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Analysis of House Space Heating System with Under-Ground Seasonal Energy Storage Using PV Electricity Generation

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Abstract - In this article, the heat storage for small dwellings with seasonal storage in Estonia is modelled. The system consists of low temperature underground insulated unit, an auxiliary buffer tank inside the building and PV panels as an energy resource. A more detailed seasonal storage model has been designed to evaluate the heat storage and extraction processes. This work's novelty is the usage of solar PV panels as an electricity producer for supplying energy for space heating with seasonal storage. For energy storage, sand/soil is used as media, but it is acknowledged that modelling with other materials is also possible. The energy is carried to the storage unit and extracted by the water pipes register. The media around the pipes in the model is divided into layers, simplifying the unit's calculation of heat exchange processes. The buffer water tank is used for short-period energy storage and tap water heating. The system is designed so that the energy is not supplied to the main unit in the spring. The main storage is used at the beginning of summer and early autumn. By this design, energy loss within the main unit is minimised. The results show, that when the main unit has sufficient capacity and proper insulation thickness, it is likely to adequately cater to residents´ heating and warm water demand throughout the year. In the case of shorter periods of high temperature in the storage tank, energy loss is minor.

Keywords Home energy management, seasonal energy storage, solar heating, solar energy, greenhouse gas, energy recovery.

1. Introduction

Reducing greenhouse gas emissions in the atmosphere and decreasing the human footprint is the main target today for humankind [1-3]. European Union targeted an increase in the share of power generation from renewables up to 32% by 2030 [4, 5]. One viable method of diminishing the human footprint is to adopt energy production technology that is CO_2 free [6, 7]. It is extremely important to disseminate the generated renewable electricity within the immediate environment [8-10]. Source [11] describes the importance of combining storage devices, smart grid and power grid for load balancing. Society accepts attractive and innovative renewable energy solutions with storage devices [12]. The local microgrid (MG) must be connected to the main electricity network (EN). The power electronics enable easy division of power flows inside MG and between the MG and EN [13-15]. EN accounts for a boundless energy storage environment, but the main EN in Estonia needs more support for resilient measures [16, 17]. At the same time, wind and PV panels' energy are converted and do not have an excess heat energy component for energy conversion with seasonal energy storage in STES [18]. Source [19] draws attention to the fact that storage devices can affect the economic indicators of a renewable energy solution for the worse.

Energy storage technologies are broadly divided into short-term [20] and long-term storage. Long-term energy storage is more significant for northern areas, especially seasonal energy storage (STES). In summer, there are numerous days with high solar radiation, but energy usage is usually limited to cooling/air conditioning. The need for energy increases in winter, but the sun's radiation is shallow from November to February in Estonia. To some extent, there is more wind energy in the winter. Solar PV energy production is the most straightforward technology due to the absence of moving parts in equipment to produce renewable electricity. STES will cover disharmony between seasonal energy consumption and production. Significant energy losses and a small fraction of PV energy are still problems in using large underground seasonal storage devices [21]. More complex solutions have been designed for seasonal energy storage in a private house, where sorption storage in liquids and heat pumps have been used [22]. This article aims to investigate the possibility of a storage device that is as simple and inexpensive as possible.]. One of the possible solutions is to direct the energy from the solar collector to the borehole for seasonal storage [23]. As a general rule, storing borehole energy is impossible in Estonia, as most of the country's territory is constantly moving groundwater or water in deeper layers. This makes it impossible to store energy there, while the law prohibits the construction of boreholes for this purpose. An overview [24] of heat storage technologies reports that dimensioned seasonal energy storage provides an opportunity to increase the share of the sun in building heating significantly. The source [25] provides an overview of three technologies for seasonal energy storage: an aquifer, a borehole and an underground tank. Although the underground tank may be the most expensive, it has several advantages over other technologies, including controllable efficiency and environmental impact. Whereas sensible heat storage technology is fully developed and mature, the other two are still in development. The paper [26] reviews the influence of the mismatch between supply and demand graphs on the efficiency of the energy storage process. Four methods of sensible heat storage are evaluated: tank, pit, borehole, and aquifer thermal energy storage. In [27], authors assessed three large water-based most promising STES concepts: tank thermal energy storage, pit thermal energy storage, and water-gravel thermal energy storage. STES suitable for the cold climate is evaluated in [28]. This equipment is based on thermal collectors and heat pumps with a low-temperature storage environment. Ref. [29] describes the experiment of using STES on university campuses to get a 100% renewable energy supply. The STES assesses the feasibility of integrating STES equipped with heat exchangers and heat pumps in a district heating system [30]. The solar collector and the auxiliary boiler are used in STES [31]. The coupling of STES and CHP is evaluated in [32]. A novel thermal description is given for STES's inventories based on the superposition of inter-period and intra-period states in [33]. In [34], the authors evaluate the STES in an underground pit in the non-heating season. A thorough economic analysis of pit and tank STES is performed in [35]. The genetic algorithm is modelled for STES with solar thermal collectors and a sensible heat storage device using water as a storage medium [36]. Analyses of research efforts to store moderate amounts of heat energy inside floors in residential buildings are presented in [37]. Ground source heat pumps use the passive energy storage of the earth to heat and cool the facilities [38].

