

## Article

# Increasing Solar Energy Usage for Dwelling Heating, Using Solar Collectors and Medium Sized Vacuum Insulated Storage Tank

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**Abstract:** This article describes a method for increasing the solar heat energy share in the heating of a dwelling. Solar irradiation is high in summer, in early autumn, and in spring, but during that same time, the heat demand of dwellings is low. This article describes a solution for storing solar heat energy in summertime as well as the calculations of the heat energy balance of such a storage system. The solar heat energy is stored in a thermally insulated water tank and used in the heating period. The heat is also stored in the ground if necessary, using the ground loop of the heat pump if the water tank's temperature rises above a certain threshold. The stored heat energy is used directly for heating if the heat carrier temperature inside the tank is sufficient. If the temperature is too low for direct heating, then the heat pump can be used to extract the stored energy. The calculations are based on the solar irradiation measurements and heating demand data of a sample dwelling. The seasonal storing of solar heat energy can increase the solar heat energy usage and decrease the heat pump working time. The long-term storage tank capacity of 15 m<sup>3</sup> can increase the direct heating from solar by 41%. The direct heating system efficiency is 51%.

**Keywords:** long-term storage tank; solar heat energy; solar collector

## 1. Introduction

The target of the European energy politics is to increase the renewable energy share to 27% by the year 2030, and thereby reduce CO<sub>2</sub> emissions [1]. In addition, by 31 December 2020, all of the new buildings, which need authorization for use, must be nearly zero-energy buildings [2]. Increasing the solar heat energy share for a single-family house heating is difficult, because the solar irradiation is mostly available in warmer periods, when the house heat demand is low. Therefore, is necessary to find solutions for storing the solar energy in summertime and using it in the heating period, and thereby decreasing the additional heat energy demand. Solar heating systems with seasonal heat storage for residential districts and also for the single-family houses have been researched for decades. The biggest problem with them is the energy losses from the seasonal storage. Large solar heat seasonal storage systems have been built and researched in Germany. These storages are the rock bed heat storage, the ground/soil storage (borehole storage), and the hot water tank [3]. These storage methods for high temperature heat storing are not a good solution for single-family houses, because the heat losses through the storage walls are too high. The seasonal solar heat storage methods for single family houses has not been studied much, because the ratio of the storage tank wall area and the volume is too small, and therefore the heat losses are high [4]. The higher water temperature in the seasonal storage tank allows more heat energy to be stored or a reduction in the size of the tank, compared with the low temperature tank. For example, the solar heating system with the solar collector area 147.2 m<sup>2</sup>

and with a seasonal storage tank, with a volume of  $1083 \text{ m}^3$ , is in use in Slatiňany, Czech Republic. The tank is isolated with mineral wool (thickness of 0.7 m) and has an overall U-value  $0.4 \text{ W m}^{-2} \text{ K}^{-1}$ . The U-value is a measure of the flow of heat through an insulating or building material. The heating system's operating principle is as follows: if the tank temperature is over  $36^\circ\text{C}$ , then the heat energy flows directly from the tank to the house, if the tank temperature is between  $12$  and  $35^\circ\text{C}$ , then the heat energy is extracted using the heat pump. If the tank temperature drops under  $12^\circ\text{C}$ , then the building is heated using an electric boiler. The solar fraction for heating in different years is between 63% and 77%. The maximum tank temperature of  $52^\circ\text{C}$  was achieved in October 2011 [5]. A disadvantage of such a heating system is the high heat energy loss through the tank walls, which does not allow the water temperature to rise any higher. Therefore, the amount of heat energy for direct heating is lower and the electricity usage for heating, when the heat energy in the tank is depleted, is also higher, in addition to the storage tank volume being higher. Using the storage tank with this U-value for a single-family house is not possible because of the excessive heat loss.

