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INFLUENCE OF THE DHW-LOAD PROFILE ON THE FRACTIONAL ENERGY SAVINGS: A CASE STUDY OF A SOLAR COMBI-SYSTEM WITH TRNSYS SIMULATIONS

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Abstract – In this paper the influence of domestic hot water (DHW)-load profiles with a constant total heat demand is studied for a solar combi system. Whereas so far simulation studies are usually done with a simplified DHW-load profile (e. g. according to prEN 12977), a more realistic profile was generated on a 1-min time scale with statistical means. Assumptions about the distribution of the DHW-consumption during the year, depending on the weekday, and the time of the day were made. To study the influence of the draw-off duration and flow rate as well as the daytime of DHW-consumption, TRNSYS simulations were carried out with a variety of common and fairly realistic load profiles. In this case study the investigated solar system consists of a storage tank with an internal thermosyphonally driven discharge unit. Despite a rather minor influence of the flow rate on the fractional energy savings for the given system, a fairly wide range of about 2.2 percentage points of the fractional energy savings were found for the system with some constructive changes. Furthermore, due to changes of the daytime of the draw-offs, the fractional energy savings changed by up to 1.1 percentage points for the investigated system. It can be concluded that the influence of the DHW-load profile may not be disregarded, when combistores are compared. This is true especially for combistores, for which the duration and flow rate of a DHW draw-off have a severe influence on the temperature stratification in the storage tank.

1. INTRODUCTION

The fact that the temperature stratification has a great impact on the solar energy gain of a solar system has been shown in many publications in the past. For example, Sharp and Loehrke already showed in 1979 that improvements in the system performance of 5-15% may be realized when temperature stratification in the store is achieved. Therefore, much effort has been made to improve the thermal stratification in storage tanks. A lot of studies in the literature (e. g. Lavan and Thomson, 1977; Phillips and Dave (1982); Morrison and Braun, 1985; Shyu et al, 1989) have analyzed the factors that influence the stratification, like flow rates, temperature differences, and the geometry of inlets, stratifiers, heat exchangers and of the tank design. Andersen and Furbo (1999), for example found a decrease of the thermal performance caused by mixing during draw-offs of up to 23% for small solar domestic hot water (SDHW) systems.

Consequently, the solar energy gain depends on the DHW-load profile as soon as the stratification of the storage tank depends on the DHW-flow rate, the duration of a draw-off, or the time of DHW-consumption. The impact of these quantities again depends on the construction of the store.

In the recent years new types of combistores, for combined DHW and space heating (SH), have been developed. Some of these stores are equipped with an additional internal heat exchanger, thermally connecting the storage water, used for SH, and the DHW-cycle. Tests of these stores were carried out, for example by ITW (Stuttgart, Germany) and SERC (Borlänge, Sweden). It has been shown that the temperature stratification in the storage tanks of this kind may depend strongly on constructive details (Dahm et. al., 1998, Drück and Hahne, 1998).

Hampel et al., 1999, found in a simulation study an increase of the collector output of almost 5% for a SDHW system of a multi-family house when the DHW-load is taken in the evening instead of taking it in the morning. In contrast to that, so far TRNSYS simulation studies are usually carried out with a domestic hot water profile consisting of three draw-offs during the day with a constant flow rate of 10 l/min (prEN 12977).

In this case study, a combisystem with an internal thermosyphonally driven DHW-heat exchanger is investigated and the dependence of the fractional energy savings on the flow rate, the daytime, and on the draw-off duration due to flow patterns during and after a draw-off is shown. For that purpose a fairly realistic DHW-load profile was developed. It is described in the following section. Assumptions made are based on various studies about DHW consumption in Switzlerland and Germany (Dittrich et al., 1972; Loose, 1991; Mack et al., 1998; Dichter, 1999; Nipkow, 1999; Real et al., 1999). In the third section, the model of the solar system, the reference conditions, and the applied TRNSYS deck are described briefly. The mathematical model for the DHW-discharge unit is shown in section four. In section five, one-year-simulation results of the realistic load profile are compared with results of the commonly used one, in terms of distributions of solar gains during the year. Non realistic profiles were used to analyze the influence of the DHW-flow rate, duration, and the daytime on fractional energy savings. Temperature distributions, resulting from two day simulations are shown. Also, simplifications are applied concerning the assumptions made to the statistically generated profile.

