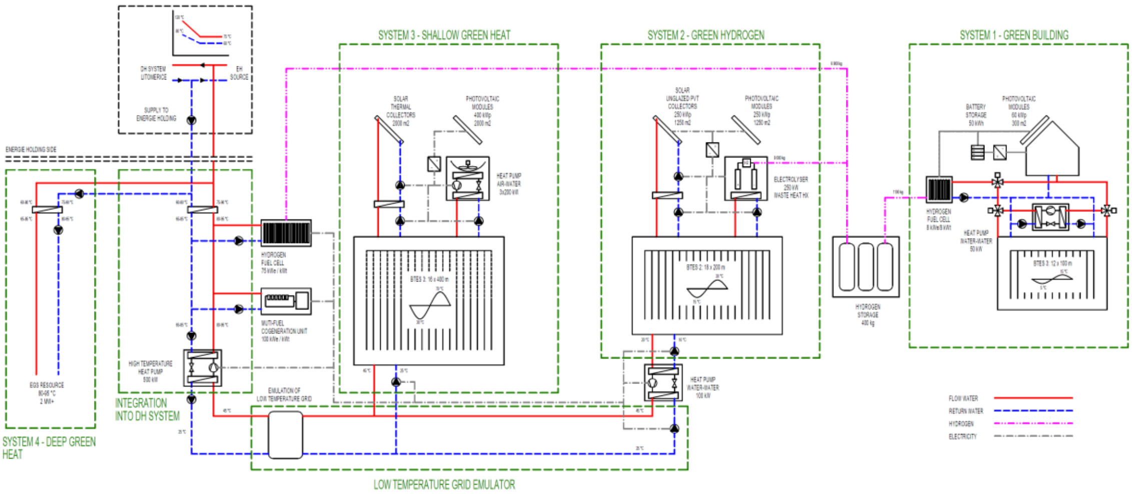

Fig. 1: Scheme of SYNERGYS project with 4 sub-systems

As a part of the technical study carried out in the planning phase using computer modeling a complex energy system consisting of four sub-systems has been designed (see Fig. 1). The core of the entire system is a deep geothermal heat source with a depth of 3.5 km and heat output in order of MW for the permanent heat supply at temperature level of 90 to 100 °C to the local district heating system. The other three systems use seasonal storage based on ground boreholes fields with different operating temperatures and depths (100, 200 and 400 m). For the annual production of up to 8 tons of green hydrogen an electrolyser with power input of 250 kW will be connected to photovoltaic-thermal (PVT) solar collectors with a peak electric output of 500 kW_p (system 2). Waste heat from hydrogen production and heat from cooling of photovoltaic cells will be stored within the borehole field in the summer and will be supplied to the DH system with use of a heat pump in winter. The building of the existing RINGEN research center will be heated and cooled by a ground source heat pump combined with a photovoltaic system and battery storage. Fuel cell will use part of the local hydrogen production from seasonal hydrogen storage (about 1 ton) to supply electricity and heat in winter for the building. The goal of the solution is to achieve a carbon neutral building operated in real time only with the help of local renewable energy (system 1). System 3 consists of large-scale solar thermal system with a collector area of 2000 m^2 with seasonal borehole storage, supplemented by air source heat pump (600 kW at A7/W35) powered only by PV system with an area of 2000 m^2. The systems 2 and 3 are interconnected by a low-temperature network 45/25 °C using heat from seasonal storage, and a high-temperature heat pump will transform the heat to the temperature level of the DH system in Litoměřice.

3. Solar systems

The presented analysis focuses on system 3 (green heat) designed as part of the SYNERGYS project to compare two renewable heat supply systems that will be connected to a common seasonal heat storage in the form of borehole field. The system SOLAR is solar thermal system, the system PV-HP is a combination of a PV and air source heat pumps for production of usable heat from the heat of ambient air using only renewable electricity from PV. The analysis thus compares a system with direct conversion of solar radiation into the heat, where the efficiency of solar collectors depends on the operating temperature and climatic conditions, and on the other hand, a system with direct conversion of solar radiation into electricity, which drives the air source heat pump, whose efficiency is also dependent on operating temperature and climatic conditions. Since both sources show a significant production of renewable heat in the period from spring to autumn, they are connected to seasonal storage with different layouts investigated.

