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Article

Cost considerations on **storage tank versus heat exchanger** for hot water preparation

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1. Introduction

The aim of this article is to give an economical evaluation of the two typical principles of preparing hot water (htw), focusing on the system as a whole.

Due to high energy prices and competitiveness performance indicators like distributed heat ab district heating (DH) plant versus charged heat to consumer, the trend within DH net sizing in Denmark is going towards smaller branch media pipe dimensions for single house areas.

The influence on the DH net pipe sizes is the hydraulic pipe load related to htw preparation and heating. An important factor for designing the distribution network is the influence of the simultaneity factor for htw and space heating.

This paper describes the hydraulic and thermal load on the DH net related to the principle of htw preparation and seasonal dependent heating load. The DH net system considered is all season low temperature operating. The htw preparation is made by means of a storage tank (ST) or a heat exchanger (HE) system.

The htw load profile is based on Danish recommendations for sizing of htw systems. The investigation is based on calculations and laboratory measurements, e.g. tapping load profiles. Some general considerations on the specific benefits for the htw principle are also made and related to the economic evaluation.

2. The thermo hydraulic rating of the district heating unit

In Denmark the htw load profiles for one family houses are specified in DS439. The profile is specified for two different situations, a one family house with shower and no bath tub and a one family house with shower and bath tub. The load profiles are shown in fig.1. The profiles are based on a tapping temperature of $T22 = 55°C$ and a cold water temperature $T21 = 10°C$. The specified power ratings are listed in table 1. The minimum tap temperature is 45°C specified for the kitchen tap. The HE unit is dimensioned for 32,3 kW regardless of, whether a bath tub is installed or not.

2.1 Storage tank unit

A typical storage tank (ST) unit used in e.g. Denmark is shown in fig. 2. To determine the hydraulic load and return temperature unit on the primary side for the ST is not as straightforward to estimate as for the HE unit. Data sheets normally state flow and powers for constant flow conditions, which only indirectly indicate the operational performance. The applied control functions, e.g. the use of a flow limiter and thermostatic valve, have large influence on the result. A number of laboratory measurements are made on a ST unit, one example is shown in fig. 2. Since these results are dependent on the applied control principle a number of measurements are also made under constant primary flow to eliminate this effect. Initial condition for this test is a storage tank filled with approx. 55°C htw. As it can been seen in fig.3, the primary flow actually peaks with the high htw flow values, and is very directly related to the htw load profile. After the second bath tub filling the htw temperature for the kitchen tap is just reaching 45°C (at time = 45 min). The primary differential pressure and the valve kvs value influence the peaks and return temperatures. For the measurements a kvs value of 1.2 is used and a differential pressure of approx. 30 kPa, which typially represents the lower end of Danish supply conditions. Due to the fact that the specifications are based on power, the htw tapping flow is increased when the htw temperature drops, see fig.4 at time 35 min. Actually the tapping temperature at time = 45 min is below 45°C and therefore too low according to specifications.

Table 2 includes an overview of the primary flow and return temperatures. To indicate a representative return temperature, the 1h maximum average return temperature and flow is used.
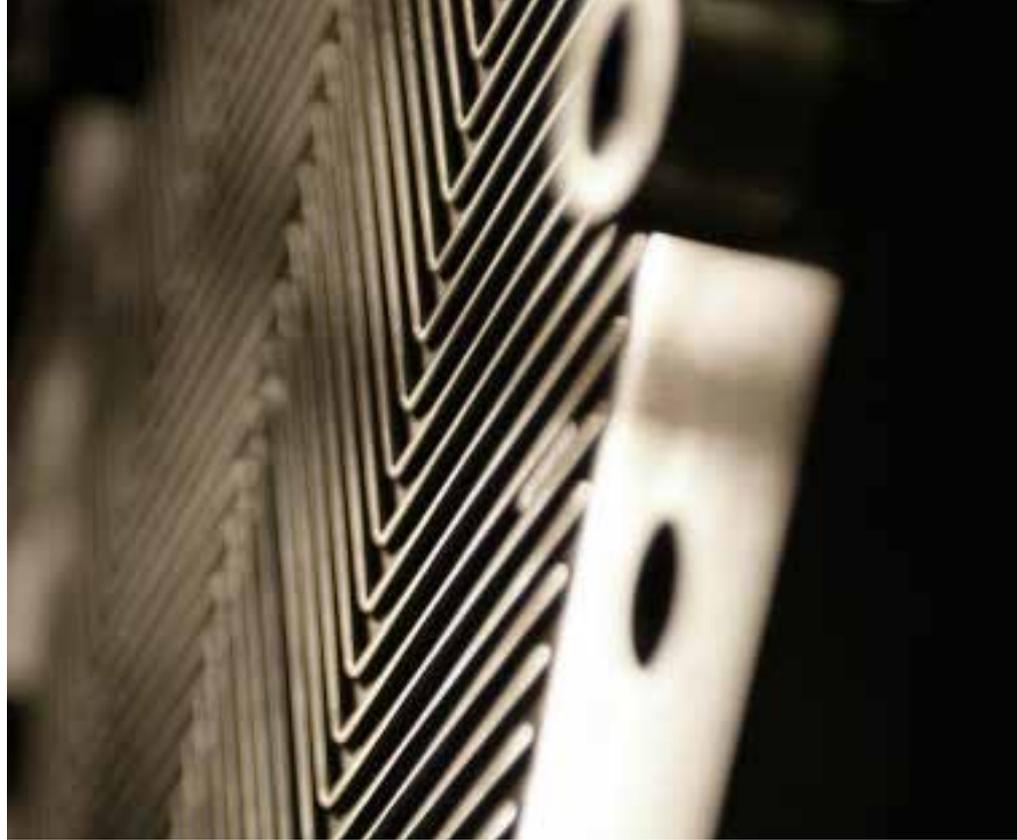
2.2 Heat exchanger unit

The heat exchanger (HE) unit performance is straightforward to describe. Fig. 5 includes the tapping program with a typical HE for htw for a one family house w/o. bath tub.