2. REALISTIC DHW-LOAD PROFILE

A load profile for the domestic hot water demand for a period of one year was generated. In order to take into account fairly realistic conditions, a time step of one minute was chosen. The values of the flow rate and the times of the draw-offs were selected by statistical means. The first three days of the the profile with a daily mean draw-off volume of 200 l are shown in figure 1.

a) Basic Assumptions

Four categories of loads were defined. Each category-profile was generated separately and superponed afterwards. For each category a mean flow rate was defined. The actual values of the flow rates are spread around the mean value with a gaussian-distribution (figure 2):

$$prob(\dot{V}) = \frac{1}{\sqrt{2p}\, s} \exp \frac{-(\dot{V} - \dot{V}_{mean})^2}{2s^2} \qquad (1)$$

The values chosen for s , for the duration of every load, and for the medium number of incidences during the day are shown in table 1. With this approach, it is assumed that there is no correlation between the weather data and the DHW-load profile.

The following assumptions are made:

- the mean load is 200 l/day
- four categories to describe the different types of loads are defined:
  - cat A: short load (washing hands, etc.)
  - cat B: medium load (dish-washer, etc.)
  - cat C: bath
  - cat D: shower

A probability function, describing variations of the load profile during the year (also taking into account the (European) daylight saving time), the weekday, and the day was defined for every category. The course of probabilities during the year is described by the product of probabilitiy distributions during the year, during the day, at weekdays and during the holiday season:

$$prob = prob(year)^* \; prob(weekday)^* \; prob(day) \; ^*prob(holiday)$$

- *prob(year):* The course of probabilities during the year is described by a sine-function with an amplitude of 10% of the daily discharge volume. Mack et al., 1998, found variations of the energy consumptions according to a sine function with an amplitude of 25% and a maximum during winter and a minimum during summer time. This variation is due to variations of the cold water temperature, variable consumption during the year, and due to holidays, taking place mainly in the summer. Since holidays are taken into account separately (see below) and the cold water temperature is not defined by this load profile, the amplitude given by Mack et al. was reduced.

- *prob(weekday):* At different days of the week the probability for taking a bath and the mean distribution for the total volume per day are shown in figure 3. For the categories A, B, and D the probability for every day of the week is assumed to be the same. The average of DHW-consumption for the four categories is according to the results found by Dichter, 1999.

	cat A: short l.	cat B: med. l.	cat C: bath	cat D: shower
flow rate in l/min	1	6	14	8
duration in min	1	1	10	5
inc/day	28	12	0.143*	2
sigma	2	2	2	2
vol/load in l	1	6	140	40
vol/day in l	28	72	20	80
portion	0.14	0.36	0.10	0.40

*once a week

Table 1: Reference conditions for the load profile: Four categories are defined with a mean flow rate and a constant duration of every DHW-draw-off. The volumes of the loads were chosen with the assumption of a load temperature of 45°C. The number of incidences are refered to a single family house with a mean consumption of 200 l/d.

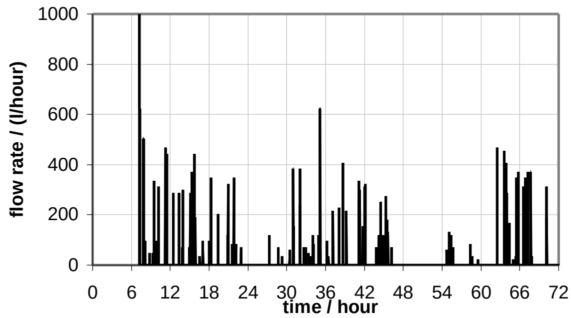


Fig. 1. Realistic load profile, Jan 1st to Jan. 3rd , generated with statistical means. Mean draw-off volume of the year: 200 l/d.