The aim of the simulation analysis performed in TRNSYS was to compare the overall efficiency of heat production and supply from both systems, including the effect of seasonal storage, with the same installed area of solar collectors / photovoltaic modules, under the same climatic conditions and conditions of heat supply to a low-temperature DH system with a permanent load power of 500 kW (from October 1 to April 30) at the temperature level of 45/25 °C. The heat supply system is considered for preheating of the return water, with the fact that the required temperature of the supply water to the DH is not exceeded.

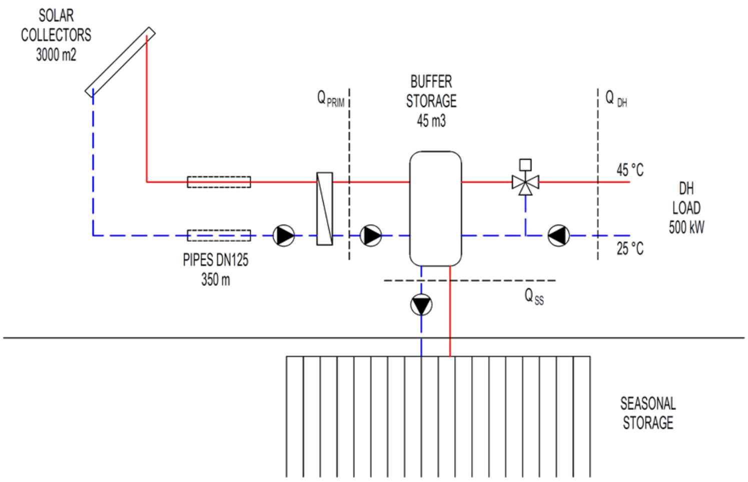

Fig. 2: Scheme of variant SOLAR

The basic SOLAR variant considers the solar thermal system with standard flat-plate solar collectors (η_0 = 0.75, a_1 = 3.8 W/m^{2}K, a_2 = 0.014 W/m^{2}K^2) with a total area of 3000 m^2, installed with slope of 45° and orientation to the south. The collector field is connected by DN125 pipe (length of distribution 350 m) to a buffer storage tank with a water volume of 45 m^3. A simplified scheme is shown in Fig. 2.

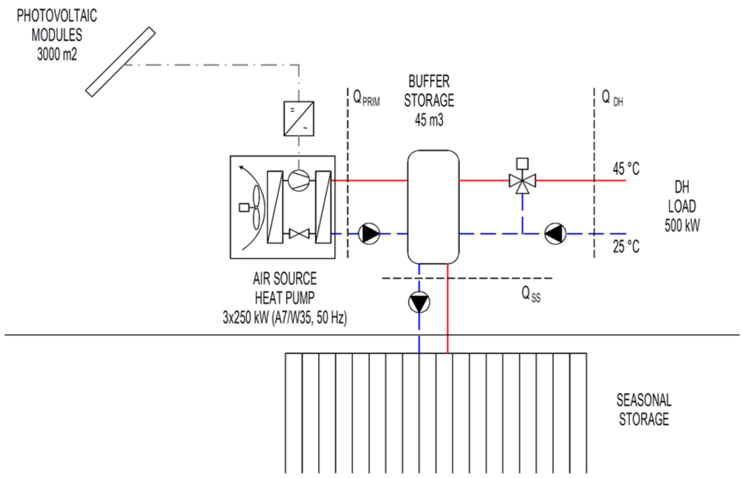

Fig. 3: Scheme of variant PV-HP

The basic PV-HP variant represents a combination of photovoltaic system and air source heat pump and is considered as an equivalent to the solar thermal system (see Fig. 3). The area of the photovoltaic modules is assumed to be the same 3000 m^2 with the same slope and orientation. With a reference efficiency of PV modules of 20 %, this practically means 600 kW$_p$ peak output of the PV field. The real operational efficiency of the entire system is at the level of 16 % (effect of module temperature, inverter efficiency, electric losses, etc.). The heat pump is considered as a cascade of three units at 250 kW (at A7/W35, 50 Hz), each with continuous power control of compressor from 30 to 120 Hz. The heat pump units are connected to a buffer storage tank with a water volume of 45 m^3. Based on the produced power of the PV system and the temperature in the buffer tank, the system controller determines how many heat pump units and with what compressor frequency they should be operated so that their electric power input is equal to the actual electric power of the PV system. This is to achieve that the heat pump does not consume any electricity from the grid and uses only renewable electricity. The simplified model for the controller uses an equation created from the detailed characteristics of given heat pump for different frequencies, temperature to the evaporator and temperature to the condenser. Fig. 4 shows an example of controlling the heat pump's electrical input according to the electrical output of the PV system in simulation. It is evident that the control is not perfect due to the inaccuracy of the simple model for controller. However, the inaccuracy of the control, expressed by the share of electricity that the heat pump had to take from the grid during the whole year, is under 2%.