Compared to fig. 3 the maximum primary flow has approx. the same value, and this is also the typical experience from DH nets using HE compared to DH nets using ST.

2.3 Thermal hydraulic load comparison

Table 2 includes the htw thermal and hydraulic loads related to the unit types. The maximum one hour means that values are used for calculating the respective thermal and hydraulic load for the ST. To use the peak flow values from e.g. fig. 3 would be too pessimistic, since the control principle has highly influence on the peak values. On the other hand, to base the primary flow on the constant flow result, which clearly indicates the storage tank performance with no influence from the applied control equipment, would be too optimistic, since this does not represent a common control solution.
An assumption to use the maximum 1h average values has been applied and the calculated 1h flow values are slightly higher than the constant flow results.
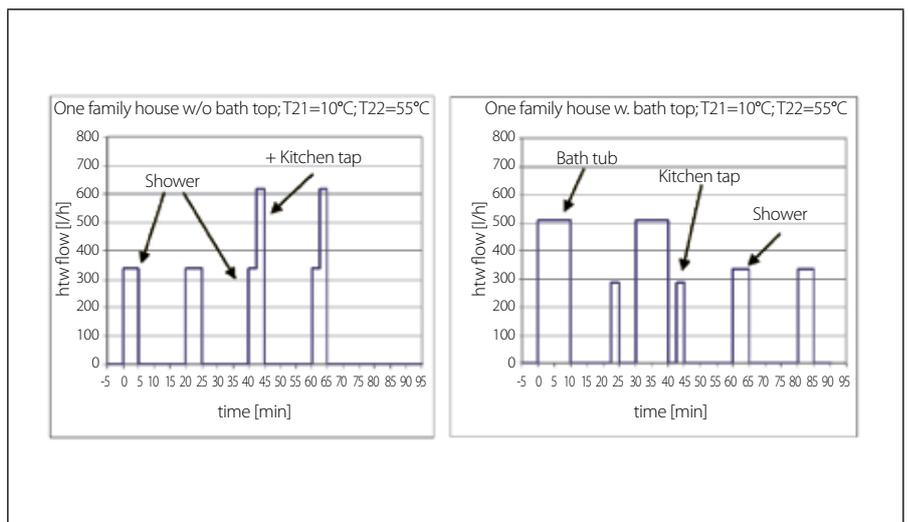

FIGURE 1: htw load profiles specified in Denmark, according to DS439.

	w/o. bath tub	w. bath tub
Kitchen sink	14,7 kW	
Bath tub		26,4 kW
Shower	17,6 kW	
max. power	32,3 kW	26,4 kW

TABLE 1: htw power ratings according to DS 439.

3. Effects on design and operation of the distribution network.

3.1 In short about the simultaneity factor

A simple method to calculate group design load of N consumers, Q(N) [kW], each having a design load of qmax [kW/cons] according to design standard, would be:

(Design group load of N consumers) $= N \times q_{max} = N \times Q(1)$ [kW]

However, the group load is found to be lower, as all of the N consumers do not tap water at the same time, and do at least not use their maximum load at the same time. Further reduction is caused by overdesign of q_{max}, etc. The simultaneity factor S is defined as:

$S(N) = Q(N) / (N \times Q(1))$
[% Design group load]

where Q(N) is the maximum load from N consumers. Right evaluation of the simultaneity can save a considerable amount of investment and operation costs of the pipe network, fig. 6.

In the literature the S(100) can be found in a surprisingly big range, even for similar types of units. Part of the reason may be different definitions or uncertainty about Q(1). On the other hand, Q(100) is a much more "stable" value than S(100). So instead of comparisons between simultaneity factors, the comparison of the average unit load, that is Q(N)/N [kW/consumer], is preferred in this paper.

3.2 Pure HTW load on pipe network

A number of the previous works in Denmark regarding simultaneity of hot tap water DH load are included in the reference list. The most relevant results for this paper are presented as group loads [kW] and compared in fig. 7.

The loads found in e.g. Poulsen 96 are based on principles in DN4708, however adjusted to Danish conditions. They show 1 minute maximum and 10 minute maximum load of 12 hours time interval. Curves of Brydow 84 and Lawaets 85 are based on measurements, and show lower loads. Lawaets works with a storage unit with a max of 12 kW. The last two curves in the figure are two cases of the formula used for all unit types in this paper:

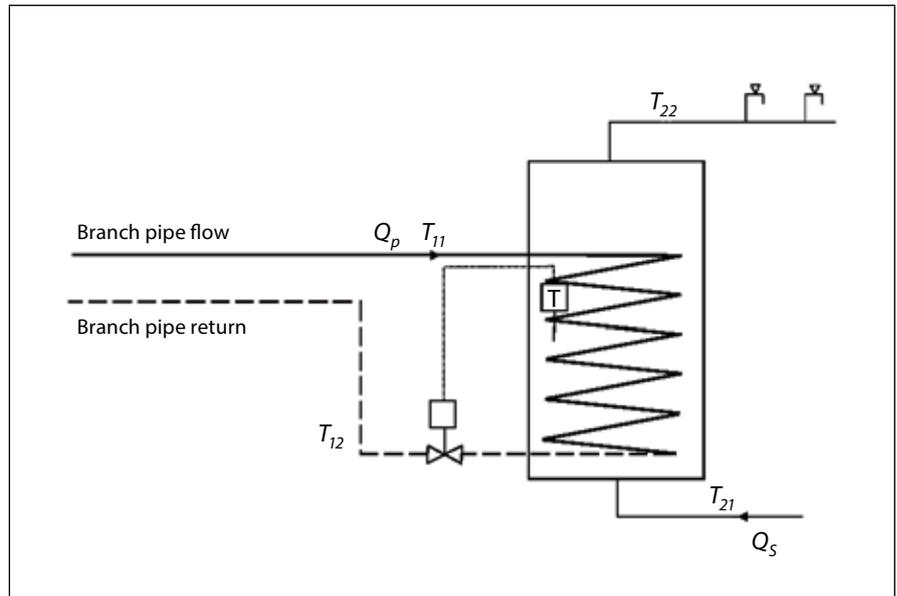$Q(N, q_{max}) = a \times N + b(q_{max}) \times N^{1/2} + c(q_{max})$ [kW]