Our research objective is to determine that the STES are the easiest to use and most flexible to maintain solutions amongst other options. Heat collectors have high efficiency during periods of the year when they are not needed. They do, however need help with surplus energy in periods of overproduction. PV panels are less efficient than solar collectors but can deploy excess energy to EN.

The remaining sections of the paper are organised as follows: Section 2 describes the heating system, the input data, the seasonal storage, the model, and the modelled situations. Section 3 presents the results and discussion. Finally, Section 4 introduces the main conclusions of the paper.

2. Materials and Methods

2.1. Description of the Heating System

The energy system, which is the subject of study for heating the building is shown in Figure 1. The PV panels and inverter part is a classic micro-producer power plant connected to the power grid. In this system, an electric heater for the buffer tank is driven by an automatic system, which should be not discussed in this article. The heater must have a power that can be selected stepwise to ensure water heating at a different output power of the PV panels. Its selection and control are, however not discussed in this article.

The use of electricity produced by the PV panels is prioritised so that the water in the buffer tank is first heated and then used both for heating the building and producing domestic hot water. When the water temperature in the buffer tank rises above 95°C, the sand in the seasonal storage start to heat up through a network of pipes. When the temperature of the sand in the seasonal storage rises above 95°C, the rest of the energy is sent either for self-consumption or to the grid.

The addition of thermal energy to the buffer tank, boiler DHW, as well as STES is calculated using the following formula:

$$Q = m \cdot c \cdot (T_1 - T_2), \qquad (1)$$

where:

Q is the amount of heat energy added or removed, kW·h;

m – the mass of water or sand in the container, kg;

c – specific heat capacity of the corresponding medium (water or wet sand), kW·h/(kg·K;

T_1 – ambient temperature before the cooling or heating process, K;

T_2 – ambient temperature after the cooling or heating process, K.

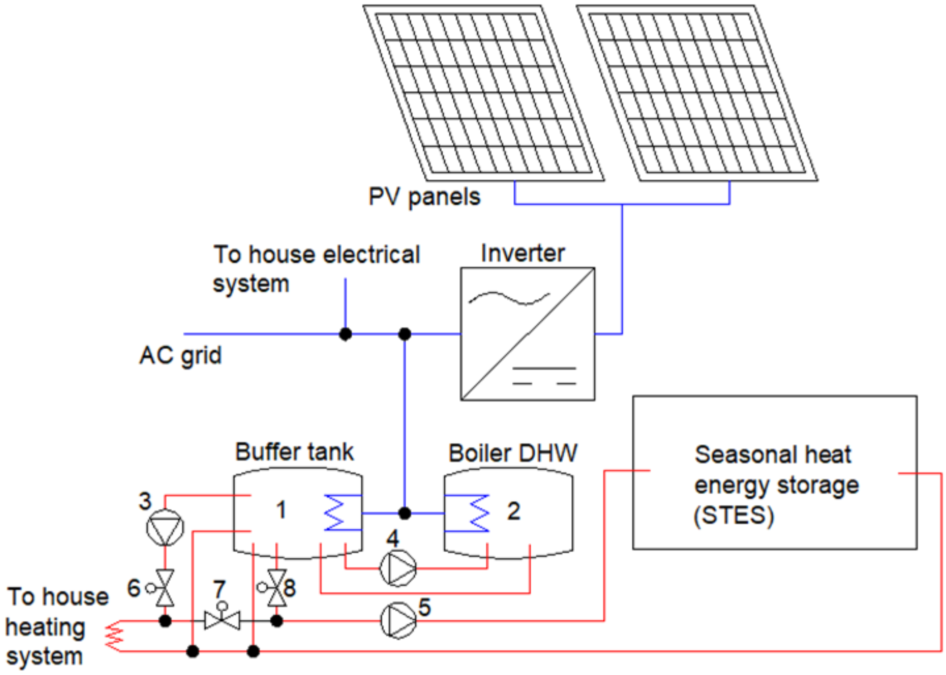

Fig. 1. Principle diagram of the studied heat energy system: 1 – buffer tank; 2 – boiler for DHW; 3…5 – pumps; 6…9 – valves for different heat flow settings.

Energy for heating the domestic water (DHW) boiler is taken from the buffer tank when the temperature of the buffer tank is above 65°C. Figure 1 shows the pumps and valves which enable the selection of different operating modes of the heating system.