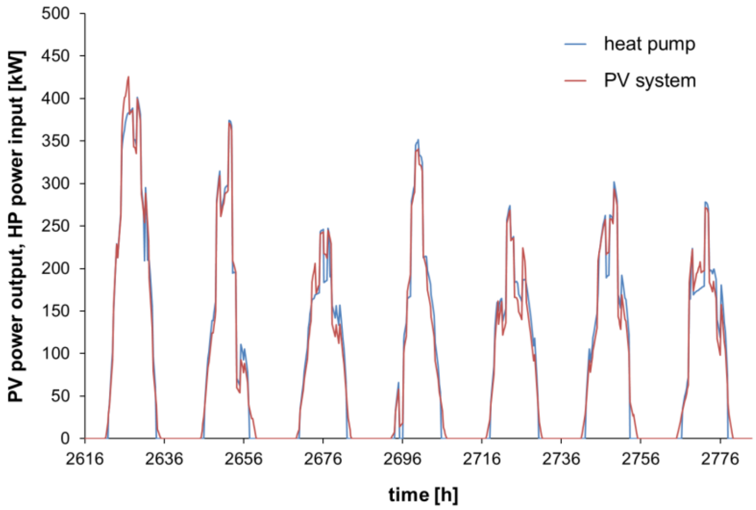

Fig. 4: Adaptation of power input of heat pumps to power output of PV system

For both systems, the same variants of seasonal storage were considered using a borehole field with a concentric tube and bentonite filling: a) 32 shallow boreholes with a depth of 200 m; b) 16 deep boreholes with a depth of 400 m, but with the upper 200 m filled with a heat-insulating mixture to prevent heat loss and eliminate the thermal influence of the upper layers of the subsoil with possible groundwater flow. The total active length of the ground boreholes is thus considered the same with generally comparable costs of the seasonal storage. In all cases, boreholes are considered with a spacing of 5 m. The rock profile up to a depth of 500 m was defined on the basis of a geological survey of the given SYNERGYS infrastructure site. An underground thermal energy storage with longer boreholes can count on a higher temperature of the massif, but its total storage volume is finally smaller than in the case of an underground storage with higher number of shorter boreholes. Thus, shallow borehole field has a larger active storage volume than in the case of deep boreholes, where the upper half of the boreholes is insulated for the heat transfer. It is clear from the scheme of both systems that the seasonal storage is used to store actual excess heat from the buffer tank. The renewable heat source supplies heat primarily to the buffer tank, and when the defined temperature 45 °C is exceeded, the seasonal storage charging pump is started.

4. Comparison

Due to the same area of solar collectors and photovoltaic modules and the same considered configurations of seasonal storage, it is possible to make a direct comparison of the total renewable heat delivered to the buffer storage from primary production side (Q_{PRIM}) and the usable heat transferred further to the low-temperature DH system (Q_{DH}) during the year. At the same time, the balance of the seasonal storage (Q_{SS}) is shown in all variants (input: in, output: out). The results of the comparison are presented in Tab. 1 for all variants with basic sizing (area of solar systems 3000 m^2).

Tab. 1: Annual energy balance of variants with solar collectors area 3000 m^2

Variant	Q_{PRIM} [MWh]	$Q_{SS,in}$ [MWh]	$Q_{SS,out}$ [MWh]	Q_{DH} [MWh]
SOLAR 400 m	1571	1259	722	1034
SOLAR 200 m	1580	1301	715	994
PV-HP 400 m	1869	1450	816	1235
PV-HP 200 m	1912	1526	831	1217

Comparison of solar energy systems (SOLAR, PV-HP) producing renewable heat shows that PV-HP combination brings approximately 20 % higher heat gains both on the primary side of the system and in usable heat for low-temperature DH supply, despite the fact that the solar thermal system has relatively high specific heat gains of over 500 kWh/m^2.a. The heat pumps in PV-HP variant work with annual COP of 3.53 (400 m) and 3.61 (200 m), the photovoltaic system produces around 177 kWh/m^2 of module area (gross area) per year.