where

FIGURE 2: Storage tank unit, 110 litre volume, 17 meter of 3/8" coil installed
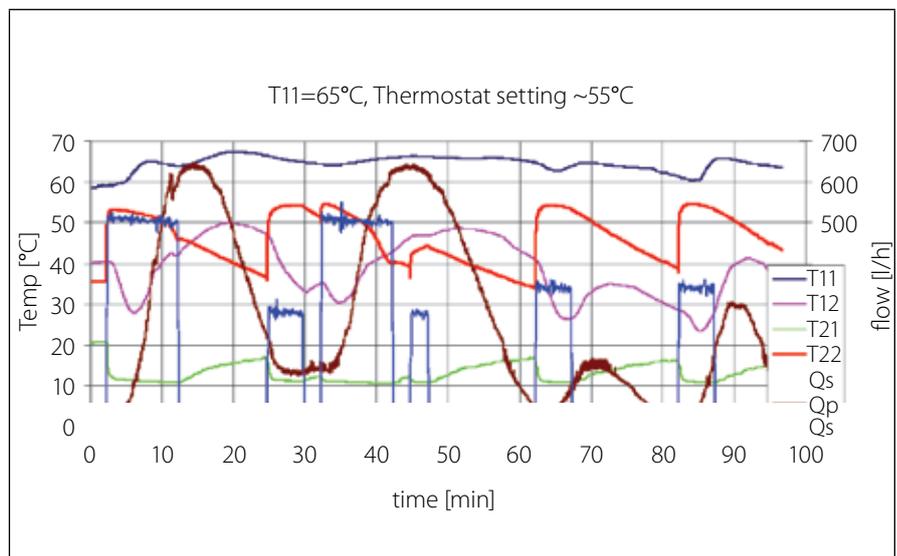

FIGURE 3: Example of tapping profile measurement applied on a 110 litre ST unit
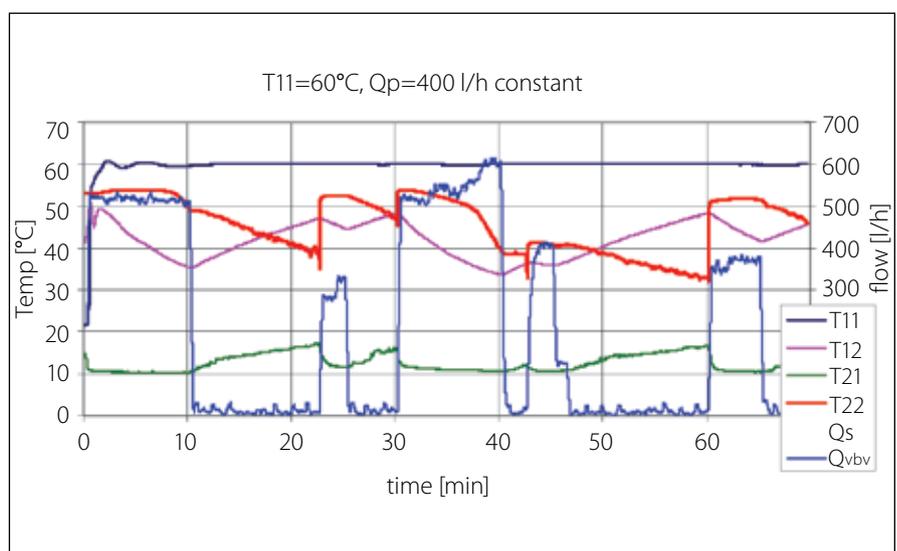

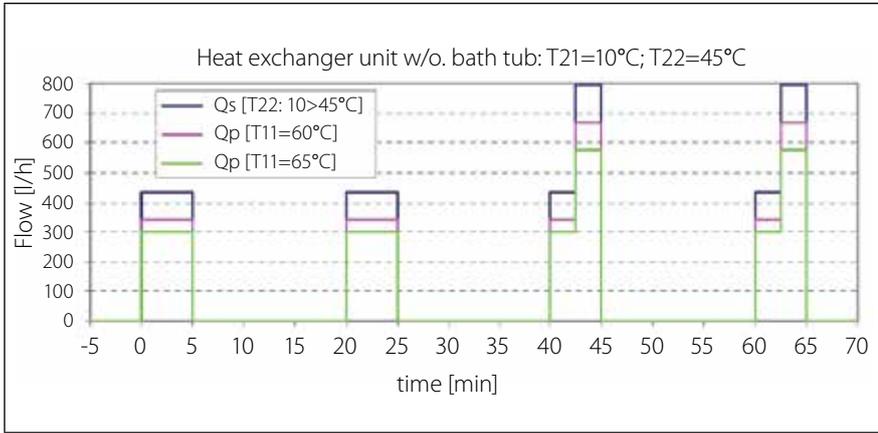*FIGURE 4: Example of tapping profile measurement applied on 110 litre ST unit, primary flow is constant*