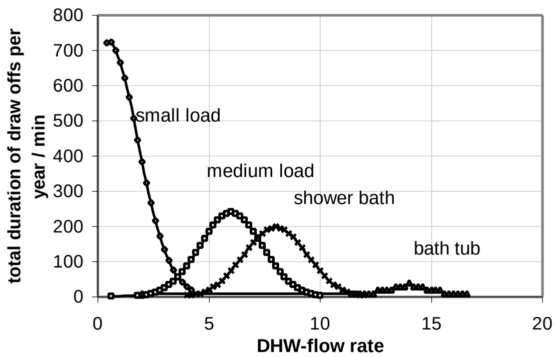


Fig. 2. Realistic load profile: Nr. of draw-offs during one year as a function of the DHW-flow rate. These are distributed with a gaussian function (eq. 1) around the mean values, also given in table 1.

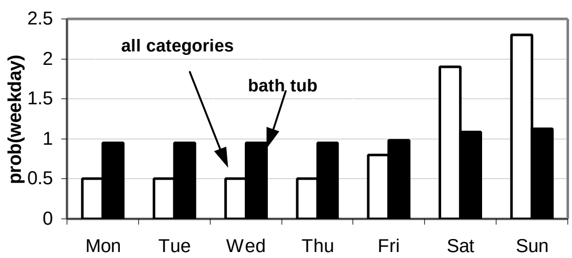


Fig. 3. Distibution of probability for category C: Bath tub filling (grey columns). In categories A, B, and D no day of the week was privileged compared to another.

- *prob(day):* The assumptions for the daily distribution used, are shown in fig. 4. For a short and medium load the probability is distributed equally between 5:00 and 23:00 h. For the shower bath, a clear peak in the morning and for the bath tub filling (which mainly occurs on weekends), a peak in the evening were applied.
- *prob(holiday):* For every 100 l/d of consumption the probability was set to zero during a period of two weeks during the summer. Therefore, for a one family house with a total daily mean consumption of 200 l/d, two periods in which the consumption is reduced by one half are taken into account. The start day of every holiday period is generated by a random generator. The generator is set in a way that for a consumption of 200 l/d the two periods of reduced consumption do not coincide, but start on Jul. 14th and Aug. 8th, respectively. The function *prob(holiday)*is defined as follows:

$$prob(holiday) = \frac{mean\ volume\ of\ daily\ load - reduced\ volume}{mean\ volume\ of\ daily\ load},$$

hence with a consumption of 200 l/d:
prob(holiday) = ½ Jul. 14th..28th, Aug. 8th.. 22nd
prob(holiday) = 1 else

b) Method

The cumulated frequency method was used to distribute the draw-off incidences among the year according to the probability function. As shown in fig. 6, the probability function *prob* was integrated over the year and normalized. Afterwards the number of draw-offs during the year was calculated. The same number of random values between zero and one were generated and assigned to a flow rate in the order of occurence. With fig. 6, every random value (value on the y-axis) was then assigned to a minute of the year (value on the x-axis).

In this way load profiles were generated for different demands as well. The basic load is 100 litres/day. Profiles were generated in dual order (100, 200, 400, 800 litres..), with different initial random values. Therefore, it is possible to get any load profile with consumptions in steps of 100 l/day for a multi-family house by superposition of the generated files. For different consumptions the number of incidences, shown in table 1, will be adjusted to the mean draw-off volumes.

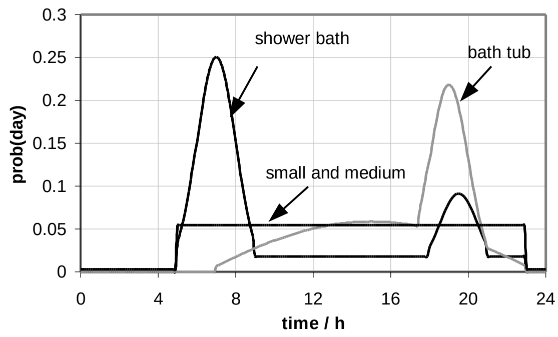


Fig. 4. Distibution of *prob(day)* during the day.

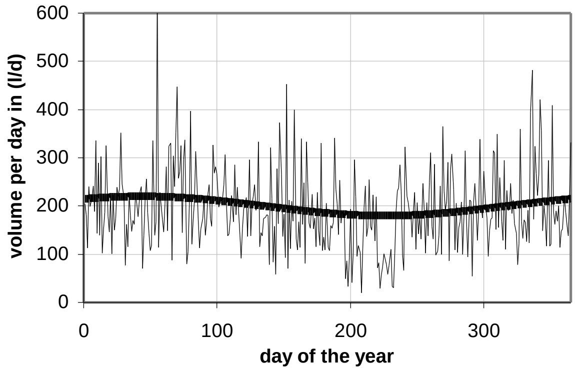


Fig. 5: Realistic load profile: Daily DHW-load volume in the course of the year. Mean value: 200 l/d.