To use the seasonal storing of the solar heat energy for a single-family house, it is important to use a storage tank, with a low heat loss. One solution is to use a tank where the working principle is similar to that of thermos. The technique of the vacuum insulated tank with expanded perlite has been previously used for the storage of liquid gases. The vacuum insulated storage tank operational principle is similar. Using vacuum insulation, the thermal resistance is up to 10 times higher compared with conventional insulation materials [6]. The company Hummelsberger Stahl- und Metallbau built the vacuum isolated storage tank with a volume of  $16.4 \text{ m}^3$  in the year of 2010. The tank has a double-walled steel cylinder construction. The annular gap between the cylinders is filled with expanded perlite and is evacuated [7]. Such thermal insulation has been also investigated by the University of Stuttgart, where the different heat insulation materials are studied in a vacuum [7]. The results are similar to the parameters of the vacuum insulated tank insulation. The tank was put outside in winter and filled with  $90^\circ\text{C}$  water. The measurements showed an average temperature loss of  $0.23 \text{ K day}^{-1}$  for a period of 11 weeks in winter [8]. It was found that the tank heat loss power is  $1.98 \text{ W K}^{-1}$  [9]. The heating system, with a similar  $11 \text{ m}^3$  vacuum storage tank, and the solar collector with an area of  $55 \text{ m}^2$ , is in use in Germany. The entire heating system can be watched in real time [10]. The measurement data shows that the maximum temperature in the storage tank is achieved in May [10]. The share of direct heating is 55% [11]. Also, the climate in Germany is warmer than in Estonia. In Germany, a tank with vacuum panels insulation was also studied, of which the calculated U-value was  $0.36 \text{ W m}^{-2} \text{ K}^{-1}$  [12]. The average U-value is high because of joints between the vacuum panels, which are thermal bridges.

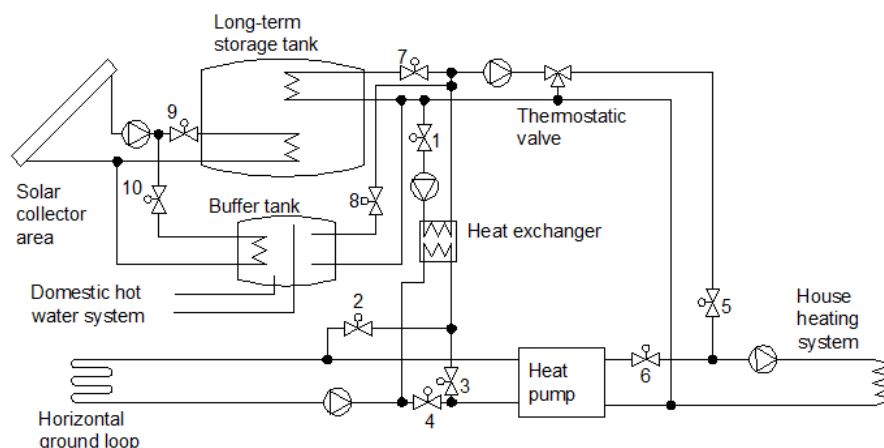
It is possible to store solar energy using latent heat storage, where phase change materials are used [13]. These storage systems are more complex compared to conventional storage and the heat insulation that is also needed. Using chemical storage systems are not economically feasible [14]. Nonconventional storage methods are not investigated in this article.

The seasonal storage tank for the solar heat energy with vacuum insulation has not been previously investigated in Estonia or in the countries with a similar climate. Using solar energy for dwelling heating is not widely used in Estonia. The vacuum insulation storage technology is novel and allows for storing heat energy for a longer period for small buildings. In Estonia, there are no studies at all about the solar heat energy storage in residential heating systems. This article describes a simplified solution based on calculations of how and how much the vacuum insulated long-term solar heat energy storage tank in the solar heating system will increase the solar heat energy share for a single-family house using direct heating, in Estonian and other countries with a similar climate. Using solar energy to direct heating for dwelling can reduce the demand for other heat energy sources.

## 2. Materials and Methods

The calculations are based on the climate data of 2017 in Tartu, measured by the weather station. The weather station Vantage Pro+ is located on a building's roof at  $58^\circ 23' 19'' \text{ N}$ ,  $26^\circ 41' 37'' \text{ E}$ , at the

height from ground 25 m. The measurements are taken by steps of 5 min. The yearly average temperature in this location is 5.8 °C and the solar potential 350 kWh m<sup>-2</sup>. The solar collectors are facing towards the south and the inclination angle is 60°. The heating system simplified circuit is shown in Figure 1. The system allows for the use of different heating modes, which are presented in Table 1. This paper describes only the solution of solar heat energy that is used for direct heating via a buffer or long-term heat storage tank. The tank stratification has not been taken into account. The calculations are based on the flow of energy.