FIGURE 5: Heat exchanger hydraulic performance, heat exchanger type Danfoss XB06-1-34H
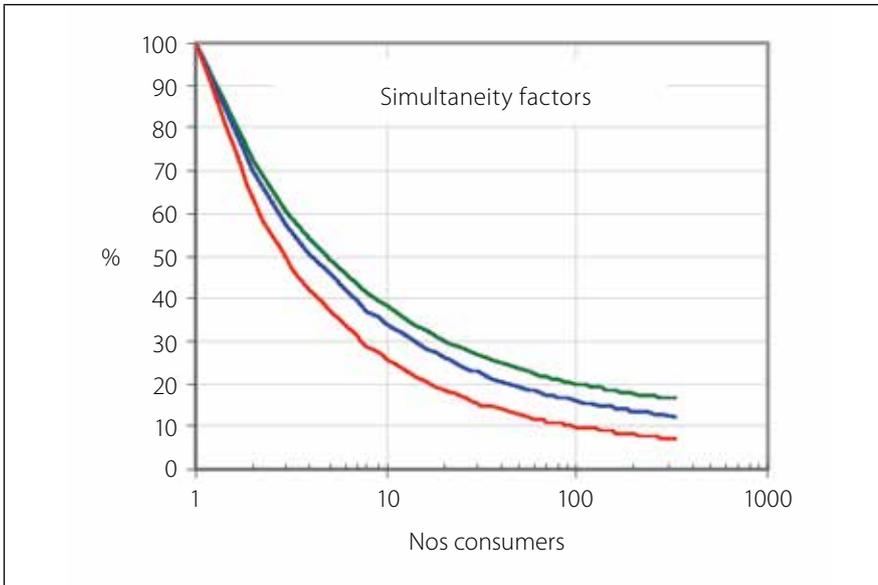

FIGURE 6: Example of simultaneity factors

$a = 1,19$

$c(q_{max}) = 13,1 \times (q_{max}/32,3)\, 2,3$

$b(q_{max}) = q_{max} - a - c$

The values/formulas of a, b, c are a result of evaluation of the curves of the previous works. The relative difference of the storage tank and heat exchanger load fits with Lawaets. The load Q(N) of the heat exchanger fits with Danish design precondition of 32,3 kW, which is approximately the average of the one minute max and 10 minute max load of Poulsen 96. The value 1,19 kW of the constant "a" represents the asymptotic or eventual average unit load regardless of the type of unit.

In the following, we will compare three cases from the previous section, the DH load of respectively the HE unit 32,3 kW (with or without bath tub), storage tank unit (ST) with bath tub 8,5 kW, and the storage tank unit (ST) with shower 5,8 kW. For the HE unit, the load Q(1) is the maximum momentum load, while for the storage units, Q(1) the maximum is one hour average, (and not maximum, to take into account improvements in control of the storage tank). In all three cases, the forward temperature is 60°C and 65°C. The comparison of the heat load is found on the left side of fig. 8.

It appears from the diagram, that the load of the HE unit is biggest, but decreases faster than the load of the ST units. The reason is of course that since the loads of the HE unit are "higher" on the kW scale, they are also "smaller" on the time scale, which gives smaller simultaneity. Both ST unit and HE unit

Unit type	T11 [ºC]	T12* [ºC]	T11-T12 [ºC]	T22[ºC]	Qp* [l/h]	P [kW]
Storage tank 110 l w/o. bath tub	60	42	18	55	280	5,8
Storage tank 110 l w/o. bath tub	65	38	27	55	215	6,7
Storage tank 110 l w. bath tub	60	45	15	55	490	8,5
Storage tank 110 l w. bath tub	65	42	23	55	360	9,6
Heat exchanger	60	18	42	45	660	32,3
Heat exchanger	65	16	49	45	570	32,3

*) Max. of 1h average value

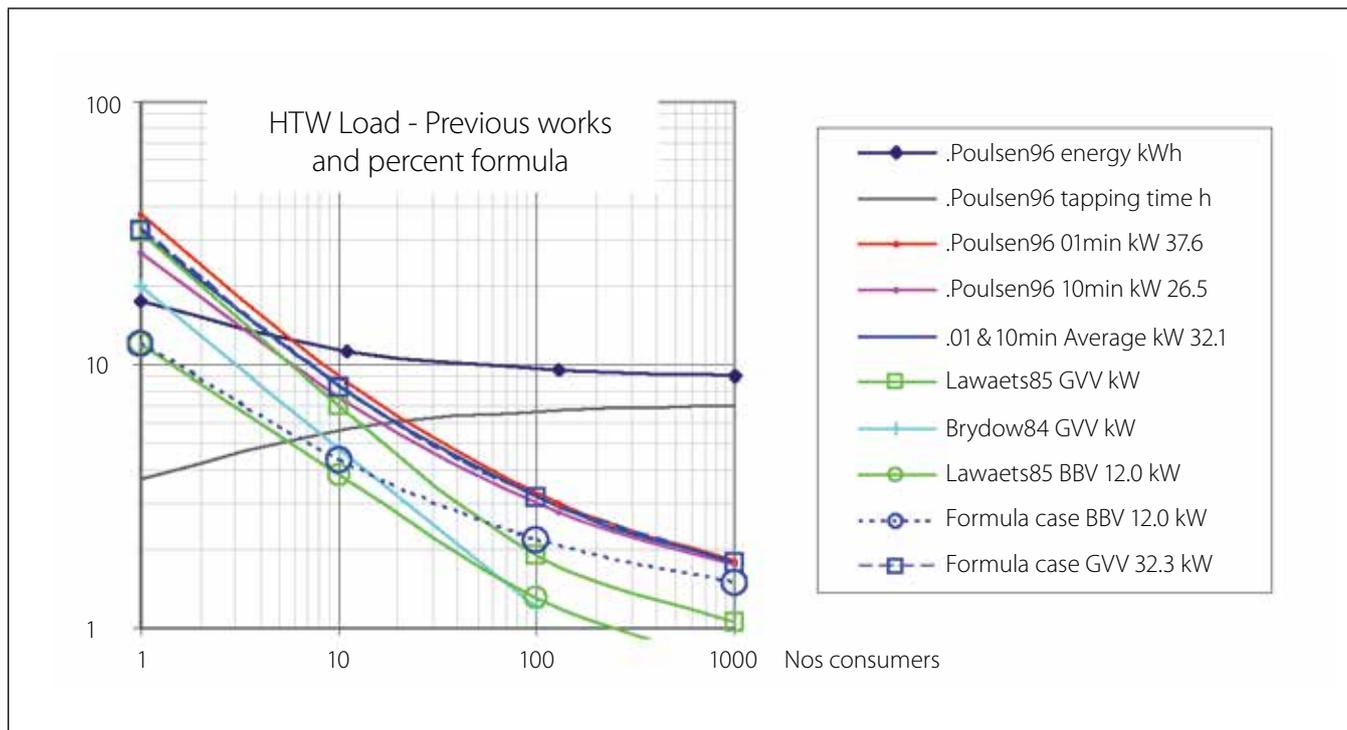**TABLE 2: Thermal hydraulic load comparison**