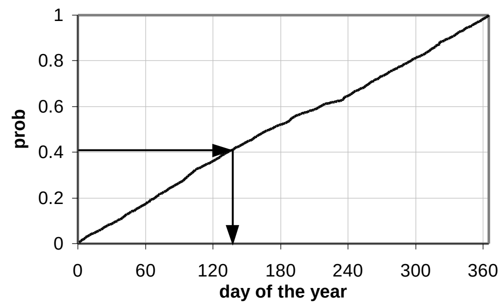


Fig. 6: Accumulated frequency method: Integral of the probability function prob.

3. INVESTIGATED SOLAR SYSTEM

a) TRNSYS Deck and Reference Conditions

A solar combisystem for a one family house in Zurich is regarded, with fractional energy savings of about 25%. A scheme of the TRNSYS deck used is shown in fig. 7. The weather data as well as a set of space heating data were implemented as data files. The space heating data from IEA-Task 26 (International Energy Agency, Solar Combisystems) were used with input and output temperatures and the flow rate for the space heating cycle. The DHW-load was either read in from a data file, in case of using a statistically generated profile. Alternatively, conventional load patterns were implemented with the type 14 time dependent forcing function.

For the thermosyphonally driven discharge unit of the combitank, a user contributed plug-flow heat exchanger model was developed (type 104). Other than that, standard components, including the type 140 multiport storage type (Drück, 1994), were used.

The solar system consists of a 14 m² flat plat collector, an external solar heat exchanger, and an 817 l combistore with an internal thermosyphonally driven DHW-heat exchanger. A scheme of the combitank is shown in fig. 8a. When domestic water is heated, the water inside a containment surrounding the heat exchanger is cooled, and flows through an adjacent tube to the bottom of the store.

Depending on the storage temperatures and on the flow rate, the storage water flow needs to be slowed down, in order to cool it down in the heat exchanger sufficiently. This is done with a valve in the vertical tube, placed below the heat exchanger (fig. 8b). The valve is connected with a thin cylinder containing an expansible material that is placed at the domestic water outlet. For stationary conditions, the angle of the valve is a (linear) function of the domestic water outlet temperature. Therefore, the pressure drop at the valve increases, if the DHW-temperature rises. This leads to a decrease of the storage water flow rate and storage water outlet temperature of the heat exchanger. In this way, it can be avoided that hot water flows from the top to the bottom part of the store.
Some of the reference conditions assumed, are listed in table 2.

b) Definition of the Target Function
According to prEN 12977, the energy savings shall be calculated by ‘comparing the gross auxiliary energy demand of the auxiliary heater of the solar heating system to the gross auxiliary energy demand of a conventional heating system.’ Additional to the definition given in the norm, the electric energy demand for pumps was taken into account: (2)

$$f_{save} = 1 - \frac{Q_{burner,aux} + \sum Q_{pump} \cdot \dfrac{h_{burner}}{h_{pump}}}{Q_{SH} + Q_{DHW} + Q_{l,conv} + Q_{pump,conv} \cdot \dfrac{h_{burner}}{h_{pump}}}$$

with $Q_{l,conv} = 644\,kWh$ and $\dfrac{h_{burner}}{h_{pump}} = \dfrac{85\,\%}{40\,\%} = 2.125$.

$P_{pump} = 30W$, $P_{burner} = 10\,kW$

The value of $Q_{l,conv}$ was calculated with values of UA_{store}, a storage size, and set temperatures according to prEN 12977. To calculate the running time of the pumps to load the store of the conventional system, the total energy demand of the conventional system (including storage losses) was divided by the assumed power of the burner. Running times of the solar system pumps result from simulations.