**Figure 1.** Simplified circuit of the heating system.

Figure 1 shows also a heat pump part, which is not considered in detail in this paper. Ignoring the heat pump part does not affect the results of the calculations, because this article describes only the heat energy from the sun to the direct heating. In the article, only the heat energy is mentioned, which is needed to cover all of the house's heat energy demand. This heat energy can be extracted using the heat pump. The amount of the additional heat energy is used to calculate the direct heating share.

Vacuum isolated heat storage tanks [15], solar collectors, and buffer tanks with the volume of 15 m<sup>3</sup> have been selected for the calculations. A prototype of the vacuum insulated tank is showed in Figure 2.



**Figure 2.** Vacuum insulated prototype tank (a) and inner container sketch with pipelines (b) [8].

The solar collectors Ensol ES2H/2.65 S are a flat plate type [16]. The main parameters of the heating system components and the house are described in Table 2. If the buffer tank temperature

is greater than 45 °C, then the heat energy for domestic hot water will be also taken into account in the calculations. The daily hot water consumption is 150 kg and the temperature raise is by 50 K. The demand profile is not used. The calculations are made using steps of 5 min.

The single-family houses that have been used in the calculations are two-story and the shape is rectangular. To simplify the calculations, the external border area is summarized. The whole building is shown as one room and the occupancy pattern and lightning pattern are not used. The ventilation system is natural. The external border area, with a mean U-value  $0.17 \text{ W m}^{-2} \text{ K}^{-1}$ , was taken in for the calculations. The free heat power ( $3 \text{ W m}^{-2}$ ) and dwelling mean U-value were based on the standards in Estonia.

**Table 1.** The working modes of the heating system.

Heating Mode	Open Valves	Closed Valves
Direct heating using buffer tank.	5, 8	1, 2, 3, 4, 6, 7
Direct heating using vacuum insulated tank.	5, 7	1, 2, 3, 4, 6, 8
Using residual heat from buffer tank to increase heat pump inlet temperature.	1, 3, 6, 7	2, 4, 5, 8
Heat pump is working and input energy delivered from ground loop.	4, 6	1, 2, 3, 5, 7, 8
Overproduced heat energy is stored in to the ground.	1, 2, 7	3, 4, 5, 6, 8

**Table 2.** The main parameters of components of the heating system.

Description of System Component	Symbol	Value
Solar collector absorber area	$A_c$	$2.44 \text{ m}^2$
Solar collector zero lost coefficient	$a_0$	0.824
Solar collector linear loss coefficient	$a_1$	$2.905 \text{ W m}^{-2} \text{ K}^{-1}$
Solar collector quadratic loss coefficient	$a_2$	$0.03 \text{ W m}^{-2} \text{ K}^{-1}$
House average heat transmission coefficient	$U$	$0.17 \text{ W m}^{-2} \text{ K}^{-1}$
House surface area	$A_b$	$434 \text{ m}^2$
House inside temperature	$t_{in}$	$21 \text{ }^\circ\text{C}$
Free heating power	$P_f$	$3 \text{ W m}^{-2}$
House floor area	$A_{house}$	$160 \text{ m}^2$
Storage tank volume	$V_{tank}$	$15,000 \text{ kg}$
Storage tank surface area	$A_{tank}$	$52.4 \text{ m}^2$
Storage tank heat transmission coefficient	$U_{tank}$	$0.07 \text{ W m}^{-2} \text{ K}^{-1}$
Storage tank maximum operating temperature	$t_{op}$	$110 \text{ }^\circ\text{C}$
Buffer tank volume	$V_{buf}$	$1000 \text{ kg}$
Buffer tank surface area	$A_{buf}$	$6 \text{ m}^2$
Buffer tank heat transmission coefficient	$U_{buf}$	$0.4 \text{ W m}^{-2} \text{ K}^{-1}$
Daily hot water energy consumption	$Q_{water}$	$10.5 \text{ kW}\cdot\text{h}$