These operating modes are presented in Table 1, from which the part related to domestic water heating is omitted. The last two of the three methods described in Table 1 cannot co-occur.

Table 1. Different working modes of the heating system

Pump 3	Pump 5	Valve 6	Valve 7	Valve 8	Mode description
on	off	open	closed	closed	Buffer tank discharging for house heating
off	on	closed	closed	open	STES charging process
off	on	closed	open	closed	STES discharging for house heating

2.2. Input Data

The input parameters of the model are the heating power needed to ensure a comfortable microclimate in the building, the power of the PV panels, the average temperature of the ground and the power needed to heat DHW. The building's heating capacity is calculated based on the difference between the annual change in outside temperature and the desired inside temperature. For this purpose, data representing the thermal technical parameters of the building and the measured outdoor temperature for one year have been extracted and used. The building's necessary daily heating energy demand from May to the end of April next year is presented in Figure 2 and is 6 MW·h in total. Maximum heating power is 3 kW. The output data of the solar power plant (with a nominal capacity of 2.2 kW) has been measured between 01.12–30.11 for one year. During modelling, the power data is multiplied by the power scaling factor k (Formula 2) to obtain the output power data of a more powerful PV power plant. This allows more powerful energy systems to be modelled based on available data. Figure 2 shows aggregated (k = 6) daily energy production. The daily amount of energy required for heating DHW is 11.3 kW·h, which is needed to raise the temperature of 150 kg of water by 65°C.

The scaling factor k is calculated with the following formula:

$$k = P_{n*} / P_{n'} \qquad (2)$$

where:

k is the scaling factor;
P_{n*} – the new requested nominal value, kW;
$P_{n'}$ – the initial nominal value, kW.

To find the heat loss of the seasonal storage, the ground temperature is required, taken as 10 °C in this study [39]. All data used in modelling are 5-minute averages.

2.3. *Seasonal Storage*

Wet sand is used as the heat-storing material of the seasonal storage in this study. Still, theoretically, it is possible to use the same soil that is removed during the storage construction. The thermal conductivity coefficient of wet sand is 2.5 W/(m·K), and the heat capacity is 1600 J/(kg·K). Reinforced concrete has been selected as the material for the tank shell, whose thermal technical parameters have also been considered in the tank model. The shell material must ensure the mechanical strength of the container. The shell is waterproofed.

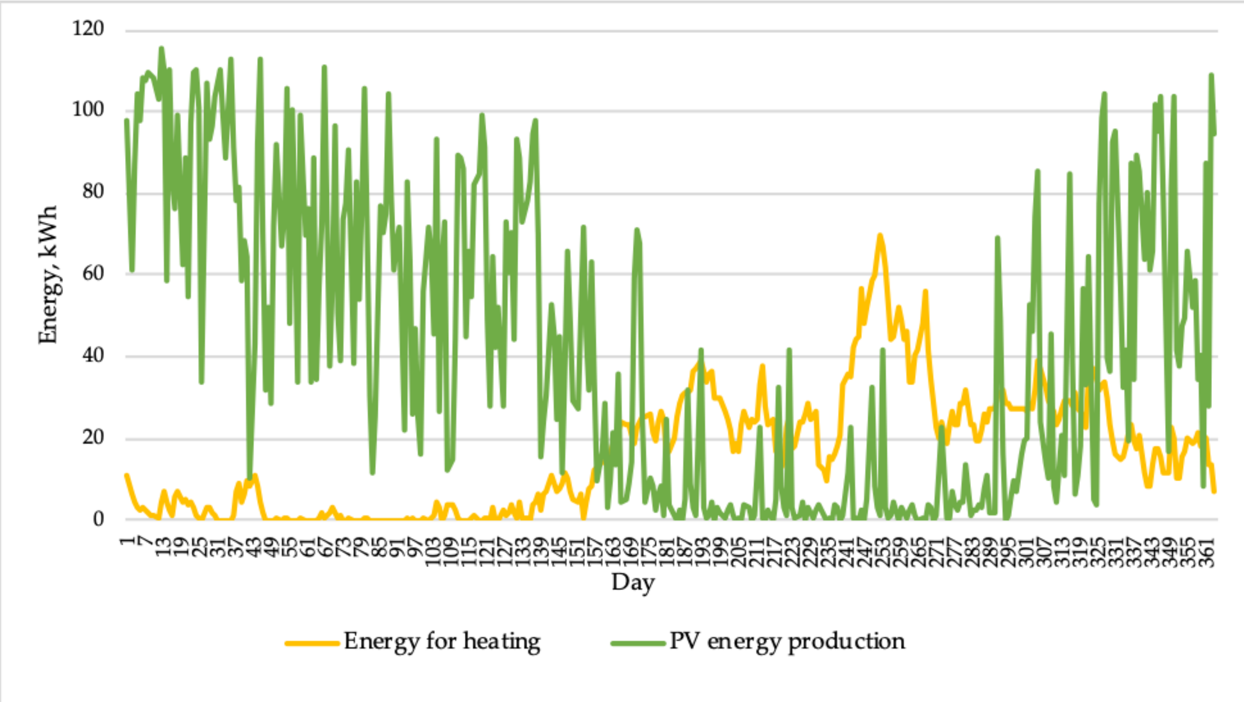

Fig. 2. House heat energy demand and PV electricity production.