FIGURE 7: DH group load (kW) from pure htw consumption. Previous works in Denmark and formula used in this paper (GVV: HE heat exchanger, BBV: ST storage tank).

decrease towards the sameeventual value.

The flow load on the pipe network can be found on the right side of the figure. It depends on the heat load and the temperature drop at the consumers. The DH forward temperature is 60°C, and the previous section showed the return temperature of the heat exchanger unit of 18°C, and return temperatures of the tank units (1 hour average) of 42°C and 45°C. The DH flow load of the three units is found on the right side of the figure.

It appears from the diagram that in case of few consumers the flow load of the HE unit is higher than the flow load of the storage unit. In case of sufficient number of consumers, the flow load of the HE unit is lower than in both cases of the storage unit.
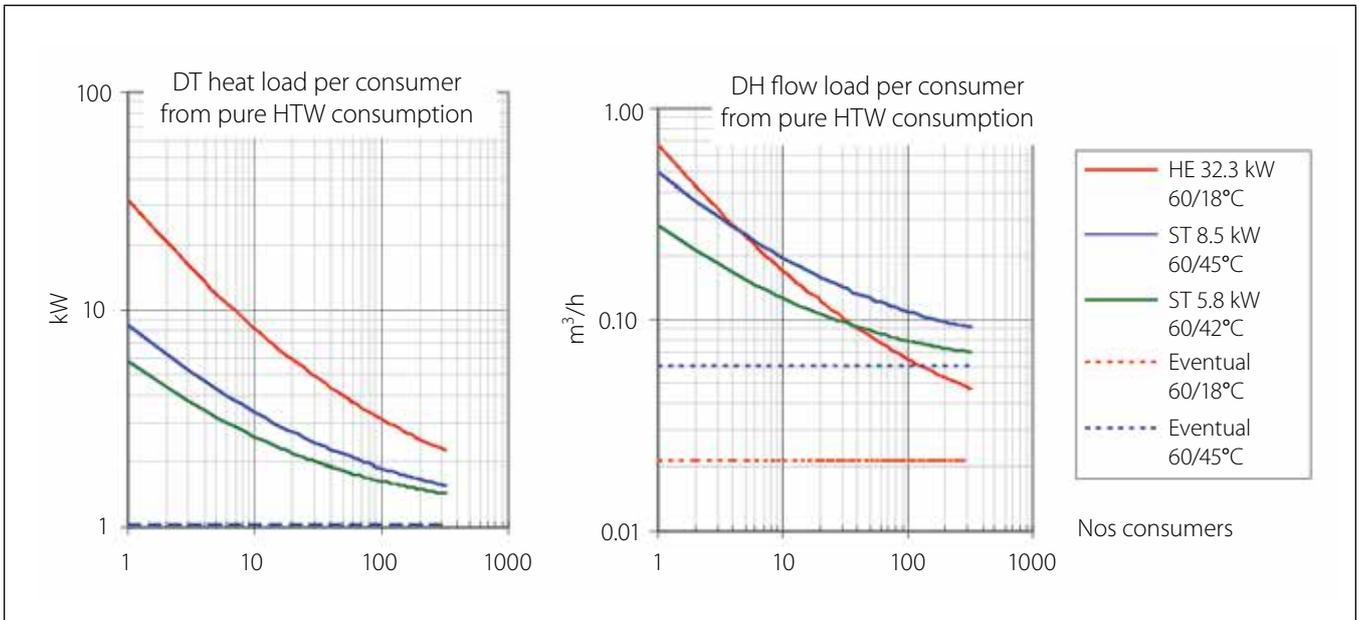
FIGURE 8: *DH heat load per consumer and DH flow load per consumer of pure hot tap water consumption in the three cases with forward temperature 60°C, respectively HE unit 32,3 kW, ST unit w. bath tub 8,5 kW, ST unit w/o. bath tub, 5,8 kW.*
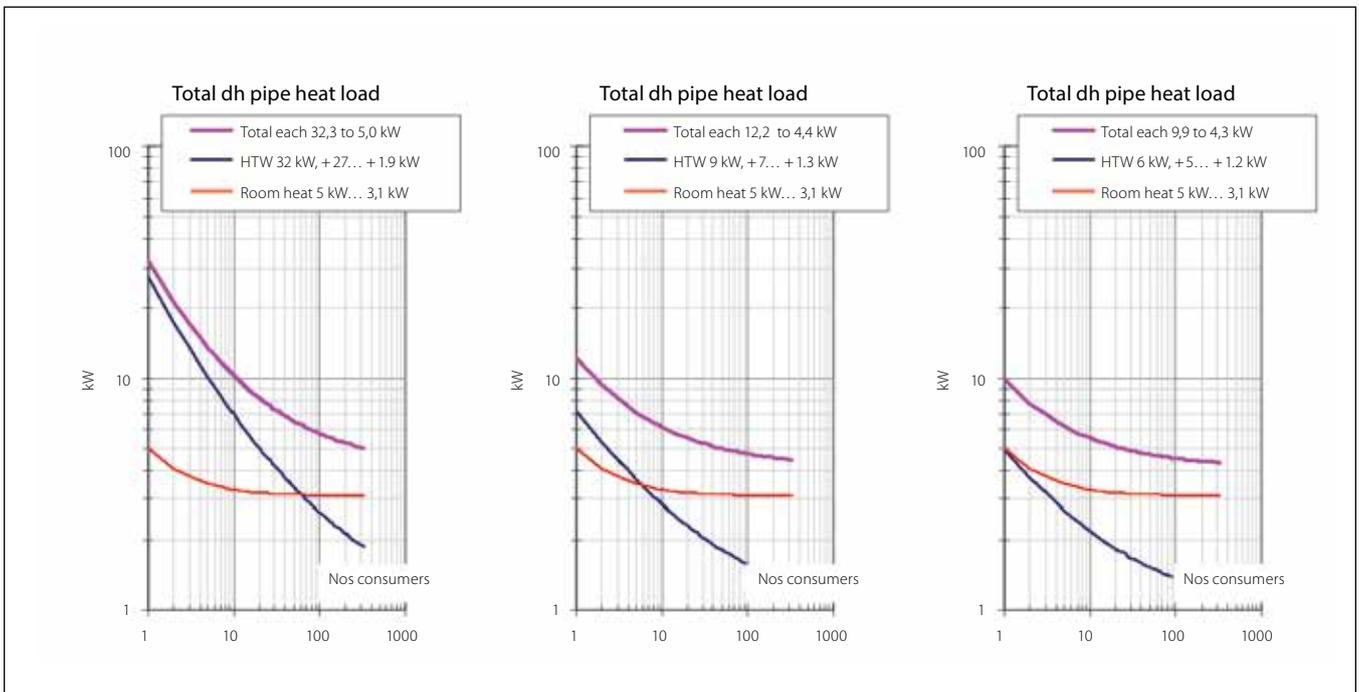

