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The Most Common Mistakes when Designing a Hot Water Storage Tank

The aim of the paper is to highlight the most common mistakes in sizing the domestic hot water (hereinafter only DHW) storage tanks and heat sources for DHW preparation. The article describes two basic ways of design: The method using heat supply and demand curves of the DHW preparation system and the method of priority DHW preparation. Sizing of the DHW storage tank should primarily correspond to the used heat source and expected hot water consumption profile. When using the heat supply and demand curve method, the designer places the greatest importance on the minimum size of the DHW storage tank (i.e., the shape of the supply curve), regardless of the potential changes in the DHW consumption profile (i.e., the demand curve). When using the so-called priority DHW preparation, the basic precondition is often neglected where the required heat output of a common heat source must comply, not only with the DHW preparation system, but also with other connected heat consumption points.

Keywords: calculation methods, hot water, hot water storage tank, heat source

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Method of delivery and heat distribution of the DHW preparation system

The DHW heating curve Q_2 depends on the hot water consumption V_{DHW} over time τ. The heat supply curve for DHW Q_1 is dependent on the heat supply from the heat source in the same time interval. Important prerequisites for compiling the curves above are the following two necessary points:

1. The heat supply curve Q_1 is always above the heat demand curve Q_2,
2. The heat supplied by the hot water heater is equal to the heat removed from the heater $Q_{1p} = Q_{2p}$.

The heat supply curve must always be above the heat demand curve, otherwise there will be a lack of energy to heat the water to the desired temperature, so that the water temperature at the sampling point does not have the required temperature (55°C). The delivery and heat consumption curves are not decreasing with increasing time, as they are in principle cumulative curves that add up to individual times of the energy supplied or withdrawn from the DHW preparation system. The inclination of the tangent to these curves to the timeline represents the value of instantaneous heat output. At zero power, the waveform is horizontal with the x-axis, with the maximum curve slope being the assumed heat output of the maximum P_{2max} (see **Figure 1**).

The volume of the hot water tank is determined from the maximum difference between the heat supply and demand curves as:

$$V_{DHW} = \frac{\Delta Q_{\max}}{\rho \cdot c \cdot (t_2 - t_1)} \cdot 3600 \cdot 1000 \quad [l] \qquad (1)$$

In the case of designing a DHW system with storage (DHW tank), the heat supply curve Q_1 can be constructed in two basic variants. The first case occurs when we assume that the heat supply to the DHW cylinder is constant over a period of time (**Figure 2**). This means that the heat source heats the DHW throughout the heating time (typically 1 day). The second case occurs when we think that we will use the heat in the tank from the previous warm water heating period, and the heat supply will be shorter than the DHW period (**Figure 2**).

For heating with a reservoir, the required heat output of the heat source is determined as:

$$P_{1n} = \left(\frac{\Delta Q_s}{\tau}\right)_{\max} \quad [kW] \qquad (2)$$

where the ratio $(\Delta Q_s/\tau)_{max}$ represents the maximum inclination of the tangent to the time axis.

In the case of permanent heat supply from the hot water heater during the whole period (**Figure 2**), $\Delta Q_s = Q_1$. In the case of intermittent operation in several different time phases of one warming period, the maximum value is considered for the calculation according to (2).

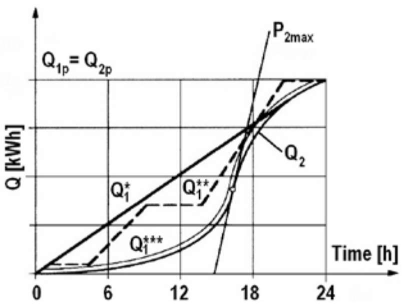

Figure 1. Example of heat supply and demand curves for DHW heating with different time intervals of heat sources: Q_1* – heat sources with continuous operation and storage tank; Q_1** – heat sources with intermittent operation and storage tank; Q_1*** – heat sources with sufficient output that are continuously controlled according to the domestic hot water consumption without a storage tank (flow-through heating).

It follows, from the above procedure, that for a shorter supply of heat from the source to the DHW storage tank, it is necessary to design a larger tank volume, but at the same time require a higher heat output of the heat source than the permanent supply of heat to the tank during the entire hot water collection period (**Figure 3**). Thus, if we have a sufficiently large heat source with continuous heat output regulation, it would be possible to design the DHW heating system without a reservoir, i.e., in a flow-through manner.

