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# An Elementary Approach to Evaluating the Thermal Self-Sufficiency of Residential Buildings With Thermal Energy Storage

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*Thermal energy storage (TES) plays a pivotal role in integrating renewable energy. Nevertheless, there are major challenges in the diffusion of TES such as selection of the optimum system size, system integration, and optimization. A key target for using TES is to increase the thermal self-sufficiency of a building or an entire district. Thermal self-sufficiency, unlike total energy self-sufficiency, concerns space heating and domestic hot water exclusively. Thus, it measures the ability of a system to meet its heating demand from local renewable energy sources. Thermal self-sufficiency is an important metric for practitioners and researchers in the design, optimization, and evaluation of energy systems, especially when considering TES. Unfortunately, no comprehensive method exists in the literature for determining thermal self-sufficiency with TES. Energy profiles and simulations are required to determine it. This article aims to close this gap and presents a new method for evaluating thermal self-sufficiency for a building with a TES. Using this approach, the upper and lower limits of the building thermal self-sufficiency are derived for various heat storage capacities and annual heat demands, demonstrating the impact of a TES on the system. A mathematical model applied to a case study of a single-family house illustrates the effect of different TES capacities on the thermal self-sufficiency: small TES significantly improves the thermal self-sufficiency, with a 20-kWh TES reaching 50% thermal self-sufficiency, while higher thermal self-sufficiency values require exponentially larger storage capacities.* [DOI: 10.1115/1.4066068]

*Keywords: heat self-sufficiency, seasonal thermal energy storage, power-to-heat, potential analysis, autonomy potential, building, cities, clean energy, environment, net-zero energy, photovoltaics, renewable, sustainability, thermal comfort*

## 1 Introduction

The building sector accounts for a large share of global energy consumption and consequently $CO_2$ emissions [1–3]. The building stock in Switzerland consumes about 90 TWh of energy which represents about 40% of the country's total energy demand [4]. Today, almost 60% of the heat in Switzerland is generated with fossil energy sources (heating oil and gas), which leads to about one-third of the domestic $CO_2$ emissions [4,5]. Due to the continuous increase in the world population and the building stock, the demand for heat in the building sector is expected to further increase in the coming decades [6].

Accordingly, it is important to achieve a sustainable heat supply for the building sector worldwide. This requires effective ways to meet the heating needs of the building sector while minimizing the dependence on external fossil energy. Thermal energy storage (TES) is a promising solution to increase the energy independence of individual buildings or whole districts, by storing excess renewable or waste energy for use during periods of high demand [7,8]. TES can be integrated into several aspects of the energy system and thus make an integral contribution to sector coupling. The contribution includes reducing heat losses, recovering waste heat, and implementing energy-saving concepts to increase system efficiency [9]. For example, the thermal storage of surplus energy relieves the electricity grid during hours of high production and thus balances supply and demand. Therefore, TES contributes to the creation of a more flexible, highly efficient, and reliable thermal energy system [10]. This leads to a holistic and efficient use of resources in various energy sectors and thus supports sustainable development.

However, the deployment of TESs faces several challenges, including integrating TESs with power grids to achieve system reliability, system-level performance, the ability to handle system dynamics, choice of optimal storage capacity, choice of TES technology, and location [11–15].

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To take full advantage of TES, these barriers must be overcome. To do so, it is helpful to analyze which share of the demand can be covered by the potential of heat generation from renewable sources and storage. In this context, thermal self-sufficiency (TSS) defined in this contribution is a valuable metric. This metric indicates to what extent the heat demand of a system can be met from local (renewable) energy sources and is considered a TES. TSS can serve as relevant performance criteria for the development of targeted strategies that promote the integration of TES into sustainable energy systems and increase efficiency and independence from nonrenewable energy sources.

A comprehensive understanding of the concept of TSS or how to determine TSS does not exist in the scientific literature, which makes it difficult to assess or quantify it. This article presents a new method for estimating the TSS of a building with a TES and by this fill the gap of a missing TSS definition. It presents a method for assessing the TSS for a building with a TES. Using this approach, the upper and lower limits of the building's TSS are derived for various heat storage capacities and annual heat demands, demonstrating the impact of a TES on the system. This approach provides an assessment of the potential TSS for a residential building based solely on the available thermal storage capacity and the heat demand per year. It is envisioned that this approach can be implemented with minimal data and resources while being largely technology agnostic. The results of this approach should make it possible to estimate comparable systems and to estimate the TSS without further simulations. The methodology considers its solar energy input, ambient temperature, heat demand, and nonheat-related residential electricity consumption. The TSS model calculates various levels of TSS based on different TES capacities. These values show the influence of TES on the thermal self-sufficiency. Within the presented model, a system without heat losses and a system with losses are considered upper and lower bounds, respectively. As a demonstration of the functionality of the methodology, this article applies it to a single-family home. In a further step, the methodology will be applied to a collection of archetypes to find generic dependencies.

## 2 Thermal Self-Sufficiency

Self-sufficiency can be defined as "the ability to produce or provide enough of a commodity to supply one's own needs," according to the Oxford English Dictionary [16]. Mazur et al. [17] emphasize that self-sufficiency involves a conscious attitude and a sequence of actions aimed at achieving full or partial independence. This pursuit of independence aims to ensure access to resources in the long term and can be applied in different areas such as economy, society, and energy.