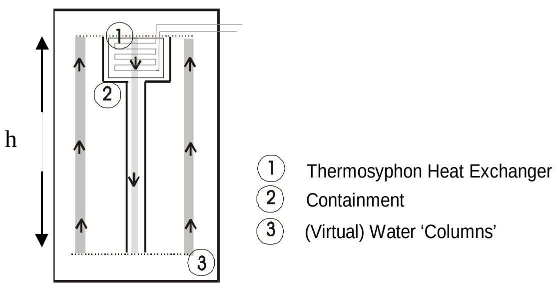


Fig. 8a: Combistore with thermosyphonally driven discharge unit: During a DHW draw-off storage water is driven by density differences inside the tank.
Fig. 8b: (a) Regulation device, composed of a valve placed in a vertical tube below the heat exchanger and a thin cylinder containing an expansible material. (b) angle of the valve j. (c) A mixer for the domestic water.

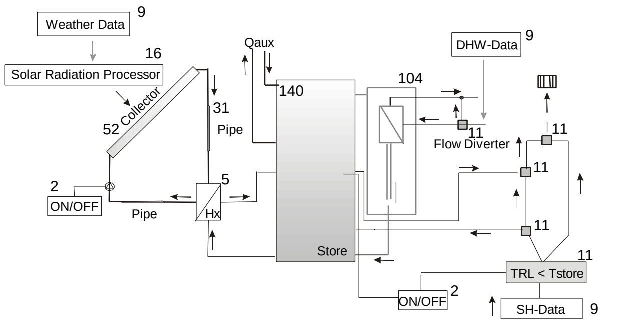


Fig. 7: Scheme of the TRNSYS-deck, with a new developed user contributed component Type 104 for the discharge unit (plug flow heat exchanger model combined with thermosyphon driving pressures). The numbers indicate the TRNSYS type numbers used.

Table 2: Reference Conditions

weather data	Zurich (Meteonorm), Δt = 1h
collector area	14 m², 40 l/m²h
collector orientation	south, tilt angle: 45°
store volume	817 l
space heating demand	8400 kWh/a (140 m², 60 kWh/m²a)
flow rate auxiliary heating	430 kg/h
auxiliary set Temp.	57°C + 5K
daily DHW-load volume	200 l
DHW-set temperature	45°C (-1K)
design temp. SH-distr. syst.	40°C / 35°C
domestic cold water temp.	(9.7 ± 6.3)°C, sine-func., min. at May 1st

4. MODELLING

a) Relations of the Thermosyphon Loop
The model of the discharge unit is described in Jordan et al., 1999. In the following, a short formulation of the equations that are implemented into type 104 is given.

A common approach to model a density driven circulation loop is the one dimensional steady state momentum equation for incompressible flow, as the balance of the pressure and frictional forces. The driving forces for the storage water flow in the discharge unit are expressed by density differences. Frictional forces are described by the kinetic pressure drop of the storage water. The pressure drop coefficient is a function of the geometry of the discharge unit, the angle of the valve, as well as the flow rate of the storage water.

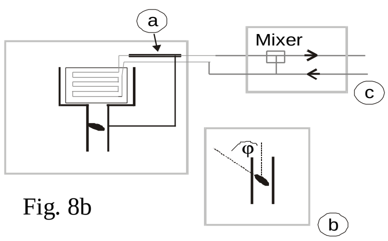


Fig. 8b

$$g\left(\frac{h_{tube}}{n}\sum_{i}^{n}(r_{i,store}-r_{i,tube})+\frac{h_{Hx}}{m}\sum_{i}^{m}(r_{i,store}-r_{i,hx1})\right)=$$

$$V_{store,out}\,\frac{r_{store,out}}{2}\,v_{store,out}^{2}-V\,\frac{r_{store}}{2}\,v_{store}^{2} \qquad (3)$$

with $v_{store,out} >> v_{store}$, $V = V(j, \dot{V}_{store}, d, ...)$,

and r, n, and V : density, velocity, and pressure drop coefficient, respectively. The index i indicates the temperature nodes in the store, the heat exchanger (Hx) and in the vertical tube below the heat exchanger. Due to the fact that the velocity of the storage water in the vertical pipe is much higher than the upwards velocity of the storage water in the tank, the second term on the right hand side in eq. (3) may be neglected.