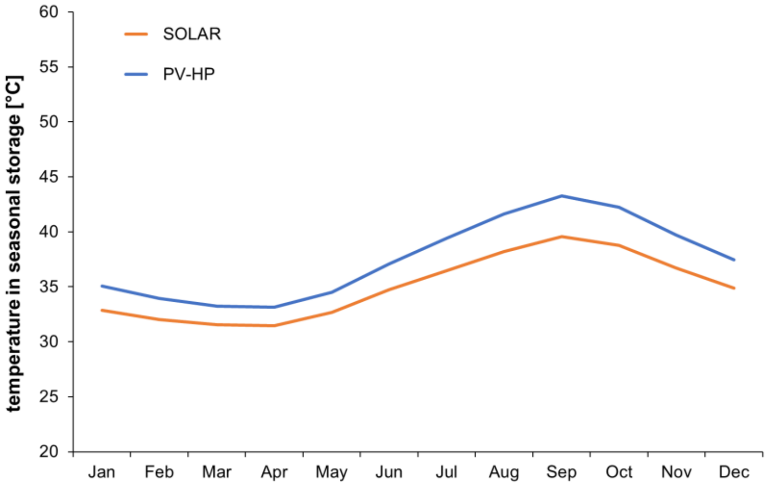

Fig. 5: Monthly average temperature of seasonal heat storage volume (borehole field)

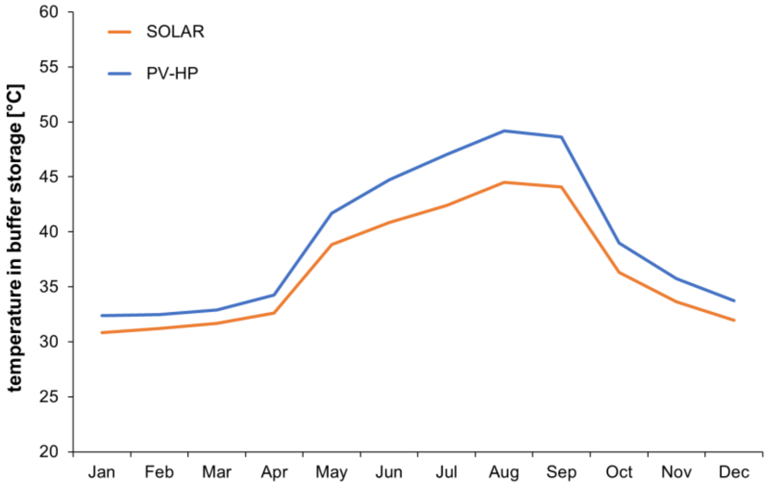

Fig. 6: Monthly average temperature of buffer water storage

Tab. 2: Comparison of performance indicators for variants

Collector area [m2]	SOLAR		PV-HP	
	Coverage [%]	Specific gains [kWh/m^2.a]	Coverage [%]	COP [-]
1500	15	564	23	4,1
3000	39	527	48	3,6
4500	61	498	65	3,3

Results also showed that the layouts of the seasonal storage do not differ much from each other. The efficiency of the heat storage as a ratio between the output and the input of the seasonal storage varies between 54 % and 57 %, as the seasonal storage in general is burdened by a significant share of heat losses. It follows that it is not economically advantageous to perform deep ground boreholes (400 m) with thermal insulation compared to conventional ground boreholes up to 200 m due to the need to use more expensive drilling technology. For additional information, the graphs in Fig. 5 and Fig. 6 shows the temperature evolvement in the seasonal storage and in the buffer storage for both system variants with 200 m boreholes. The displayed temperature in the seasonal storage is the average temperature of the entire ground mass within the borehole field. The temperature is higher in the center and around the boreholes, and the temperature is lower then the average towards the edge of the borehole field. It is evident from the comparison of the temperature trends that the heat pumps, by giving more energy, also get the seasonal storage at a higher temperature. The highest temperatures are reached at the end of September, the lowest in March.