Energy self-sufficiency (ESS) describes the ability of an energy system to fully function and meet its energy demand without external support except from its own local energy generation, storage, and distribution systems [18]. The degree of ESS describes the ratio of self- or locally generated energy to energy consumption and indicates how self-sufficient a system is [19–22]. Equation (1) corresponds to a frequently used equation to describe the degree of energy self-sufficiency [23]:

$$\text{ESS}\ (\%) = \frac{\text{local generated energy} - \text{exported energy}}{\text{local energy consumption}} \cdot 100 \leq 100\% \tag{1}$$

TSS is based on the same concept as energy self-sufficiency but focuses explicitly on the thermal energy of a system. Although the concept TSS is applied in the literature [24–27], a clear definition is missing. In the context of this article, we rely on the definition of energy self-sufficiency and define TSS as follows: *the TSS assesses the ability of a system to be fully functional and to meet its own thermal energy needs through its own energy generation, storage, and distribution, without external sources. The TSS only considers loads relevant to heat generation and expresses the relationship between the locally generated heat and the heat demand of a system.* On this basis, an equation for TSS (Eq. (2)) can be established analogous to Eq. (1), and thus, TSS can be defined :

$$\text{TSS}\ (\%) = \frac{\text{local generated heat} - \text{exported heat}}{\text{local heat consumption}} \cdot 100 \leq 100\% \tag{2}$$

In most situations, the application of Eq. (2) is not possible because the calculation does not consider how the locally generated electricity is used, i.e., whether it is converted into heat or used in other ways. Additional data are required to provide information on the proportionate use of the energy.

The approach presented here yields only a lower bound on the quantity above because it prescribes a clear hierarchy of how the excess PV power is used for the different tasks. A more rigorous treatment would include solving a linear programming optimization problem that goes beyond the scope of this paper. Furthermore, Eq. (2) does not allow the consideration of TES. In contrast to purely electrical systems, numerous factors such as temperature levels and simultaneity effects must be considered in thermal systems.

## 3 Methodology

The starting point of this methodology is the assumption that buildings with a similar structure and function also have similar thermal behavior [28,29]. If the influence of a TES on the TSS for a specific building is known, this knowledge can be transferred to similar buildings with a certain degree of approximation. Following this idea, this method uses known data to determine results that show the relationship between the capacity of the TES and its influence on the TSS. This allows for some transferability and estimation of TSS for buildings with less available data.

The central element of this publication is a mathematical model of the TSS, which processes input data from one or more residential buildings and provides information on the behavior of the TSS in relation to varying TES capacities. The model is explained and discussed using exemplary input data of a reference case from the literature. In addition, the data and the underlying model of the reference case allow a comparison and the possibility to validate the results.

The collection of additional data for a larger number of residential buildings to obtain generally valid results for the behavior of TSS in relation to TES is the subject of parallel projects that interface with this work. From this input data, the TSS model determines values that enable a direct relationship between thermal storage capacity, annual heat demand, and TSS for comparable systems.

**3.1 Thermal Self-Sufficiency Model.** This section describes the assumptions, structure, and operational principles of the TSS model. The model assumes that the underlying heating system contains a photovoltaic (PV) system and an air/water heat pump (HP), as shown in a simplified representation of the energy model in Fig. 1. In the TSS model, it is assumed that an HP has no maximum output, meaning that any excess PV power can always be fully converted into heat, and in addition, the HP is not subject to any control logic. The TES is considered a black box technology to achieve technology independence and generalizable results. To show the upper limit of the TSS, both an ideal TES without heat

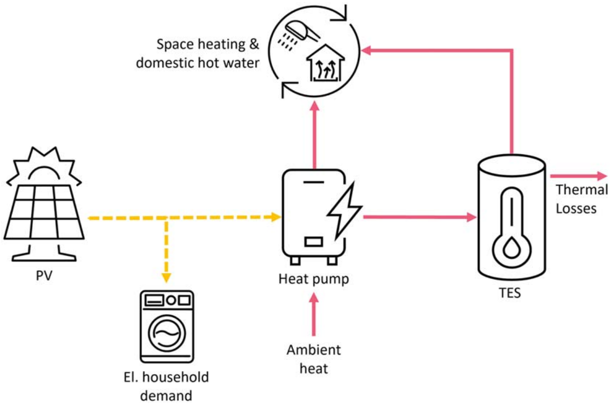

**Fig. 1 Simplified energy model, with electrical (dashed line) and thermal flows (solid line)**

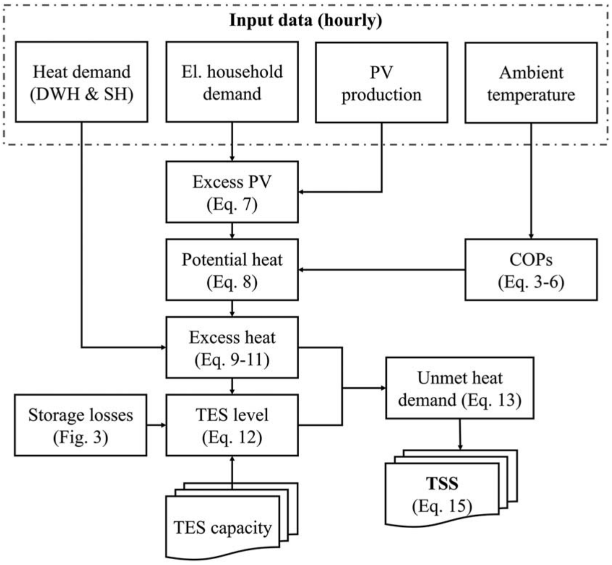

**Fig. 2 Overview of data flow and equations of the TSS model**

losses and a TES with storage losses are considered to cover a variety of possible scenarios.