FIGURE 9: *DH heat load per consumer of room heating and hot tap water in the three cases with forward temperature 60°C, respectively HE unit, ST unit with bath tub, ST unit with shower*

3.3 Total load and sizing of pipe network

The room heat load Qr(N) also follows a simultaneity curve, though much less dramatic with an eventual simultaneity factor of about 50 - 75% of Qr(1), depending on installations. Here we use S (eventual) = 62% and Qr(1) = 5 kW, that is design room heat load, and DH

design temperatures of 60/35 and 65/35 °C (forward/return).

In principal the service pipe capacities are designed according to maximum htw load or maximum room heat load, at least in case of HE unit (the maximum of the two values). In single family houses, this usually means the maximum htw load. In case of a storage tank, the design load may be slightly higher than the maximum of the room heat and htw part, the reason for this is

that the ST unit occupies the service pipe for a longer period than the HE unit.

Other pipes in the network are basically designed to have capacity for both maximum room heat and maximum hot tap water demand to some extend. According to a traditional convention, only part of the htw load is added to the room heat load, as maximum htw load and maximum room heat load occur rarely. However too much
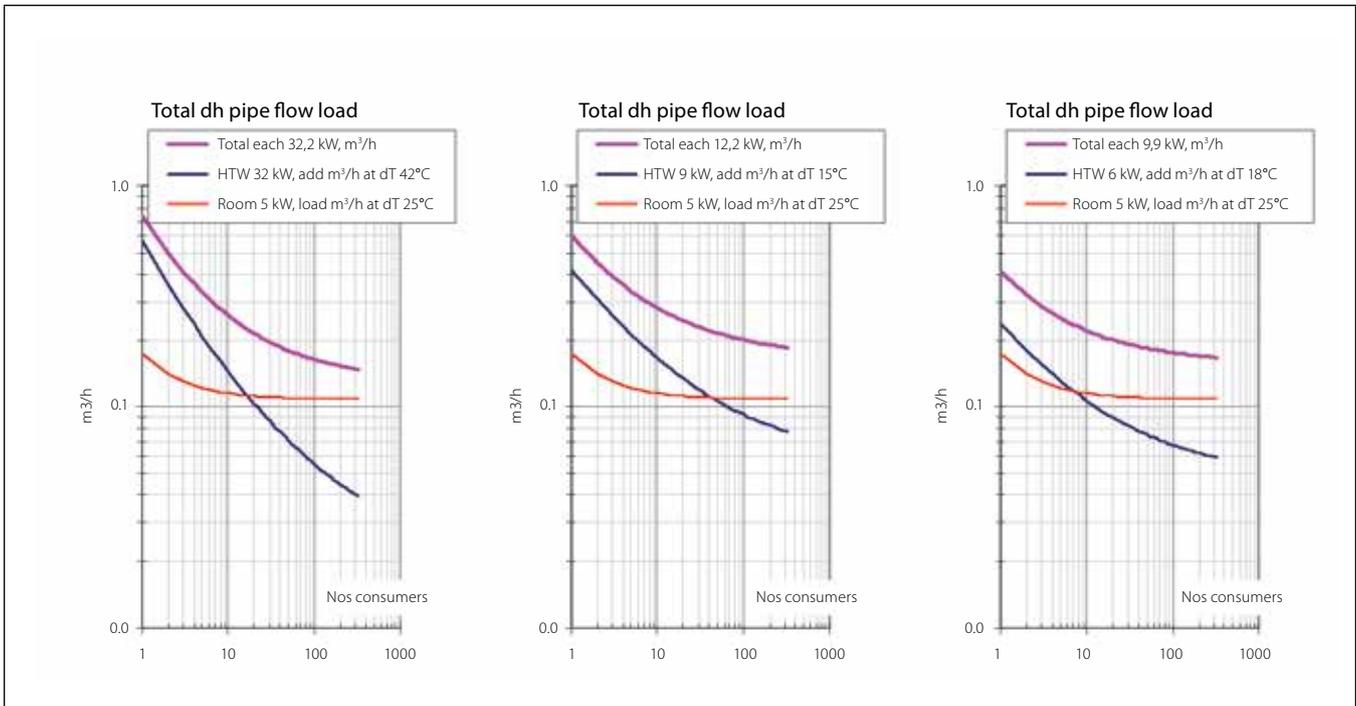
FIGURE 10: DH flow load per consumer of room heating and hot tap water in the three cases with forward temperature 60°C, respectively HE unit, ST unit with bath tub, ST unit with shower.