The concept of the container is presented in Figure 3. It is essential to use insulation materials with the lowest possible water absorption, and that is suitable for use in the soil. The thermal conductivity coefficient of the insulation is 0.032 W/(m·K), and its thickness is 1000 mm. The heat loss through the boundaries of the STES tank depends on the heating parameters. During the construction of the tank, water pipes are also installed in the sand at different heights to transfer energy.

Compared to other seasonal storages, the advantage of such a tank is its relatively simple and fast construction, resulting in a low cost. We won't delve into the specific construction technical details of the container here because its design can be approached in various ways depending on the availability of construction materials in the market.

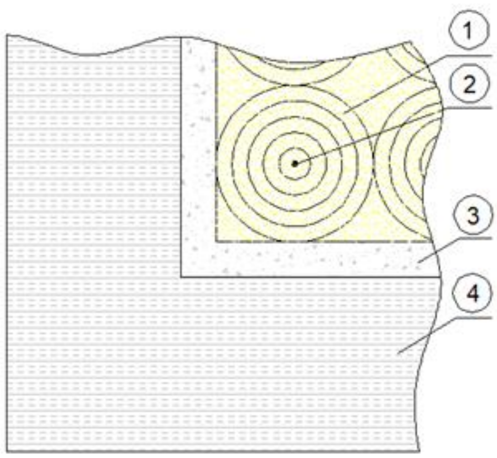

Fig. 3. Cross section of STES. 1 –- sand layers; 2 – pipe for heat transfer; 3 – concrete walls with hydro isolation; 4 – insulation.

Three pipe layers are used at different heights, and there are five pipes in each layer. They form a network of pipes. Pipes must be corrosion-resistant and be able to withstand high temperatures. For thermal engineering calculations, the heat-storing material around each pipe is conditionally divided into five layers (Figure 3) to achieve a more accurate result in modelling. In addition, the contact surface of the outer layers is also taken inconsiderably. Each layer's cross-section area has been calculated, which is the basis for finding the thermal resistance and heat capacity according to the storage material used.

2.4. Model Description

The energy system model is built in the Scilab 6.0.2 Xcos graphical environment using the Coselica add-on module. This additional module allows the use of heat transfer blocks, which contain everything necessary for modelling heat processes. Thermal conductors, heat capacitors, heat flow and sensor blocks have been used as basic blocks in constructing the STES model. The model considers the heat capacities of the water in the buffer tank and all components of the seasonal storage, as well as the mutual thermal resistance of the components Scilab Scinotes environment, a script has been created for the model, the task of which is to calculate the value of the variables used in the graphic model (heat capacity, heat resistance). The script's basic input parameters are the tank's dimensions, the thermal technical parameters of the heat storage material, the thicknesses of the buffer tank and the STES insulation layers, and the thermal technical parameters. Sensor blocks provide feedback from the model about temperature and heat flow. Based on the temperature, the system´s operation is controlled, which means directing energy to different system components. The work of the model can be conditionally divided into two parts: the first part directs the extracted solar energy into the storage devices (Figure 4). In contrast, the second part handles the use of the stored energy for heating the building and domestic water (Figure 5).