The transient behaviour of the valve is described by

$$t\dot{j} + j = a\,(T_{dom,out} - T_b) \qquad (4)$$

The value for t was determined experimentally by the response of the angle of the valve to step changes of $T_{dom,out}$. The heat exchanger is modeled with the energy equation (eq. 5a and 5b). A plug flow heat exchanger model was implemented into type 104.

$$(5)$$

$$C_{dom}^{i}\,\frac{\partial T_{dom}^{i}}{\partial t} = UA\cdot(T_{dom}^{i} - T_{store}^{i}) - \dot{M}_{dom}c_{p}\cdot(T_{dom}^{i} - T_{dom}^{i-1})$$

$$C_{stor}^{i}\,\frac{\partial T_{store}^{i}}{\partial t} = UA\cdot(T_{dom}^{i} - T_{store}^{i}) + \dot{M}_{store}c_{p}\cdot(T_{store}^{i} - T_{store}^{i+1})$$

the heat capacity rate (*UA*) was described as a function of the domestic water flow rate.

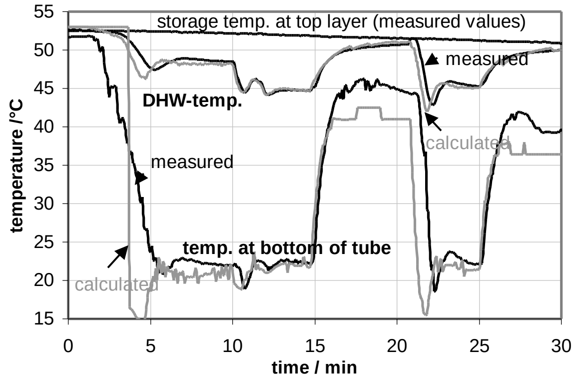
b) Experimental Validation

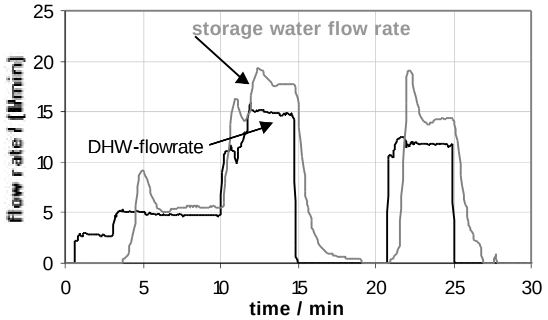
Temperatures on a vertical ledge at 15 positions in the storage tank, as well as inlet and outlet temperatures of the heat exchanger and the domestic water flow rate were measured. The storage temperatures at the ledge were input data to the simulation. In fig. 9 the measured and calculated outlet temperatures of the heat exchanger, the measured domestic water flow rate, and the calculated storage water flow rate are shown. The domestic water flow rate was varied during the measurement. The reaction of storage water to the domestic water flow changes occurs much smoother and with a time delay. The measured and calculated values of the storage water outlet temperature differ considerably for low storage water flow rates. These effects, however, do not influence the energy balance severely. As shown in fig. 9, the domestic water outlet temperature is descibed quite well with the model.

5. ONE YEAR SIMULATION RESULTS

5.1 Comparison of Results with the Realistic and Conventional Profile.

In prEN 12977 reference conditions necessary for simulation studies are proposed. According to this norm, the DHW-profile is supposed to be composed of three draw-offs during the day, at 7 a.m., 12 a.m., and at 5 p.m. The total load should be devided up in the proportion 2/5, 1/5, 2/5, respectively.





Validation of the heat exchanger model (without store).

Fig. 9a: Comparison between measured and calculated outlet temperatures of the heat exchanger.

Fig. 9b: Measured value of DHW-flow rate and calculated storage water flow rate.

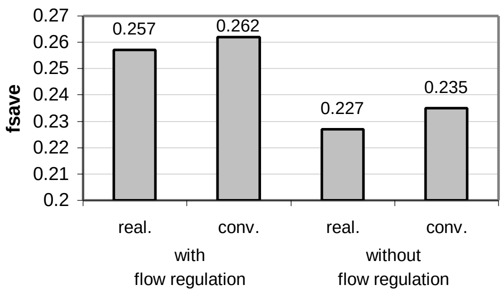


Fig. 10: Fractional energy savings: Comparison of one-year simulation results with realistic and conventional DHW-load profile (with 3 draw-offs during the day), and with and without storage water flow regulation.