The TSS model requires five representative annual profiles as input with hourly steps: the local PV production, the heat demand for space heating (SH) and domestic hot water (DHW), the electricity demand of the electrical consumers without heat generation, and the outdoor temperature. The model allows flexibility regarding the scale of the input data, so that several buildings can theoretically be combined, or heating networks can be considered as one large consumer by scaling the analysis performed below.

The TSS model is based on a PYTHON model, and its workflow can be seen schematically in Fig. 2. It shows the model architecture, the variables required for the model calculations, and the relationships relevant to the calculations. In addition, the equations relevant to the TSS model are referenced in Fig. 2. Figure 2 is not an energy flow diagram.

The starting point of the TSS model is the input data shown on the top of the TSS model structure. Based on the ambient temperature ($T_{\mathrm{am}}$), the target temperatures ($T_{\mathrm{ta}}$) for DHW and SH, and the efficiency according to the second law ($\eta_{\mathrm{2nd}}$), the COPs (see Eq. (4)) are determined in an hour resolution for both DHW temperature and SH temperature. $T_{\mathrm{ta}}$ is assumed to be 313.15 K for SH and 333.15 K for DHW, considering therefore two different COPs. The $\eta_{\mathrm{2nd}}$ is defined as the ratio between the real COP and the Carnot COP (see Eq. (3)–(6)) and is assumed to be constant at a value of 0.4 in the TSS model:

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{T_{\mathrm{ta}}}{T_{\mathrm{ta}} - T_{\mathrm{am}}} \tag{3}$$

$$\eta_{\mathrm{2nd}} = \frac{\mathrm{COP}}{\mathrm{COP}_{\mathrm{Carnot}}} \tag{4}$$

$$\mathrm{COP}_{\mathrm{SH}_{(t)}} = \eta_{\mathrm{2nd}} \cdot \mathrm{COP}_{\mathrm{Carnot\ SH}_{(t)}} \approx 0.4 \cdot \frac{313.15K}{313.15K - T_{\mathrm{am}_{(t)}}} \tag{5}$$

$$\mathrm{COP}_{\mathrm{DWH}_{(t)}} = \eta_{\mathrm{2nd}} \cdot \mathrm{COP}_{\mathrm{Carnot\ DWH}_{(t)}} \approx 0.4 \cdot \frac{333.15K}{333.15K - T_{\mathrm{am}_{(t)}}} \tag{6}$$

The TSS model assumes that the local electricity demand of the electrical consumers, excluding the electricity demand of the heating system, is always covered first by the locally generated electricity from the PV system.

The TSS model uses Eqs. (7)–(11) to quantify the hourly excess heat. First, the model calculates the excess PV electricity by subtracting the electrical household demand from the PV production. The electrical household demand refers to the electricity consumption by all household appliances and devices, excluding any electricity used for heat generation. The model uses this excess electricity to calculate the potential heat supply for hot water production by multiplying the excess PV by the COP of hot water, thus converting the DHW heat demand into an SH demand requiring the same amount of electrical energy. Next, the model subtracts the actual DHW demand from to the potential DHW to determine the excess DHW demand; the latter value can be negative if the DHW demand exceeds the available excess PV electricity. This surplus is then used to calculate the heat supply for space heating, setting a maximum of zero in case the excess DHW was negative. If this was the case, the excess heat is determined as the difference of excess DHW and SH demand. Otherwise, the excess heat is computed as the different between excess SH and SH demand. Note that the vector excess heat can have negative values (indicating that the heat demand at that time cannot be covered with excess PV only):

$$\text{Excess PV}_{(t)} = \text{PV production}_{(t)} - \text{El. household demand}_{(t)} \tag{7}$$

$$\text{Potential DHW}_{(t)} = \text{Excess PV}_{(t)} \cdot \mathrm{COP}_{\mathrm{DWH}_{(t)}} \tag{8}$$

$$\text{Excess DHW}_{(t)} = \text{Potential DHW}_{(t)} - \text{DHW demand}_{(t)} \tag{9}$$

$$\text{Excess SH}_{(t)} = \max\left(\text{Excess DHW}_{(t)} \cdot \frac{\mathrm{COP}_{\mathrm{SH}_{(t)}}}{\mathrm{COP}_{\mathrm{DHW}_{(t)}}}, 0\right) \tag{10}$$

$$\text{Excess Heat}_{(t)} = \begin{cases} \text{Excess SH}_{(t)} - \text{SH demand}_{(t)} \text{ if Excess SH}_{(t)} > 0 \\ \text{Excess DHW}_{(t)} - \text{SH demand}_{(t)} \text{ if Excess SH}_{(t)} = 0 \end{cases} \tag{11}$$