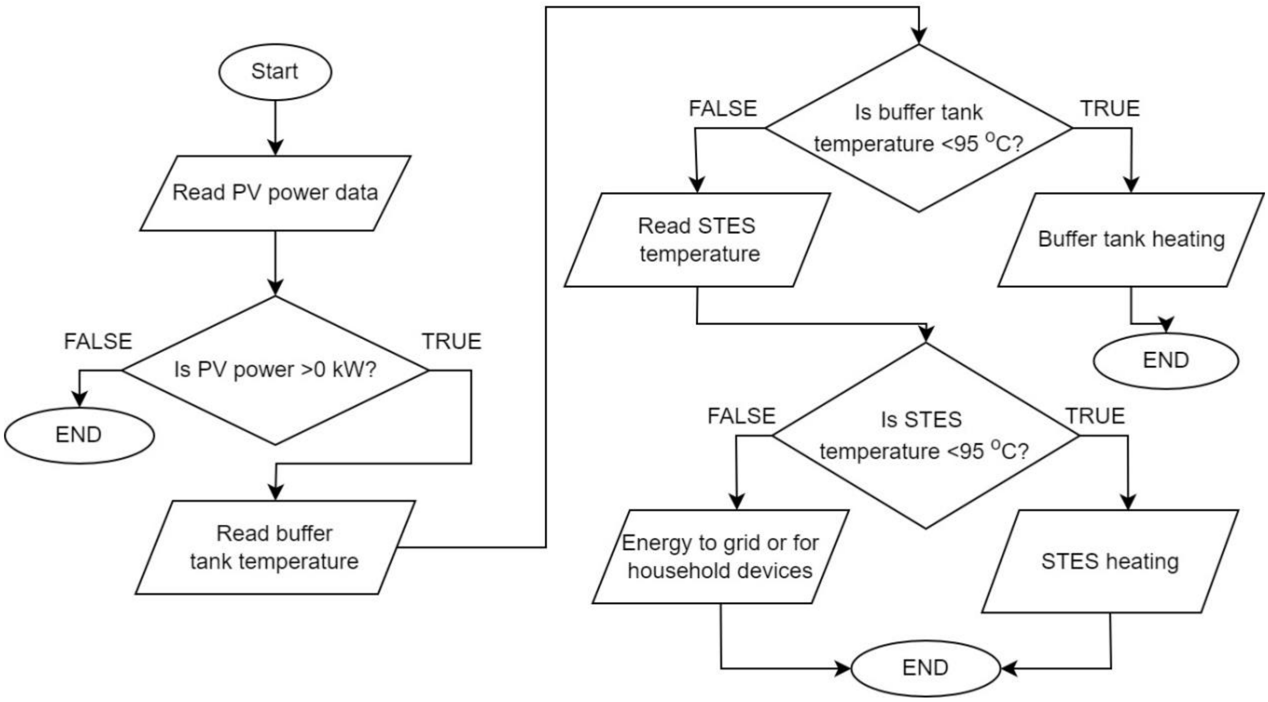

Fig. 4. Principal flow chart for energy storage process in the model.

Figure 4 shows the algorithm based on which the buffer tank and STES thermal energy are supplied from the PV panels. The electricity produced by the PV panels is first converted into heat in the buffer tank but provided that its temperature does not exceed 95 °C. If the temperature of the buffer tank reaches 95 °C, the electricity is forwarded to the STES, and if the temperature there exceeds the specified value, the remaining electricity is transferred to the power grid.