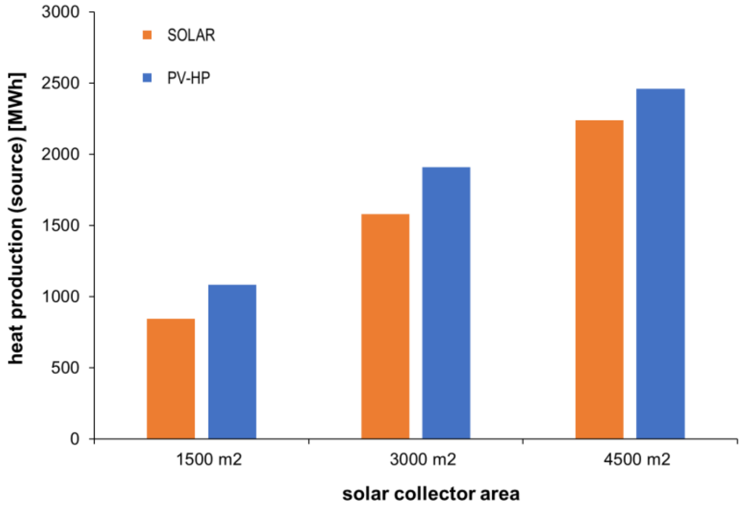

Fig. 7: Influence of sizing on heat source production

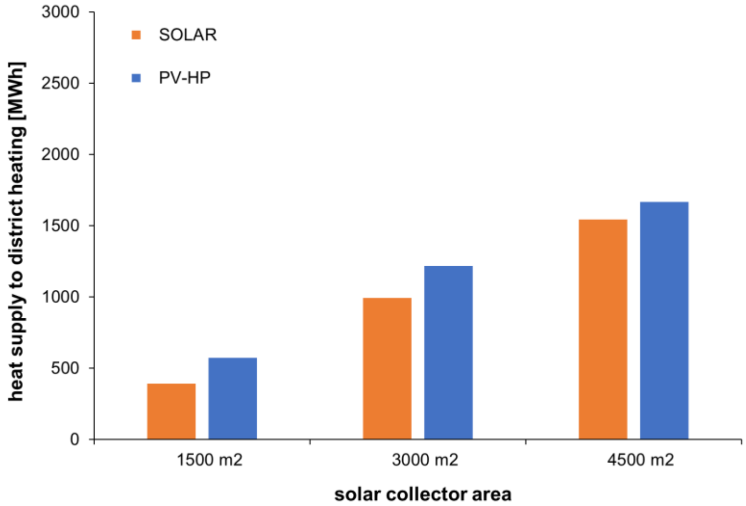

Fig. 6: Influence of sizing on heat supplied to district heating system

In addition to the basic variants of systems, sizing with 50 % larger (4500 m^2) and 50 % smaller (1500 m^2) area of solar thermal collectors and photovoltaic modules were also analyzed. As the area increased, the volume of the buffer storage tank was changed proportionally, in the case of the SOLAR variant, also the dimensions of the pipes, and in the case of the PV-HP variant, the nominal heat output of the heat pump units has been adapted. Seasonal storage with 32 ground boreholes with a depth of 200 m has been considered for all variants of sizing. The comparison of the total annual production of the heat source and the heat supply to DH system is shown graphically for the variants in Fig. 7 and Fig. 8. The resulting performance indicators of the technologies (coverage of heat consumption, specific heat gains, *COP* of the heat pump) are summarized in Tab. 2.

The results show that as the heat output of the heat source increases due sizing in both variants, the difference in performance between SOLAR and PV-HP variants decreases. In the case of variants with an area of 4500 m^2, the heat production of the PV-HP system is only 10 % higher compared to the SOLAR system, and the heat supply to the DH system is only 8 % higher.

5. Conclusion

Renewable heat sources connected to low-temperature heat supply systems will increasingly appear in district heating systems in future. Within the upcoming SYNERGYS project renewable heat production will be investigated theoretically and experimentally, using seasonal storage in the boreholes field. Presented analysis showed possible advantages of the combination of photovoltaic systems and heat pumps for (especially) summer heat production with significant efficiency. Compared to solar thermal systems, the combination of efficient PV modules with air source heat pumps shows a roughly 10 to 20 % higher heat supply with the same area of solar collectors. A certain uncertainty in the results arises from the fact that the effect of possible freezing (and therefore necessary defrosting) of the evaporator at outside air temperatures between 5 and 10 °C, typically during the transition period has not been taken into account within the simulations. Also the limitations of compressor envelope with frequency control were not included. This will be subject of further analyses.

The efficiency of seasonal heat storage was around 55 %, which is a relatively low value. The results and practical experience from other projects show that the efficiency increases with increasing collector area, with increasing storage size (compactness, lower proportion of heat loss compared to stored heat) and, naturally, with a lower temperature of intake to the distribution of centralized heat supply (low-temperature district heating systems). At the same time, it has been proven so far that the use of deeper boreholes and storage at greater depths (400 m) does not bring an advantage in the efficiency of heat storage compared to more affordable shallower boreholes up to 200 m. The results of the analysis will be used for the final design of both systems in the JTF SYNERGYS project, in which the effectiveness of the production and supply of renewable heat for the district heating will be verified in the real operation of the technologies.

6. Acknowledgments

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7. References

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