The TSS model includes the loading and unloading process of the various TES. Different TES capacities are considered in the model, whereby the range of storage capacities must be set so that a range is covered that enables a TSS of 100%. The charging and discharging of the TES are simulated by an algorithm and carried out for each of the defined TES capacities. The algorithm only needs the excess heat vector defined at Eq. (11) and the TES capacities as input. In a first step, the algorithm identifies the hours in which there is a

**Table 1 Thermal losses based on npro.energy [32]**

| Volume ($m^3$) | Losses | Loss per hour (%) |
|---|---|---|
| 0.75 | 10% per day | 0.43804 |
| 30.00 | 20% per 5 days | 0.18578 |
| 300.00 | 10% per 10 days | 0.04389 |
| 3000.00 | 15% per 30 days | 0.02257 |
| 70,000.00 | 35% per 365 days | 0.00492 |

heat surplus and marks these for charging; in a second step, the algorithm identifies the hours with a negative heat surplus (i.e., the heat demand is greater than the heat that can potentially be generated) and marks these hours for discharging the TES. In the main loop of the model, various TESs are charged and discharged hourly (if in that hour the corresponding value of excess heat is positive, the storage will be charged, otherwise it will be discharged). The TES has an upper and a lower capacity limit that cannot be exceeded or undercut; the upper limit is defined by the respective TES capacity and the lower limit by zero. This means that whenever there is a surplus of heat, this is fed into the TES until the respective storage capacity limit is reached. The energy model of the TES is based on a continuous energy balance, which considers the stored heat ($U_{\mathrm{TES}}$) of the thermal storage from the previous hour, the thermal energy input during charging, the thermal energy output during discharging, and the thermal losses ($Q_{\mathrm{loss}}$). In the TSS model, however, the vector excess heat$_{(t)}$ represents positive values for charging and negative values for discharging. If the absolute value of the negative excess heat exceeds the stored thermal energy from the previous hour (adjusted for losses), all stored heat will be utilized, resulting in a storage level of zero. Conversely, if the sum of positive excess heat and the stored heat from the previous hour (adjusted for losses) surpasses the maximum capacity ($C_{\max}$), the model caps the stored thermal energy at $C_{\max}$. The formula for the internal thermal energy in the TSS model is as follows:

$$U_{\mathrm{TES}_{(t)}} = \min\left[C_{\max},\ \max\left(0,\ \text{Excess Heat}_{(t)} + U_{\mathrm{TES}_{(t-1)}} - Q_{\mathrm{loss}_{(t)}}\right)\right] \tag{12}$$

If the heat demand for a given hour cannot be covered by the excess PV energy (i.e., the excess heat is negative), the TES is discharged to meet the demand. If the absolute value of the negative excess heat is higher than the stored energy from the previous hour (adjusted for losses), it indicates a portion of the demand that the system cannot meet. This shortfall is referred to in the model as the "uncovered heat demand" and represents the portion that would require an external source to meet the heat demand. Conversely, if the stored energy from the previous hour (adjusted for losses) exceeds the absolute value of the negative excess heat, then the storage can meet the heat demand at that time, resulting in zero uncovered heat demand. The same principle applies when the excess heat is positive. The formulas for the hourly (Eq. (13)) and annual (Eq. (14)) uncovered heat demand are therefore as follows:

$$\text{Uncoverd heat demand}_{(t)} = \left|\min\left(0,\ \text{Excess Heat}_{(t)} + U_{\mathrm{TES}_{(t-1)}} - Q_{\mathrm{loss}_{(t)}}\right)\right| \tag{13}$$

$$\text{Annual uncovered heat demand} = \sum \text{Uncoverd heat demand}_{(t)} \tag{14}$$

Finally, as shown in Eq. (15), the TSS results from the annual uncovered heat demand for each TES capacity and the total annual heat demand:

$$TSS\ (\%) = \left(1 - \frac{\textit{annual uncovered heat demand}}{\textit{annual heat demand}}\right) \cdot 100 \leq 100\% \tag{15}$$

To reduce start-up effects, the TSS model simulates 2 years and analyses only the second year. The TSS model can be set to calculate with loss-free storage or with lossy storage. The storage losses are considered in the main loop of the TSS model and subtracted from the energy stored in the TES in each time-step. These losses are modeled as relative hourly self-discharge, i.e., it is the percentage of the energy stored in the TES that is lost per hour. This twofold approach allows the determination of an upper limit on the TSS (loss-less TES) as well as a lower limit for the TSS with losses.

The amount of losses varies depending on the storage capacity of the TES. Various methods for estimating these losses can be found in the literature, see standard EN 12977-1:2018 [30] or SN 546385/2:2015 [31]. Both standards depend on the temperatures in the TES and are therefore not suitable for this technology-agnostic model. An alternative approach by npro.energy [32] estimates the losses for different sizes of TES: around 10% per day for small TES up to 1 m³, around 1% per day for large TES up to 300 m³, and around 0.1% per day for very large TES with a volume of 70,000 m³. In total, this source provides five data points for relative losses in certain periods of time from 1 day to 1 year (see Table 1).

The relative losses show a correlation between storage capacity and loss rate, whereby the hourly loss rate follow a power law with increasing storage capacity (see Fig. 3). The volumes are converted using an assumed energy density of 50 kWh/m³, which could corresponds to a water-based TES with a temperature difference of approximately 40 K.