The most common mistakes in designing the size of the DHW storage with the heat supply and delivery curve method are the options for constructing the heat supply curve Q_1. The first mistake is, if the designer is trying lean towards the design security side, this then results in a significant increase in the size of the DHW storage tank. The second mistake occurs when the possibility of changing the heat demand curve in the non-standard behaviour of the user is not taken into account, resulting in an insufficient amount of prepared DHW.

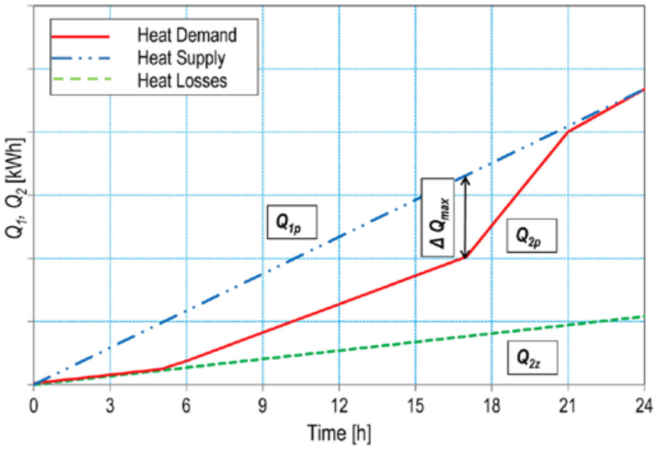

Figure 2. Heat demand and supply curves with uninterrupted heat supply to the DHW storage tank.

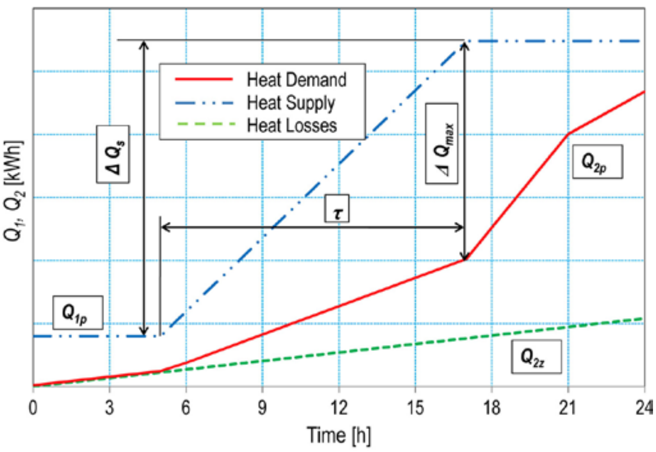

Figure 3. Heat demand and supply curves with heat supply to the DHW storage tank distributed over time.

A typical example of the underestimation of the heat supply curve Q_1 is shown in **Figure 4**. The purpose of such a design is to minimise the size of the DHW storage tank as much as possible by copying the heat demand curve. However, if the DHW production is increased during the DHW preparation period (one day, in this example), this DHW set-up system will not be able to deliver enough DHW. A more appropriate design of the same example is shown in **Figure 5**. The principle of the correct design is not to create the smallest DHW tank (i.e., the minimum difference between the heat supply and demand curve), but to create sufficient storage space for possible non-standard DHW use. Measurements in apartment buildings indicate that at least a 15% increase in the heat demand over a sampling curve is required for the heat supply curve. If a significant morning peak is expected, and if the heat source is also used for other technologies (heating, air conditioning, etc.), it is possible to cover the increase in the DHW consumption in the morning hours by increasing the volume of the tank proportionally enough to allow for a longer period of time that does not require heat to be supplied to the DHW system.

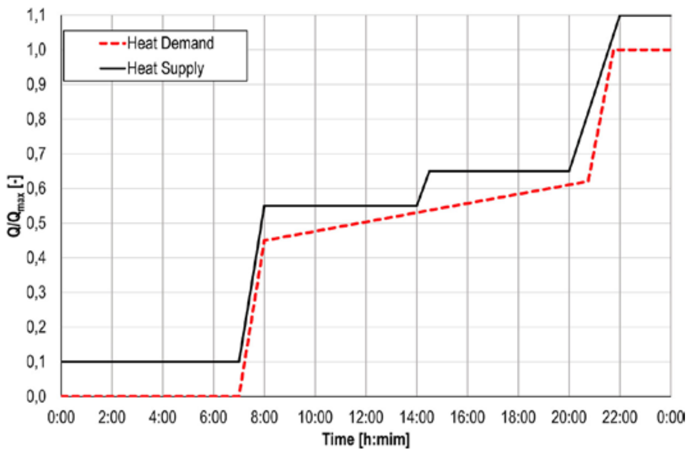

Figure 4. Heat demand and supply curves for an inadequately chosen charging regime of the DHW storage tank.