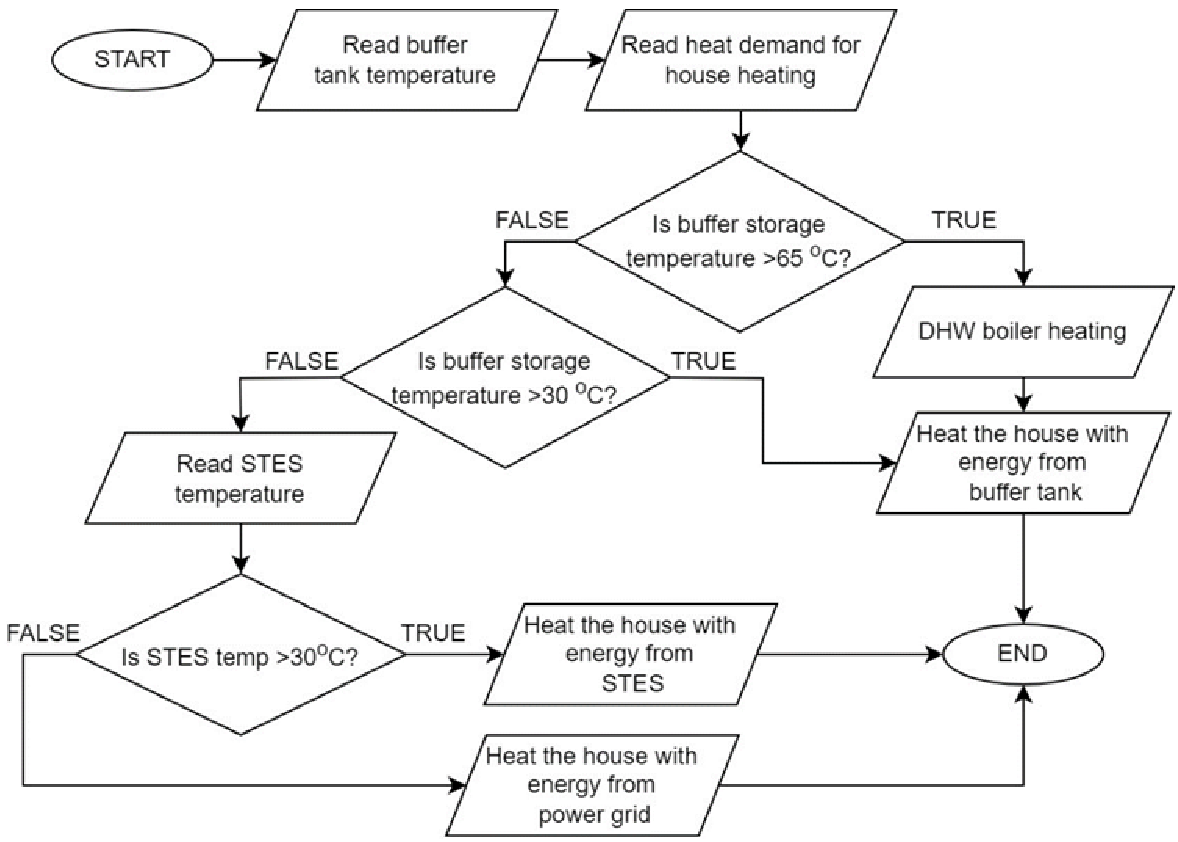

Fig. 5. Principal scheme for energy discharging process in the model.

Figure 5 shows the algorithm for heating the building from STES. First of all, the heat demand of the building and the temperature of the buffer tank are fixed/distinguished. Next, it is determined whether the temperature of the buffer tank is above 65 °C. If this is the case, the valve is opened, and the warm water flows into the DHW boiler, after which it moves on to the building's heating system. When the buffer tank temperature is between 30–65 °C, the valve opens, and warm water also moves into the building's heating system. If the temperature of the buffer tank is below 30 °C, the STES temperature is checked: if it is above 30 °C, warm water is taken directly from the STES to supply the heating system of the building. If not, additional energy for heating the building is taken from the electricity grid.

The model simulation step is taken to be 5 minutes, which is the same as the input data step.

Domestic water is heated by circulating the water in the buffer tank through the heat exchanger in the DHW boiler, and it takes place if the temperature of the water in the buffer tank is above 65°C. This temperature is chosen to prevent the spread of legionella bacteria in the DHW boiler [39], which are found naturally in freshwater environments like lakes and streams. It can become a health concern when they grow and spread in human-made building water systems. Although the domestic water in the DHW boiler can also be heated directly with an electric heater, the model still considers that the energy is first taken from the buffer. This allows the energy stored in the buffer to be used for DHW heating even when solar energy is unavailable.

2.5. Modelled Scenarios or Cases

The energy system is modelled at STES tank volumes of 100 m^3, 150 m^3, 200 m^3 and 250 m^3. For the annual electricity production of PV panels, approximately 15,000 kW·h is used in all modelled cases, corresponding to the capacity of a 15 kW PV park under Estonian conditions. The output parameters of the model are the temperature of the buffer tank and the STES tank, the energy taken from the buffer tank and the STES tank for heating the building, the energy loss of the STES tank, the energy for heating DHW, the energy surplus and the energy consumed from the network. Energy from the STES tank is not used to heat DHW.

3. Results and Discussions

The modelling period of the heating system is three years, for which the data of one year was used as the same for all years. Modelling for a more extended period is essential because, in the first year, much energy is spent on preheating the storage. From the second year, the system under study is stable. Due to the year's data similarity, the third year's results are similar to those of the second year.

As for the results, the data ofsecond year's dataesented from the end of the heating period to the end of the next heating period in the third year, i.e. from the beginning of

May to the end of April of the following year. Such a period has been chosen because it facilitates monitoring the STES tank's behaviour during one heating period. Energy storage in the STES tank during warm weather can also be monitored.

Modelling the heating system with four different tank volumes (Figure 6) demonstrates that the larger the tank volume, the greater its heat loss. Heat loss highly depends on how long the storage tank is kept close to the maximum temperature. At STES capacities of 200 m^3 and 250 m^3, the share of heat loss from the renewable energy provided by the system differs significantly from, for example, the same indicator in a comparison of 150 m^3 and 200 m^3. This is because with the same renewable energy production, the 250 m^3 STES tank does not heat up to the final temperature (Figure 7) because of the energy deficit, and the temperature difference between the ground and the tank remains smaller.