The complete PYTHON code of the TSS model is published on GitHub [33]. In the following section, we give an overview of the

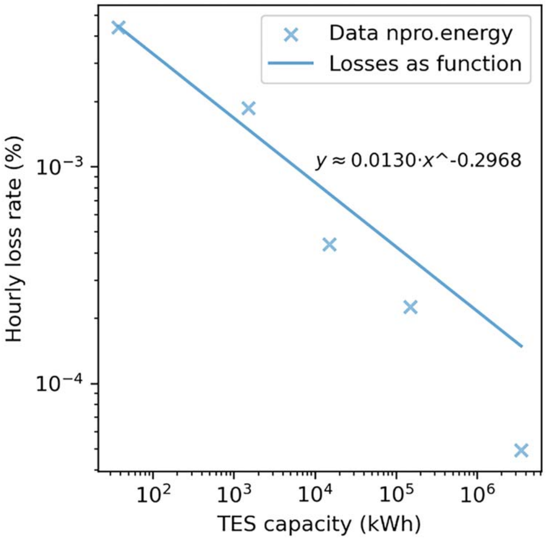

**Fig. 3 Hourly loss rate as a function**

code and summarize the TSS model described in this chapter and Fig. 2. The TSS code can be divided into six basic parts: the first part consists of importing libraries and initializing parameters. Important parameters such as the COP of the heat pump, target temperatures for hot water and space heating, and various TES capacities are defined here. In the second part, the excess heat is calculated: the dynamic COPs for domestic hot water and space heating are determined based on the target and ambient temperatures. The potential heat generated by excess photovoltaic production is then calculated, and it is determined how much excess heat could be stored and how much heat demand cannot be met by excess electricity only. The third part of the code models the loss for the TES. The fourth section contains the algorithm for charging and discharging the TES. This section determines the times when the storage tank should be charged and discharged based on the vector excess heat, the TES level, and the TES capacity. The fifth part is the main simulation loop. In this step, the data structures for the simulation are initialized, including the storage levels, heat surpluses, and heat deficits. Based on these data, the main simulation is performed, calculating the charging, and discharging processes with and without losses. Finally, in the last section, the TSS is calculated.

**3.2 Reference Case.** The SFH considered in the study by Berger et al. [34] is a model that was simulated with Polysun™ 11.3 from Vela Solaris, Winterthur, Switzerland. Both the model and the results of this publication are available from this study. The virtual SFH is located in Bern, Switzerland (longitude 7.44 deg, latitude 46.95 deg), at an altitude of 540 m above sea level. It is a renovated low-energy house that meets the “Minergie-A” standard, with a net energy requirement of less than 60 kWh/m² per year. The energy reference area of the house is 140 m². The annual heating requirement is 6396 kWh and the hot water requirement is 3325 kWh. Heat is supplied by an air/water HP, which distributes the energy via underfloor heating. The photovoltaic system comprises 40 modules with a total output of 11.7 kWp and an annual energy yield of around 12 MWh. For further calculations, the Polysun™ model provides data on the building’s energy consumption (for both electricity and heat) and PV production. The outdoor temperature data for this location are provided by Switzerland’s national weather service, MeteoSwiss [35]. These input data are shown graphically in Fig. 4.

## 4 Results

In this section, the TSS methodology is applied to a reference single-family house (SFH). The aim is to show how the model is applied and to quantify the dependence of TSS on the capacity of the TES. The single-family house data from the study by Berger et al. [34] serve as a reference.

For the SFH, TES with a storage capacity in the range from 1 kWh to 4500 kWh are investigated, with 1 kWh being considered as the extreme case. It should be noted that the TSS model does not take the storage capacity of a building into account separately. Therefore, small TES capacities can be considered for the capacity of a building and larger TES represent long-term or seasonal TES.

The charging and discharging behaviors of the simulated TES correspond to expectations: smaller TES with a capacity of less than 5 kWh (loss-free) show a daily cycle: the TES is charged or discharged depending on the current demand and available excess heat. This results in several complete charging and discharging processes within 1 day or spread over the week. Long-term storage over a period of more than 1 month is not possible. TES with a long-term storage effect shows an annual cycle: during the cold winter days, the TES is discharged and reaches its lowest state of charge. In the following sunny spring, it is recharged to its maximum capacity. This state is largely maintained during the summer, although discharges can occur due to weather conditions. Discharge then takes place again. These patterns are exemplified in Fig. 5 for four different storage capacities, with the start of zero hours set to April 1. In addition, the loss-free cycle shows the lossy cycle of the accumulators, which discharges correspondingly faster. Figure 5 shows the annual cycles of four TES with different storage capacities. The upper line displays the situation for a loss-less storage system to estimate the maximum potential. The lower line considers losses and indicates the least potential. In addition, the respective uncovered heat demand is shown in red.