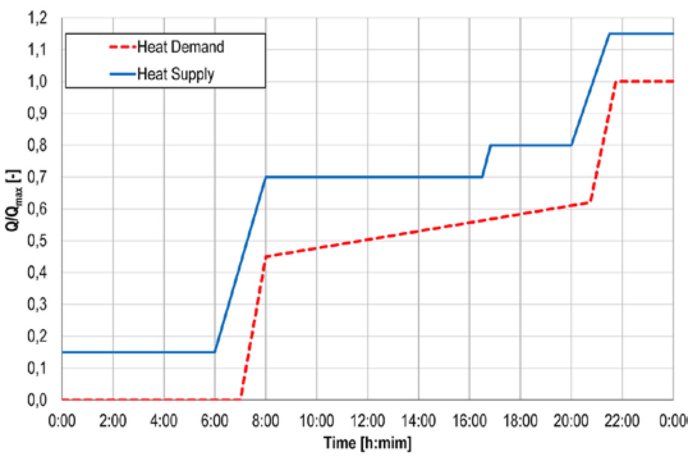

Figure 5. Heat demand and supply curves with the optimised charging of the DHW storage tank

For the examples in **Figures 4** and **5**, it is interesting to compare the size of the calculated DHW storage tank and heat demand of the heat source. The results in **Table 1**, respectively **Table 2** show that a heat source, for both examples, will be required with a power of 30 kW, based on the percent ratio of the heat to the y-axis in the graphs in **Figures 4** and **5**, where 1% = 1 kWh (2). On the other hand, the storage tank is about 250 litres and about 480 litres with respect to the size of the DHW storage tank in the example of **Figure 4** and **Figure 5**, respectively (1).

From the solution shown in **Figure 5** it can be seen that stagnation of the heat demand for the DHW between 8.00 and 16.20 can be expected, which is the possibility of using the heat source for other purposes (technology) than just DHW preparation. However, for the solution of **Figure 5**, it is still necessary to include in the overall energy and cost balance of the proposed system, both

Table 1. Sizing of the DHW storage tank and heat source according to the example in **Figure 4**.

Charging time	Required volume of the DHW storage V_{DHW} [l]	The rated heating power of the DHW P_{1n} [kW]
6:00 to 7:00	It is not critical for the maximum difference	**30.0**
7:00 to 9:00	It is not critical for the maximum difference	7.5
14:00 to 14:30	**248.4**	20.0
20:00 to 22:00	It is not critical for the maximum difference	22.5

Table 2. Sizing of the DHW storage tank and heat source according to the example in **Figure 5**.

Charging time	Required volume of the DHW storage V_{DHW} [l]	The rated heating power of the DHW P_{1n} [kW]
6:00 to 8:00	**477.7**	27.5
16:30 to 16:50	It is not critical for the maximum difference	**30.0**
20:00 to 21:30	It is not critical for the maximum difference	23.3

in the increase in the static heat loss of the DHW tank and the financial costs associated with the acquisition of a larger DHW tank.

Method of previous DHW preparation

The advantage of preferential hot water heating is the possibility of using the maximum heat output of the heat source, which is primarily designed for e.g., the heating system. If the DHW is taken from the storage tank, the water temperature in the t_{DHW} tank will drop. Upon reaching the water switching temperature DHW_{Vmin}, the heat source control preferably provides heat supply to heat the DHW. In the case of the hydraulic connection shown in **Figure 6**, this means that the heating system circulation pump is switched off and the three-way switching valve in the direction of charging the DHW storage tank switches. At the same time, the heat source increases the boiler water temperature (usually a fully rated output to a maximum output temperature, e.g., up to 80°C), and the control switches the DHW tank charging pump. When the water temperature in the tank reaches the set (required) value, the control switches the entire system back into the heating mode. It is, therefore, obvious that the greater the switching difference ($\Delta t_{DHW} = t_{DHW} - t_{DHWspin}$), the longer the time it is to charge the tank. Switching differences are usually selected at 5 K or 10 K depending on the type of DHW storage tank. However, the time required to heat up the DHW tank should not be too long to interfere with the thermal comfort in the heated area during the heat supply interruption to the heating system. e.g., for light buildings with minimal heat accumulation, the time required to heat the water τ_a in the DHW tank should not exceed 10 minutes. For moderate and heavy buildings with masonry storage capacity, the reheat time τ_a should not be longer than 20 minutes.