The output power of the solar collector depends on the solar irradiation, collector area, and collector heat losses. The heat loss is related to the collector temperature and the ambient temperature. The higher difference between the solar collector and the ambient temperature causes a bigger heat loss. The solar collector temperature is related to the mean temperatures of the buffer tank and the long-term storage tank. The output power of the solar collector is calculated by the following formula [17]:

$$P_s = A_c \left[ n_0 \cdot G - a_1 (T_m - T_a) - a_2 (T_m - T_a)^2 \right] \quad (1)$$

where  $P_s$  is the collector output power,  $A_c$  is the solar collector absorber area,  $n_0$  is the zero lost efficiency,  $G$  is the solar irradiation,  $a_1$  is the first order heat loss coefficient,  $a_2$  is the second order heat loss coefficient,  $T_m$  is the collector temperature, and  $T_a$  is the ambient air temperature.

Firstly, the produced heat is directed into the buffer tank. If the temperature in the buffer tank raises over  $36 \text{ }^\circ\text{C}$ , then the stored heat energy is used for the house's direct heating. The house's heat delivery system is floor heating, for which the supplied temperature is lower compared with the conventional heater [18]. If the temperature is greater than  $45 \text{ }^\circ\text{C}$ , then the energy for the domestic hot

water will be also taken from the buffer tank. If the temperature raises over 60 °C, then the produced heat energy will be directed in to the long-term storage tank. If the long-term storage tank temperature rises over 100 °C, then the heat energy is moved in to the heat pump ground loop. In autumn, when the solar irradiation is not enough for the buffer tank temperature to raise over 36 °C, the heat energy from the long-term tank is used for the house heating. The following formulas are the basis for calculating the buffer tank and the long-term tank temperature.

If  $t_b < 36$  °C, then the buffer tank temperature changes using the following formula:

$$t_b = t_{bp} + \frac{(Q_{solar} - Q_{bloss})}{m_p \cdot c_p} \quad (2)$$

where  $t_b$  is the buffer tank temperature,  $t_{bp}$  is the buffer tank initial temperature,  $Q_{solar}$  is the solar heat energy,  $Q_{bloss}$  is the buffer tank heat energy loss,  $m_p$  is the water mass, and  $c_p$  is the water specific heat capacity.

If  $t_b > 36$  °C, then the buffer tank temperature changes using the following formula:

$$t_b = t_{bp} + \frac{(Q_{solar} - Q_{bloss} - Q_{house})}{m_p \cdot c_p} \quad (3)$$

where  $Q_{house}$  is the heat energy consumption of the house.

If  $t_b > 45$  °C then the buffer tank temperature changes, using the following formula:

$$t_b = t_{bp} + \frac{(Q_{solar} - Q_{bloss} - Q_{building} - Q_{hw})}{m_p \cdot c_p} \quad (4)$$

where  $Q_{hw}$  is the heat energy for the domestic hot water heating.

If  $t_b > 60$  °C and  $t_t < 36$  °C, then the storage tank temperature changes, using the following formula:

$$t_t = t_{tp} + \frac{(Q_{solar} - Q_{tloss})}{m_t \cdot c_p} \quad (5)$$

where  $t_t$  is the storage tank temperature,  $t_{tp}$  is the storage tank initial temperature;  $Q_{tloss}$  is the storage tank heat energy loss, and  $m_t$  is the storage tank water mass.

If  $t_b < 60$  °C and  $t_t > 36$  °C, then the storage tank temperature changes, using the following formula:

$$t_t = t_{tp} + \frac{(Q_{solar} - Q_{tloss} - Q_{building})}{m_t \cdot c_p} \quad (6)$$

The heat capacity of the water is 0.001164 kW·h kg<sup>-1</sup>.

The efficiency of the direct heating system depends the stored heat energy and system losses, as follows:

$$\eta_{sys} = \frac{\sum Q_{direct}}{\sum Q_{tloss} + \sum Q_{bloss} + \sum Q_{waste}} \quad (7)$$

where  $\eta_{sys}$  is the system efficiency,  $Q_{direct}$  is the energy for direct heating, and  $Q_{waste}$  is the energy to heat the pump ground loop.