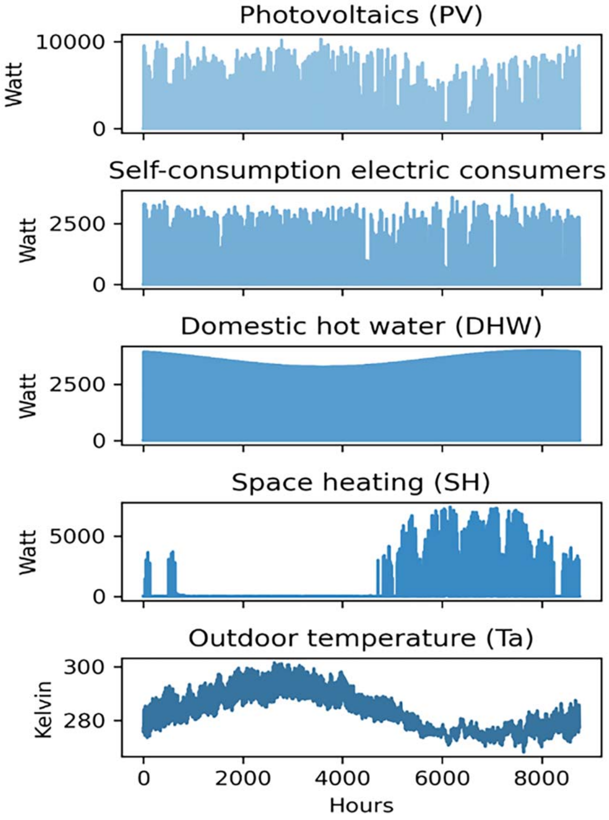

**Fig. 4 Overview of input data**

The model calculations for the TES of different storage capacities lead to an interesting behavior of the TSS, which is characterized by a clear distinction between large and small storage systems. The relationship between the different TES capacities and the resulting TSS is shown in Fig. 6, which shows both loss-free systems as the upper limit and lossy systems as the lower limit. The dimensionless index storage capacity/heat demand was chosen to enable a comparison with similar systems (annual heat demand is equal to 9.7 GWh). The initial steep increase in the TSS graph illustrates the great leverage effect of small TES and the great influence of a thermal TES on the TSS. To achieve a TSS of 50%, a TES of 20 kWh is sufficient. To achieve a TSS of 60%, an additional storage capacity of 30 kWh is required. In the case of a water-based TES, this corresponds to an increase in volume of approx. 0.6 $m^3$. However, it can also be seen that the required capacity of a TES increases drastically from 60% to 80% TSS: the latter requires a ratio of storage capacity to heat demand of 0.15, which in the reference case is around 1500 kWh of capacity. An increase of 20% from 60% to 80% therefore requires a 30-fold increase in storage capacity. To achieve a TSS of 100%, a ratio of approx. 0.4 is required, i.e., a TES with a storage capacity of 4000 kWh. This could be achieved, for example, with a water-based tank TES with a volume of 80 $m^3$ (assumed energy density of 50 $kWh/m^3$). The results of the TSS and the uncovered heat demand are also displayed in tabular format in the Appendix.