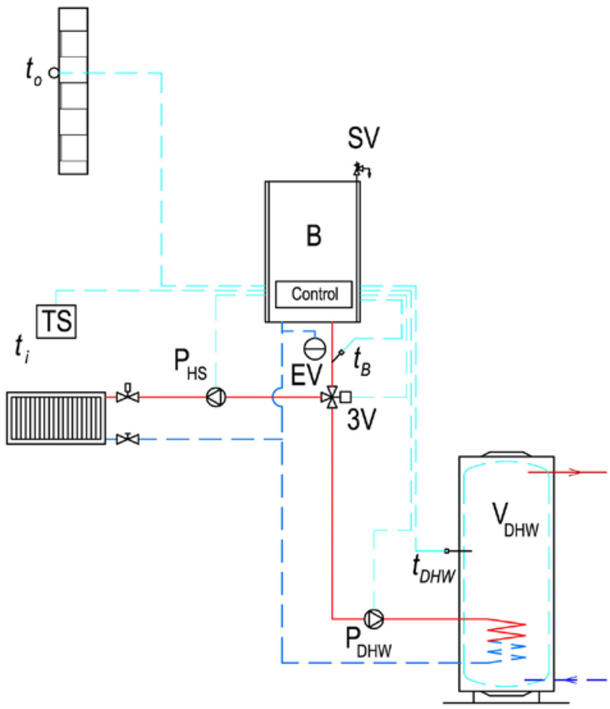

Figure 6. Example of a heat source connection in a system with priority domestic hot water preparation: P_{HS} – circulation pump of the heating system; P_{DHW} – DHW storage tank pump; EV – expansion vessel; B – boiler; TS – remote control with internal temperature sensor; SV – safety valve; 3V – three-way switching valve; V_{DHW} – domestic hot water storage tank; t_o – outdoor temperature; t_i – indoor temperature; t_B – boiler water temperature; t_{DHW} – water temperature in the domestic hot water storage tank.

In order for the above principle to work, it is necessary to meet the basic assumption that the heat output of the boiler Q_k is greater than or equal to the required power for the preparation of the DHW Q_{DHW}. And at this point, the designer sometimes underestimates it. If we realise the different requirements for the function of e.g., a low-potential heat source in a passive house, it is clear that the heating requirements will differ considerably from the requirements for the preparation of the DHW, not only with regard to the required thermal output, but also with regard to the time of use of the source heat. These different requirements make it necessary to adapt the design of the DHW storage tank.

For residential buildings, indirectly heated containers with an integrated exchanger are most commonly used. They work on the principle of natural buoyancy, i.e., the contents of the storage tank are heated from the bottom up. With these systems, it is quite problematic to ensure that the entire volume of the DHW tank is fully heated to the desired temperature. In order to calculate the actual usable content of the container, it is expedient to include the so-called correction factor y (**Table 3**) in the calculation, which is used in German standards (e.g., DIN 4708 [5]).

Table 3. Correction factor of heat consumption from the DHW storage tank [5]

Hot water tank	y [-]	
	τ_a < 20 minutes	τ_a < 10 minutes
Vertical storage	0.94	0.89
Horizontal storage (up to 400 l)	0.96	0.91
Horizontal storage (over 400 l)	0.90	0.85

The basic equation for calculating the required warming time τ_a, or the size of the DHW tank volume, is the heat supply balance of a given volume of liquid per unit time at a known temperature difference in the form:

$$Q_k = \frac{V_{DHW} \cdot y \cdot \rho \cdot c \cdot \Delta t_{DHW}}{\tau_a} \Rightarrow$$

$$V_{TV} = \frac{\tau_a \cdot Q_k}{y \cdot \rho \cdot c \cdot \Delta t_{DHW}} \Rightarrow$$

$$\tau_a = \frac{V_{HW} \cdot y \cdot \rho \cdot c \cdot \Delta t_{DHW}}{Q_k} \quad [W] \qquad (3)$$

The basic example is a family house inhabited by 4 persons, with 5+1 disposition (kitchen = sink, two bathrooms = 3x sinks, 2x showers, 1x bath). You can ignore the amount of DHW sampling for all the sinks. From the point of view of the water supply design values, the maximum hot water flow rate is 0.4 l/s = 24 l/min for the bath and 0.2 l/s = 12 l/min for the shower. From the point of mixing hot and cold water in the outflow battery, when showering and bathing is the most common, with a mixing water temperature of between 38-40°C, the design flow of hot water in these batteries is about 6 l/min. It means that, in a sample family house with simultaneous bathing (running bath) and showering, it is possible to consider the maximum flow of hot water of 12 l/min = 720 l/h. Higher water flow rates are not designed for the water pipe.