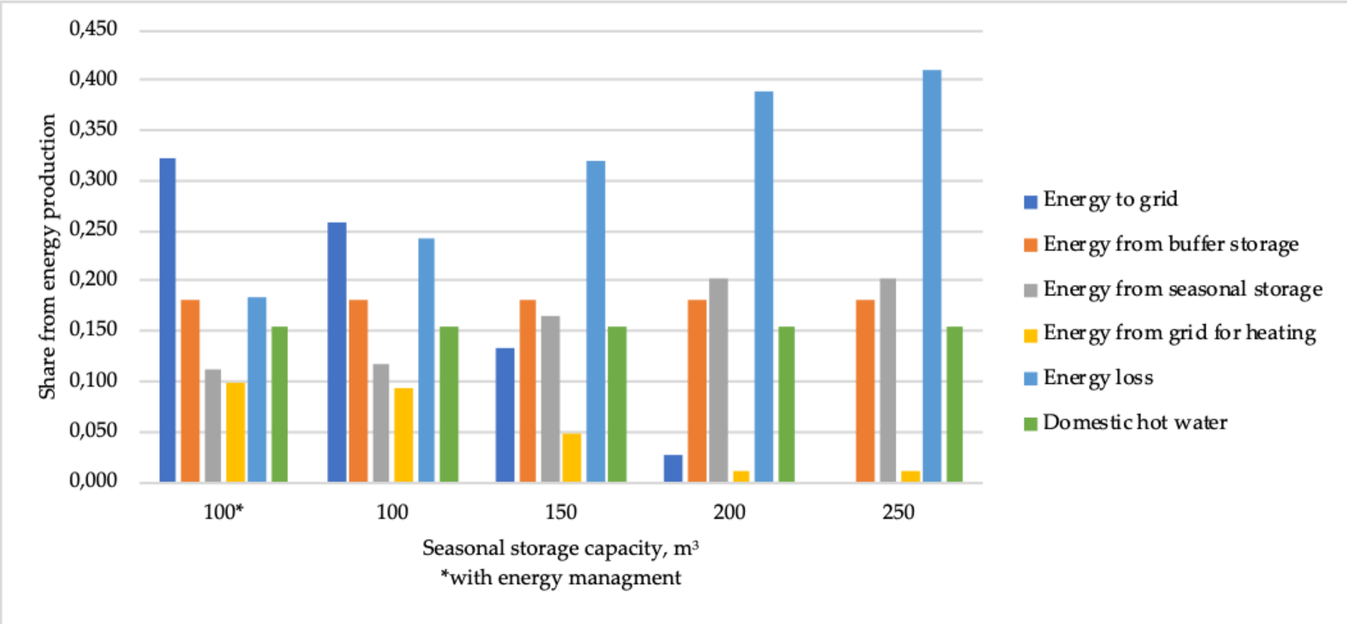

Fig. 6. Share from PV electricity production (*with delayed STES tank heating).

The smaller the volume of the STES tank, the longer it can maintain the maximum temperatures in the summer (Figure 7). This, in turn causes a higher energy loss due to the temperature difference between the ground and the STES tank. The idea here is to start storing energy in the STES tank later so that the maximum temperature is briefly reached before the start of the heating period. This situation was modelled at a 100 m^3 STES tank volume, the results of which showed a significant difference in heat losses. The results are marked with an asterisk (Figure 6) to indicate where a delay has purposely been applied in the energy storage in the STES tank. If the heating of the STES tank is started later, the share of heat loss from the total energy production of the PV park was 18.4%, and if it was started without delay, it was 24.3%. At the expense of lower heat loss, more energy can be used to cover household electricity needs or sold to the grid. Therefore, the production of renewable energy and the storage volume must be matched with each other, or else the optimal time to start storing energy in the STES storage needs to be found.

When analysing the most suitable capacity of the STES tank for the heating system of the building used in this study, a definite answer cannot be given here. If the amount of energy purchased from the network for heating is reduced to a minimum, then according to the results, a volume of 200 m^3 is suitable, in which case the share of renewable energy in heating is 97.3 %. In addition to heating energy, DHW heating also requires additional energy from the network. Numerically, all the results are presented in Table 2. At the volume of the STES tank of 250 m^3, the need for additional energy for heating and heating of DHW is the same. Still, it's heat loss and physical dimensions are more significant; therefore, under the studied conditions, such construction is not justified either economically or in terms of energy use.

When using a 150 m^3 STES tank, the share of solar energy in heating the building is 88%, which numerically equals 720 kW·h. Energy consumed from the network for heating DHW is also added.