reduction in the htw addition load becomes a dangerous method of pipe sizing in case of low room heat loads. Here, the htw add percentage in case of all unit types is found according to:

(Total load) = (Room heat load) + (htw add) (kW)
(htw add) = htw add %) × Q(N)
(htw add %) = (32,2-Qr(1))/32,3)
Here, (htw add %) = 85 % as Qr(1) = 5 kW.

The resulting total heat load per consumer on the pipe network can be found in fig. 9. The figure shows that in case of 1 – 10, maybe 20 consumers, the heat load of the ST unit is considerable lower than the heat load of the HE unit.

However, the pipes are sized according to flow load, not heat load, and the flow load of the pipe network depends on the previously mentioned values of DH temperatures. The flow load can be found in fig. 10.

To simplify the presentation, the figure shows only one case, which we have chosen to be winter design load with forward temperatures of 60°C. But in fact the pipe design takes – and has to take into account – the winter and summer situation separately, as summer conditions are critical for the pipes serving one to few consumers, while winter conditions are critical for the rest of the network.

The figure shows that the flow load of the HE unit is higher than the flow load of the ST unit in case of pipes serving

1 – 3 consumers, while the flow load of the HE unit is lower in case of pipes serving more than 30 consumers.
In case of 4 - 30 consumers the ST unit has a higher load than the HE unit in case of a bath tub, but a lower load in case of a shower.

Now we have found the design flow load for every pipe section in the network. This information we have put into a pipe network sizing software, where all pipes and pump stations are automatically sized. The pipes are sized according to the optimal design pressure gradient (bar/km), which runs from about 1 bar/km for medium sized pipes, to about 10 bar/km in case of service pipe for typical price conditions in Denmark /Kristjansson 1994/.

The next task is to compare the total distribution costs in case of the three pipe network designs, according to the three cases mentioned above.

3.4 Cost of distribution system versus system

The cost of pipe network is calculated as the sum of investment in pumps and pipes as well as operation costs including electricity consumption of pumps and heat losses from pipes.

For calculating investments, we use a model developed in Kristjansson et al. (2004). The pipe investments consist of the production costs of the pipe

itself, the component costs (branch tees etc.) which depend on the network structure, and the cost of pipe works and civil works. The model is multivariable regressed with price structures from pipe producers and entrepreneurs, and is verified with completed projects. The model includes data about typical average pipe network geometry.

For this article the net data is:
• Number of consumers: 190
• DH pipe type: steel – twin/PEX – twin
• Eat density: 1,6 GJ/m
• Dimensioning: 1 bar/km to 10 bar/km
• Insulation class: middle

Operation costs including heat losses and electricity consumption are present valued with a time horizon of 20 years and an interest of 5%. The heat loss cost factor used is 40 EUR/MWh. The results of total cost comparison is shown
in table 3.

It shows, that in case of one family house with shower, the storage tank results in a slightly cheaper distribution cost than the heat exchanger unit, savings about EUR 60. In case of on family house with bath tub, the storage unit demands a EUR 90 more expensive distribution, than the HE unit. The higher return temperature and relative high primary flow from the ST leads to relative large energy losses from the DH net, which is not sufficiently

Total distribution cost in 20 years T11 = 60°C	Relative	EUR/year /consumer	EUR /consumer	Qp* l/h	+EUR /consumer
Heat exchanger 32,3 kW (shower and bath tub)	100%	191	3830	660	0
Storage tank 8,5 kW (shower and bath tub) T11 = 60°C	102%	196	3920	490	+90
Storage tank 5,8 kW (shower only) T11 = 60°C	98%	188	3770	280	- 60

Total distribution cost in 20 years T11 = 65°C	Relative	EUR/year /consumer	EUR /consumer	Qp* l/h	+EUR /consumer
Heat exchanger 32,3 kW (shower and bath tub) T11 = 65°C	100%	190	3807	570	0
Storage tank 9,6 kW (shower and bath ttub) T11 = 65°C	100%	190	3806	360	-1
Storage tank 6,7 kW (shower only) T11 = 65°C	96%	182	3638	215	+169