The U-values that are used in this article are calculated using insulation thickness and insulation thermal resistance.

### 3. Results and Discussion

The buffer tank and the long-term storage tank temperature changes are shown on Figure 3.

The absorber area, buffer tank, and storage tank volumes are selected experimentally by trying out different parameters (solar collector absorber area, vacuum insulated tank volume, and direct

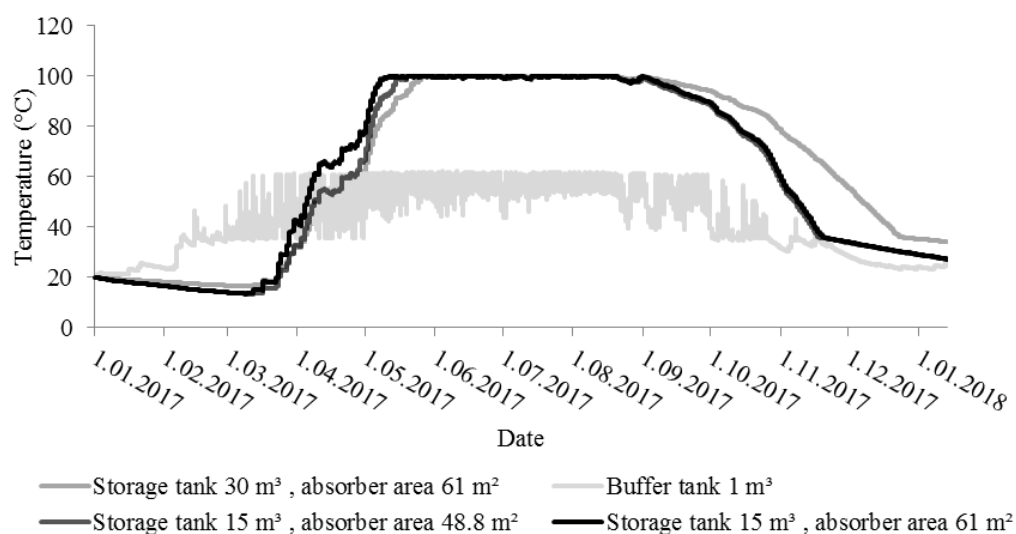
heating share). It was important that the direct heating share of the house's heat energy demand is over 40% and that the system efficiency is over 50%. The temperature of the buffer tank in all three of the analyzed conditions gave similar results, therefore, it is showed in one condition. The temperature change for the long-term tank depends on the area of the solar collectors and the tank volume. The tank, with a larger volume allows for storing more heat energy and to use it for a longer period. The time for heating up the long-term storage tank depends on the solar collector area. The maximum temperature of the long-term tank is achieved in May and the heating up time difference with different collector areas is small. The produced heat energy in the summertime is mostly used by heating the domestic hot water and by heating up the ground around the heat pump ground loop. The end of the direct heating for the house is visible in Figure 3, in the place where the long-term tank temperature drops under 36 °C.

In Figure 3, during the time between January and March, the vacuum insulated tank temperature drops, which is caused by heat loss from the tank. The tank's initial temperature is taken as 20 °C. In Figure 3, the tank temperature in January 2018 shows that the tank temperature in all three of the different volumes is higher than 20 °C, which should be a direct rise in the heating share.