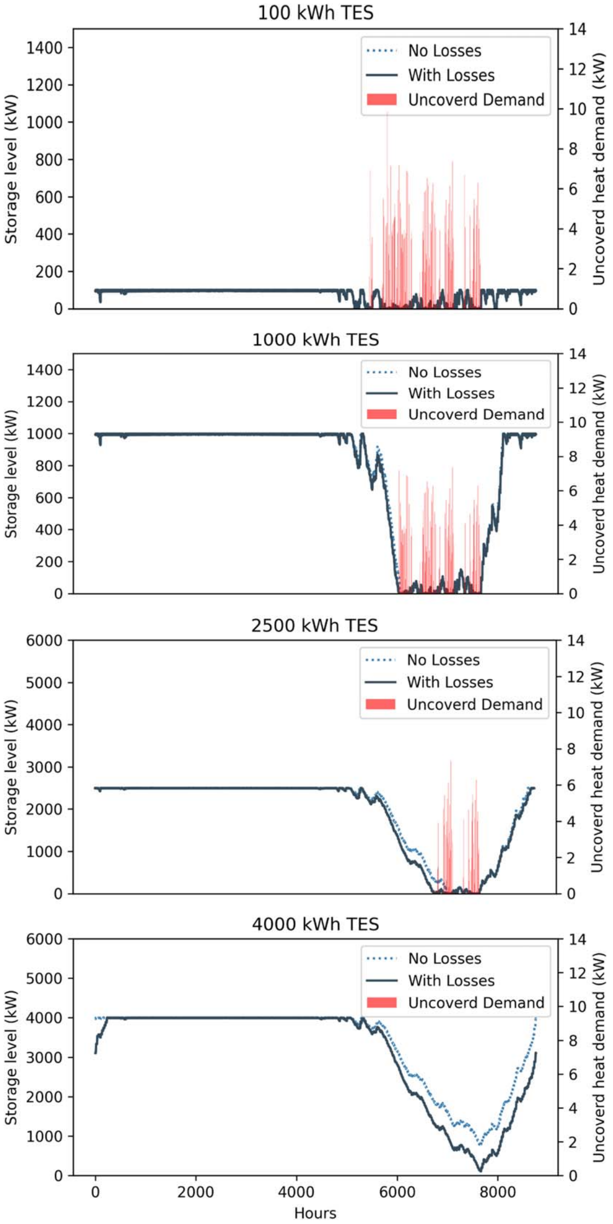

Fig. 5 Examples of the annual cycle of TES

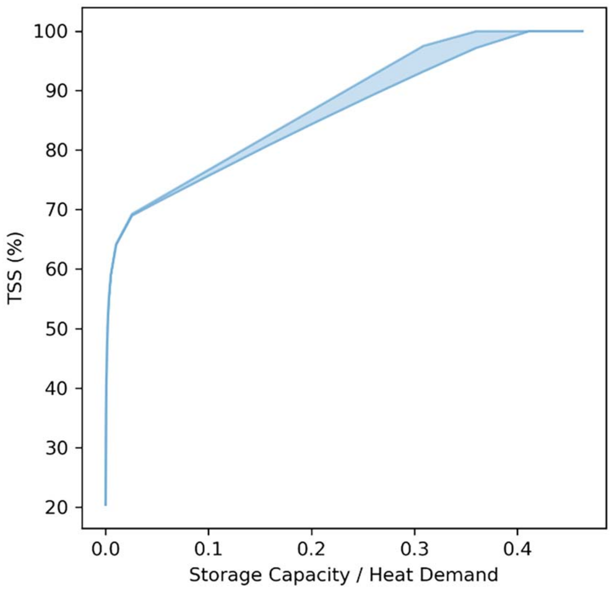

Fig. 6 Upper and lower bound of TSS based on model

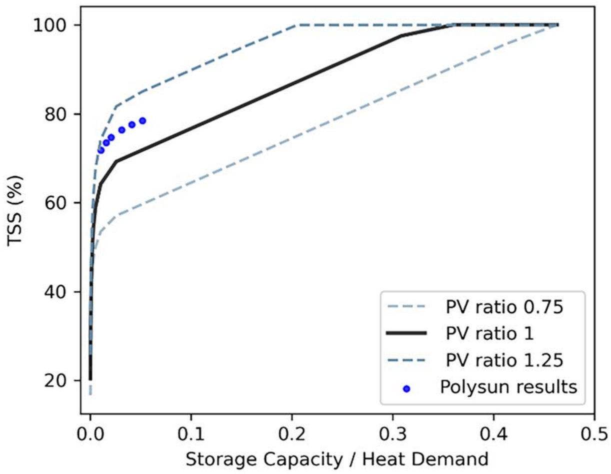

Fig. 7 Sensitivity analysis of PV performance and model validation

## 5 Discussion

The model calculation is based on various assumptions, such as the flow temperature of the HP, the HP efficiency $\eta_{2nd}$, the PV output, and the storage losses. Variations in these values lead to deviations in the calculated TSS from the model. Both the $\eta_{2nd}$ and the flow temperature of the HP influence the calculated COP and thus the potentially usable heat, as does the output of the PV system. By varying the PV power, the influence of the PV power and thus the amount of potentially usable heat can be shown (see Fig. 7). In the sensitivity analysis, two scenarios are presented in addition to the base case (PV ratio 1). The newly calculated scenarios are as follows: the PV ratio 0.75 case investigates a PV system with 25% reduced output, the PV ratio 1.25 case investigates a 25% increase in PV production, and the final PV ratio 2 case investigates a doubling of production. This comparison clearly shows that the PV system and thus the potentially storable heat have a considerable influence on the resulting TSS values. The influence of the PV system output is particularly dominant for small TES systems. For example, with a PV share of 1.25, a TSS of 60% is achieved with a TES of 30 kWh, which corresponds to a reduction of around 20 kWh or 40% compared to the reference case.

As mentioned in Sec. 1, the literature on TSS is not extensive. There are only a few scientific papers that determine the TSS for a residential building, which is a motivation for this article. However, this also means that no comparable models or papers could be found and validation via the literature is not possible—this is related to the choice to consider a system with PV and HP. Model calculations from an unpublished project were therefore used for comparison. These are based on a model implemented in the Polysun simulation tool and describe a comparable single-family house with comparable consumption but with a PV output of approx. 25 kWp. In this way, five TSS values were determined for TES with an output of 100, 150, 200, 300, and 400 kWh, which are shown in Fig. 7. Considering the higher PV power, which is in the order of magnitude of scenario 1.25, a similar trend can be seen. However, further detailed validation is required.

For the model, a system configuration was chosen that is based on a PV system and an HP. The decision to calculate with PV systems is due to the rapid global spread of PV technology and the associated potential, which is well documented in the literature [36,37]. The choice of a system with PV and HP means that the maximum storage temperature is limited to the output temperature of the HP, which is 333.15 K in the model. This has three consequences: (1) technologies that require higher temperatures are excluded from the analysis. These would be, for example, thermochemical storage systems that require temperatures higher than 333.15 K for conversion. (2) The outlet temperature has a direct influence on the efficiency of the HP and is reflected in the calculated COP: an increase in the outlet temperature leads to a reduction in the COP and to a reduction in the potentially available heat and thus to a reduction in the coefficient of performance. (3) The temperature difference, which is approx. 40 K in the model, has an influence on the energy density and thus on the volume of the TES. This means that the volume of the TES can be reduced by increasing the temperature spread. However, the storage volume is a dimension that is not discussed further in this model.

In addition, it is assumed that the HP does not have a maximum output. Consequently, the HP can always cover the required power, so that the available PV surplus can always be converted into heat. However, this also means that the power of the HP is correspondingly oversized. Specifically, the TSS model for the reference case converts up to almost 10 kWh of electrical energy per peak hour into heat on sunny days. In comparison, the model by Berger et al. [34], on which the reference case is based, uses a 2-kW HP, which is about five times smaller. When considering a larger PV system, as we did in the sensitivity analysis, the power of the HP in the TSS model is even larger. It is important to recognize that an oversized HP can result in higher capital and operating costs, inefficiencies, frequent on-off cycles, significant heat losses in the water circuit, and a shorter service life. However, the assumption of unlimited HP helps in assessing the TSS potential, which is the focus of this paper.