The "maximum" water flow rate with the simultaneous use of the shower and bathtub is important in relation to the heat transfer capability in the heat exchanger of the selected DHW storage tank. e.g., a 65-litre specific H65W cylinder has a hot water flow of 438 l/h at temperature t_2 = 45°C at a heat output of 18 kW on the primary side of the heat exchanger (i.e., on the heat source side). In other words, its steady production of hot water at 45°C, at the cold water at the inlet to the tank of 10°C, is 438 l/h. In addition, for example, with another 120-litre hot water tank S 120/5, the manufacturer reports a steady flow of hot water of 834 l/h at 34kW (at t_K = 80°C, t_2 = 45°C, t_1 = 10°C). Thus, if an extreme situation arises when the volume of the DHW storage tank is depleted from previous DHW demands (i.e., $t_{DHW} = t_{DHWspin}$) and, at the same time, the supply of heat for the collection of DHW in the form of bathing and showering is required, it would be necessary to ensure that requesting a heat source with a heat output of about 28 kW (based on the flow rate of a bath and shower in the total of 720 l/h, considering the heat exchanger surface of the exchanger in the S 120/5). This is a short, top-of-the-range sampling of 10 to 15 minutes, but it is clear that in a classical family house, such a heat source is not found today. Therefore, it is more appropriate to take into account the requirements of the sanitary installation and the size of the designed reservoir to adapt these facts to the heat source. In addition, it is clear that with the increasing number of inhabitants (supply points) the calculation flow needs to be corrected and it is appropriate to expect a higher proportion of discontinuity in the hot water consumption.

Also, in this method of preparing the DHW, setting the switching differential of the DHW tank charger remains unavoidable in relation to the position of the sensor in the tank (**Figure 6**). In the case of vertical storage, the temperature sensor that controls the switching process of the DHW storage tank is usually positioned from the middle of the tank up to 2/3 of the tank height. If the sensor is placed too high (i.e., too close to the DHW outlet to the water pipe system), a later reaction and a significant delay in charging the DHW tank may occur, when almost the entire volume of the tank will be depleted, and before the desired DHW temperature is reached again, the DHW temperature drops during the DHW demand. Conversely, in cases where the sensor is located too low (i.e., too close to the heat exchanger surface of the DHW), the heat source can be switched frequently even with the smallest DHW consumption, regardless of the actual desired amount of DHW taken.

Conclusion

Therefore, it can be seen from the examples that although the design methods of the DHW design can appear simple in principle, it is important to understand the link to other professions as well. The connection is mainly related to the profession of heating and sanitary installations in the water supply section. The marginal conditions of the hot water system design can be summarised as follows:

- total DHW demand - per unit of measurement (person, bed, shower, etc.),
- knowledge of the heat collection process - time distribution of the DHW in the object,
- temperature level of heat source for the DHW preparation,
- heat source operation requirements - time intervals of operation of other technologies,
- heat transfer capacity of the DHW tank,
- water flow on drain valves. ■

List of nomenclature

c	specific heat capacity of water [J/(kg·K)]
P_{1n}	rated heating power of the DHW [kW]
P_{2max}	maximum heat output for the DHW [kW]
Q_1	heat supplied by the heater to the DHW [kWh]
Q_{1p}	heat delivered by the heater to the DHW during the period [kWh]
Q_2	heat removed by the heater in the DHW [kWh]
Q_{2p}	heat removed by the heater in the DHW during the period [kWh]
Q_{2z}	heat lost during heating and DHW distribution during the period [kWh]
Q_k	boiler heat output (for a common heat source for the DHW preparation) [W]
Q_{DHW}	heat output required to prepare the DHW [W]
t_1	cold water temperature [°C]
t_2	hot water temperature [°C]
t_k	boiler water temperature [°C]
t_{DHW}	water temperature in DHW tank [°C]
$t_{DHWspin}$	water switching temperature in the DHW tank [°C]
V_{DHW}	DHW storage volume [m^3]
y	correction factor of heat removal from the DHW tank [-]
ΔQ_{max}	maximum possible heat difference between Q_1 and Q_2 [kWh]
ΔQ_s	heat supplied by the heater to the DHW at time τ [kWh]
Δt_{DHW}	switching differential for DHW heating (usually 5 to 10 K) [K]
ρ	density of water at medium storage temperature [kg/m^3]
τ	heat delivery time by the DHW heater [h]
τ_a	DHW retention time at the temperature difference Δt_{DHW} [s]

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Reviewer's note

The labelling of some of the quantities in the article (e.g., *P* power, *t* temperature) respects the closer and more, used Czech habits in Latin characters, as opposed to ČSN 06 0320 (2006), which uses the Greek alphabet (Φ power, Θ temperature).

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