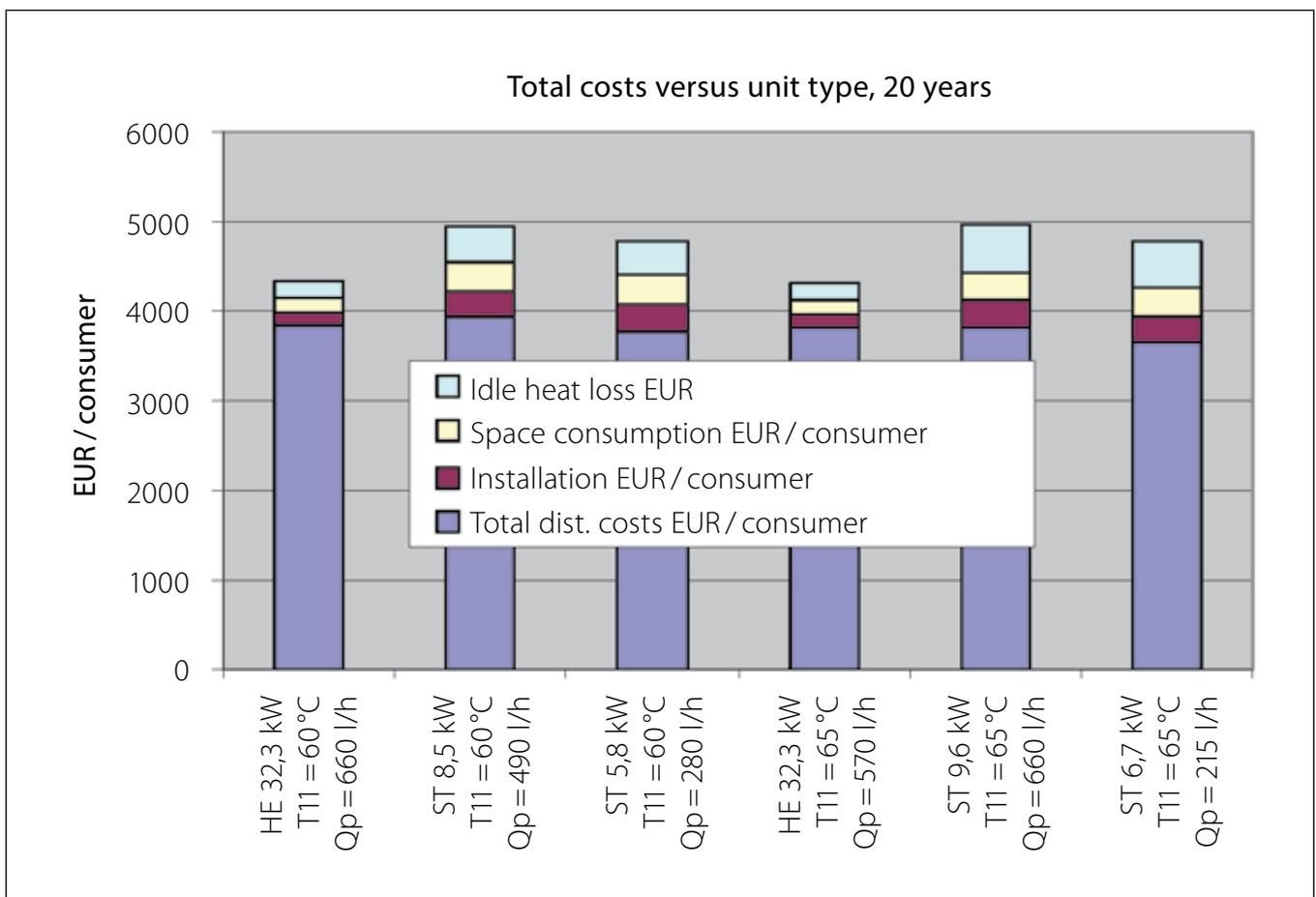*TABLE 3: Total distribution costs over 20 years versus system and primary flow temperature*

FIGURE 11: Cost of distribution system versus system and primary DH flow temp.

counterba-lanced by the reduced pipe dimensions for the last few consumers of the net.

For the 65°C situation, the saving for the ST is EUR 169, which means 4% of the costs.

For the first case (60°C) the difference between the HE unit and the ST unit with respect to distribution cost is only 2%, and this number is too low for concluding that one of the unit types

results in bigger distribution costs than the other. The second case (65°C) is more clear, however only 4% in difference.

Including other system related costs the balance will be (see fig. 11):
- Heat loss from station (ST = 150W and HE = 75W), considered as loss during ½ a year, using 40 EUR/MWh cost factor.
- Installing costs

(ST = 6 man hours and HE = 3 man hours) using 50 EUR/h cost factor.
- Reduced area consumption (ST = 0,6 m x 0,6 m and HE = 0,2m x 0,6 m) using 1500 EUR/m^2 cost factor.
- ST and HE sub station prices are assumed to be the same.

In fig. 11 the usage of the assumptions described below can be seen, the cost is in favour of the HE unit. Prices are

comparable but do not include the DH unit, the heating system etc. The price difference in favour of the HE ranges from EUR 450 to 640. This difference is very clear, expressed in percenttage it is 10–15%.

4. Qualitative considerations

The general discussion on the advantages/disadvantages related to the selected unit type is typically covering the following issues:

4.1. Benefits of the storage tank:

• Lower peak load if adequate control equipment is installed, e.g. thermostat and flow limiter.
• Htw availability is independent of short interruptions in DH supply.
• Htw flow independent tapping temperature, meaning no peak temperatures at flow change.
• Robust against scaling.

4.2. Benefits of heat exchanger:

• Space savings and more up to date technology and appearance.
• Low return temperature during tapping.
• Unlimited tapping time, improving consumer comfort and consumer energy purchase.
• Heat loss from HE unit is relative low, especially if the heat exchanger is bypassed on primary side at idle.
• Heat exchanger can be operated at e.g. 45°C htw temperature, which reduces secondary distribution heat loss compared to typically higher htw temperature for ST due to capacity considerations.
• Considered reduced risk of legionella bacteria.
• The installation requires only one installer, due to low weight of the unit, resulting in lower installation costs. The ST requires typically two installers.

5. Conclusion

Based on the assumptions in this article there are basically no net distribution cost differences over a 20 year period for the ST unit versus the HE unit. Considering other factors like building area cost related to unit space requirements, lower operational heat loss and reduced installation costs, moves the economic favour towards the HE unit. Looking at the listed qualitative considerations the benefit of the HE unit is more end customer oriented, while the benefit of the storage tank unit is more DH utility oriented. Anyhow, the lower return temperature from the HE unit is a benefit for the DH utility.

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