Another aspect that can be attributed to the simplified modeling concerns the discharging of the TES. The TES model, which only calculates in energy, allows the TES to discharge completely, as this is done mathematically. Discharging a TES below approx. 323.15–333.15 K for hot water and below 313.15 K for DHW is only possible with an HP. The energy required for discharging an HP is not considered in the model. With this amount of energy in mind, 100% TSS would probably only be achievable with the current system, which has an extremely large TES. The upper limit would be around 85–95%. This is also confirmed by rough calculations with the Polysun model (see Fig. 7).

## 6 Outlook

This study is to be continued in further research projects and the model is to be applied to a larger number of buildings to increase the transferability of the results to other systems. The model was developed in such a way that an extension to a large data set is possible in principle. In addition, further attention will be paid to the function of the TSS curve and the question of how the characteristic shape of the function comes about and what influences it. The question of costs and benefits also arises, i.e., in which cases does a TES make sense and in which cases are other options more suitable.

## 7 Conclusion

This article presents a novel definition of the TSS and an associated method to assess the TSS of buildings and neighborhoods considering thermal energy storage. The TSS model enables the evaluation of upper and lower limits of TSS for different heat storage capacities with limited data and resources, making it widely applicable and partially transferable to similar systems.

The TSS model applied to a case study of a single-family house indicates a significant impact of different TES capacities on TSS under given boundary conditions: small TES, such as a 20 kWh unit, can already achieve a TSS of 50%. However, an additional capacity of around 30 kWh is required to increase the TSS to 60%, which illustrates the exponentially growing requirements for storage capacities to achieve higher self-sufficiency values. Our results indicate that a TES capacity of over 250 kWh is necessary to achieve a TSS of 70%, while a TES capacity of over 2000 kWh is required to achieve almost complete self-sufficiency of 90%.

This study helps to assess the impact of residential TES on TSS and provides valuable insight into optimizing storage capacity. The simplified nature of this method provides practitioners and researchers with a valuable tool to quickly estimate TSS, even in the presence of insufficient data. This is particularly beneficial when it comes to calculating very large amounts of data. Future work could aim to extend the method to larger and more diverse building complexes as well as different climatic conditions to further validate and refine its applicability and ultimately enable generalization.

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## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

## Nomenclature

$t$ = time
K = Kelvin
$C_{\max}$ = maximum capacity TES
$Q_{\mathrm{loss}}$ = thermal energy loss
$T_{\mathrm{a}}$ = ambient temperature
$T_{\mathrm{ta}}$ = target temperature
$U_{\mathrm{TES}}$ = internal thermal energy of thermal energy storage
COP = coefficient of performance
$\mathrm{COP}_{\mathrm{Carnot}}$ = Carnot coefficient of performance
DHW = domestic hot water
El. = electrical
ESS = energy self-sufficiency
HP = heat pump
PV = photovoltaic
SFH = single-family home
SH = space heating
TES = thermal energy storage
TSS = thermal self-sufficiency
$\eta_{\mathrm{2nd}}$ = second law efficiency

## Appendix: Results of Thermal Self-Sufficiency and Uncovered Heat Demand for Various Thermal Energy Storage Capacities

| TES capacity (kWh) | Capacity/heat demand ratio (−) | TSS with losses (%) | TSS no losses (%) | Uncovered heat demand (kWh) |
|---|---|---|---|---|
| 1 | 0.00010 | 20.39 | 20.40 | 7738 |
| 2 | 0.00021 | 23.87 | 23.88 | 7399 |
| 3 | 0.00031 | 27.22 | 27.25 | 7072 |
| 4 | 0.00041 | 30.50 | 30.54 | 6752 |
| 5 | 0.00051 | 33.72 | 33.79 | 6436 |
| 6 | 0.00062 | 36.75 | 36.83 | 6140 |
| 7.5 | 0.00077 | 40.01 | 40.06 | 5827 |
| 10 | 0.00103 | 42.76 | 42.80 | 5560 |
| 15 | 0.00154 | 46.93 | 46.99 | 5153 |
| 20 | 0.00206 | 50.34 | 50.41 | 4821 |
| 30 | 0.00309 | 54.35 | 54.43 | 4430 |
| 50 | 0.00514 | 58.86 | 58.98 | 3988 |
| 100 | 0.01029 | 64.02 | 64.17 | 3483 |
| 250 | 0.02572 | 68.96 | 69.25 | 2990 |
| 500 | 0.05144 | 71.34 | 71.82 | 2740 |
| 1000 | 0.10287 | 75.93 | 76.96 | 2240 |
| 1500 | 0.15431 | 80.46 | 82.10 | 1740 |
| 2000 | 0.20574 | 84.83 | 87.25 | 1240 |
| 2500 | 0.25718 | 89.08 | 92.39 | 740 |
| 3000 | 0.30861 | 93.21 | 97.54 | 240 |
| 3500 | 0.36005 | 97.2 | 100 | 0 |
| 4000 | 0.41148 | 100 | 100 | 0 |
| 4500 | 0.46292 | 100 | 100 | 0 |

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