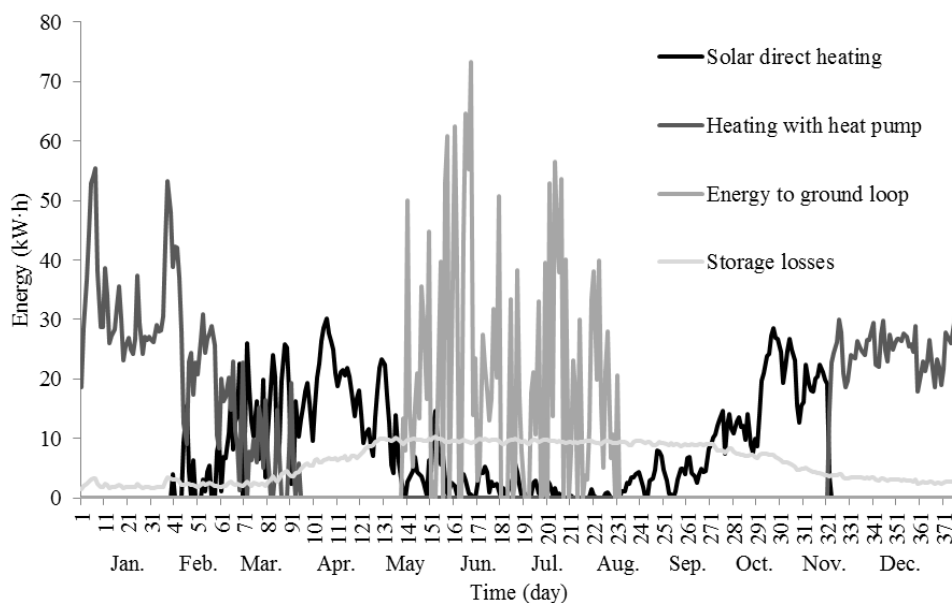
The heat energy balance for the year of 2017, with the solar collector absorber area of 48.4 m<sup>2</sup> and the long-term storage tank with the volume of 15 m<sup>3</sup>, are shown in Figure 4. Between the end of November and the beginning of April, the heat pump is used for the house heating. The rest of the time the heat pump is standing and the heat energy for heating the house and the domestic hot water is collected from the sun. The heat loss of the buffer tank and the long-term storage tank will not exceed 10 kW·h a day. Most of this heat loss is the heat loss of the buffer tank. The data from Figure 4 is summarized and shown in Table 3.

**Table 3.** Heat energy balance.

Description	Heat Energy (kW·h)
House yearly heat energy demand	6023
Produced heat energy from sun	8560
Solar heat energy for direct heating	2474
Additional heat energy demand (ground source heat pump)	3549
Energy to heat pump ground loop	1903
Buffer tank and storage tank losses	2312
Storage losses	4215



**Figure 3.** The temperatures of the buffer and long-term storage tank with different settings.



**Figure 4.** The daily energy of heating system components in the year of 2017.

If also considering the heat energy that is directed into the ground as a heat loss, then the direct heating system efficiency is 51%. The direct heating share of the house's yearly heat energy demand is 41%. The heating system efficiency for different parts is presented in Table 4.

**Table 4.** Heating system efficiency.

Description	Efficiency
Direct heating system efficiency	51%
Solar irradiation to collected heat energy efficiency	20%
Direct heating	41%
Additional energy demand	59%
Buffer tank losses	6%
Vacuum insulated tank losses	21%
Heat energy to ground	22%

Comparing the results to the similar system, which located in Germany, one can say that the solar energy share for the dwelling heating in Germany is greater (41% vs. 55%), because the climate there is also warmer [11]. The volume of the tank is 11m<sup>3</sup>.

The overproduced heat energy, which is directed into the heat pump ground loop in summertime, should raise the temperature of the ground. A higher ground temperature should reduce length of the heat pump ground loop and increase the heat pump inlet temperature in the heating season when stored solar energy is over. Increasing the inlet temperature of the heat pump will increase the coefficient of performance (COP). The COP is how many times the energy can heat the pump to move the heat pump inlet energy. This is only an assumption and will need a further investigation.

#### 4. Conclusions

This paper presents a simplified method for increasing the share of solar direct heating for a single-family house. The calculations show the use of a vacuum insulated tank for seasonal heat energy storage, which makes it possible to increase the solar heat energy share for the direct heating. The results show that the maximum temperature of the long-term storage tank (15 m<sup>3</sup>) is achieved in May. The share of the solar energy for direct heating will increase to a level of 41%. This can be further increased by using a larger long-term storage tank. The additional heat demand is 59%. A heat pump

is used for the house's heating from the beginning of December to the end of March. The solar direct heating and the heating with the heat pump are used together in March. The main conclusions are as follows:

- Heating system efficiency is 51%. This can be improved to better utilize the energy, which is directed in to the ground;
- Heating system storage losses are 27%; and
- Share of direct heating is 41%, if using a 15 m<sup>3</sup> storage tank.

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