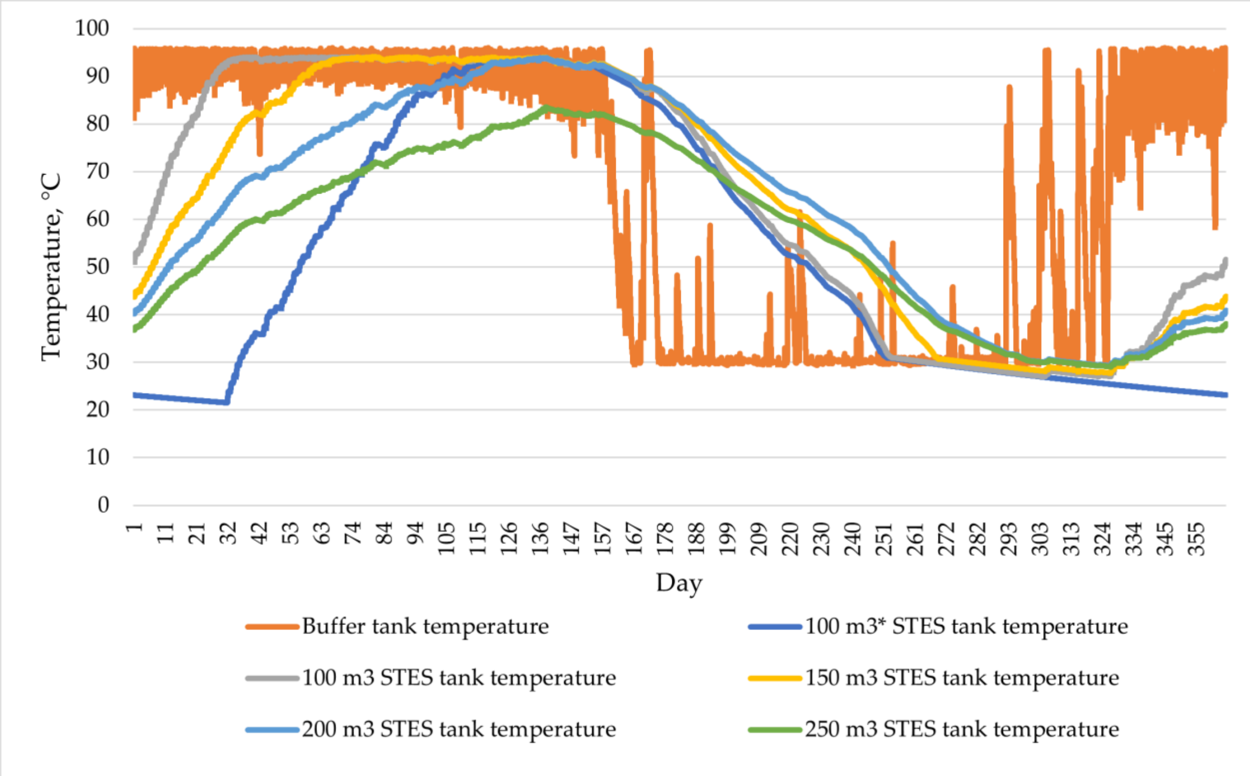

Fig. 7. Temperature curves for buffer tank and different STES tanks (*with delayed STES tank heating).

Figure 7 shows the buffer and STES tank temperature curves at different capacity values. The temperature of the buffer tank was the same in all investigated cases. The time during which this temperature is kept close to the maximum and the cooling time can be read from the STES temperature curves. The cooling time includes using stored energy for heating and heat loss. The larger the volume of the tank, the slower the drop in the temperature curve.

Table 2. Numerical results of the modelling.

STES storage capacity (m^3)	**100***	**100**	**150**	**200**	**250**
Electricity to the grid (kW·h)	4952	3972	2056	401	0
The heat from buffer storage (kW·h)	2755	2755	2755	2755	2755
The heat from seasonal storage (kW·h)	1730	1811	2534	3093	3102
Electricity from the grid for heating (kW·h)	1524	1443	720	161	152
Heat loss (kW·h)	2814	3714	4908	5955	6271
PV electricity production (kW·h)	15312	15312	15312	15312	15312
Heat for DHW (kW·h)	2351	2351	2351	2351	2351
Electricity for DHW from the grid (kW·h)	1765	1765	1765	1765	1765
Space heating share from PV production (%)	74.6	76	88	97.3	97.4

Analysing the STES tank with a volume of 100 m^3 in the heating system with delayed energy storage, the share of solar energy in heating is 74.6 % and 1524 kW·h per year is needed from the network under the conditions studied. Without delay, the share of solar energy is 1.4% higher.

The proportion of energy spent on DHW heating from PV energy is 57.1% under all the studied conditions. Without the STES tank and using only the buffer tank, the share of solar energy for heating the building is 46% of the total energy requirement for heating.

4. Conclusion

The article describes the storage of PV electrical energy as thermal energy in a STES tank to increase the self-consumption of renewable energy production and its use for building heating. Using the STES tank makes it possible to significantly increase the share of renewable energy in heating the building. In addition to the above, the seasonal energy storage makes it possible to exclude the use of heat pumps for heating, reducing the use of more complex technology. The main conclusions of STES tanks are as follows:

- The research results show the suitability and flexibility of using solar PV panels for energy supply to space heating with seasonal energy storage in STES.
- Using a 200 m^3 STES tank, providing 97.3% of the building's required annual heating energy with produced solar energy is possible.
- In the investigated system, at least 57.1% of the DHW energy demand can be covered with the produced PV electricity.
- STES optimal tank volume depends on the building's electricity production and heating energy requirement.
- Without the STES tank, it is possible to cover 46% of the building's heating needs with locally produced renewable energy.

Further study would involve modelling a heat pump system and investigating the suitability of different storage media for seasonal storage. A heat pump system allows for the utilisation of low-temperature stored energy. Additionally, the construction of the described storage device is relatively simple, which is why the modelling results described in the article serve as a basis for building a test tank.

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