This profile, with the time of the evening draw-off changed to 7 p.m., will be considered as the 'conventional' profile in the following. None of the distributions described in section two of this paper are taken into account for the conventional profile. The only time dependant variable used, is the cold domestic water temperature. It is described by a sine-function, depending on the climate of the specific location. Since the same total DHW-volume is assumed for both, the realistic and the conventional profile, the energy demand for the two profiles differ slightly.

For the simulations shown in the following and with the cold water temperature as described in table 2, the energy demand is reduced by about 13.5 kWh (< 0.5% of the overall DHW-demand), when applying the realistic compared to applying the conventional load profile. Therefore, the simulation results of the fractional energy savings are expected to be reduced slightly for the realistic compared to the conventional profile due to the smaller overall energy consumption.

In figure 10 one year simulation results of a solar system with the realistic and the conventional load profile, with and without a control valve for the storage water flow, are shown. The differences between the simulation results with identical system construction turn out to be rather small: With use of the flow regulation device, the fractional energy savings are reduced by 0.5 %-points for the realistic profile compared to the conventional one. Without flow control, the reduction increases to 0.8 %-points. The differences between the results with and without flow control are 3 %-points for the realistic and 2.7 %-points for the conventional profile. Regarding absolute values, the difference of the collector energy gain and the store losses is increased by about 360 kWh/a (16 %) compared with the value without use of the flow regulation device, when the realistic DHW-load profile is applied.

In Fig. 11 the yearly distribution of the solar system gains are compared. Monthly mean values of the solar system gain are shown, as the difference between the heat transfered in the heat exchanger of the the collector circuit and the storage losses. The two curves at the top of fig. 11 show the values obtained with flow regulation device. To indicate the influence of the flow regulation device, the two curves at the bottom of fig. 11 show the differences between the values of the solar system gain with and without the flow regulation device for the two profiles. The following results are indicated:

i) Distribution of the Solar Energy Gain During the Year

The highest solar gains are not obtained during the summer, but during spring and fall. This is mainly due to the distribution of the space heating demand during the year. The variations of the solar energy gains are quite small compared to the ones for typical SDHW-systems. For the realistic profile the maximum value, obtained in April, is about 2.4 times the December value. During the months Nov. to Jan. even 78 % of the solar gain are obtained, compared to the values between Jun. and Aug.

ii) *Improvements due to the Flow Regulation Device in the Course of the Year*

During the whole year there is a positive impact of the flow control. The difference between the solar gains with and without flow control is highest during the winter (40 kWh/month) and decreases to about one forth in August. The higher the temperatures of the store, the smaller the influence of the flow control. One reason for that is that due to an increase of efficiency only little more energy can be delivered into the store, if the temperatures in the store are high. A second reason is that the driving pressures of the storage water flow are higher for a cold than for a hot store. Therefore, there is a higher impact of the flow regulation device in a cold store, to reduce the storage water flow rate.

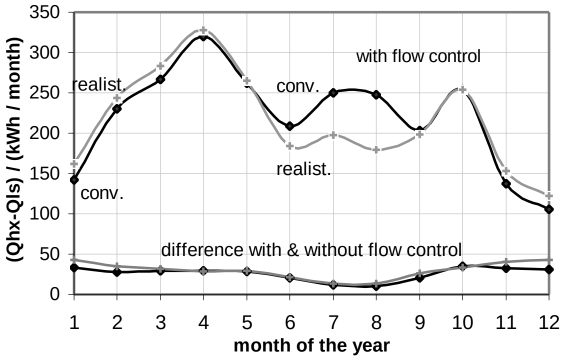


Fig. 11: Difference between the heat transfered in the heat exchanger of the the collector circuit and the storage losses for the conventional and realistic profile, with and without flow regulation. Monthly mean values are shown.

iii) Differences of the Solar Energy Gain due to the DHW-Profiles

The Values of the solar energy gain for the realistic profile are much lower during the summer and higher during the winter than the values applying the conventional profile. This is mainly due to the reduced consumption during the summer (sine-distribution of the probability function) and the holiday season that is taken into account with the realistic profile.

5.2 Influence of the Flow Rate and Draw-Off Time of the Day

In order to study the influence of the flow rate on the fractional energy savings, three types of DHW-load profiles similar to the conventional one were created:

1.) with a total load of 200 l/d, the load-division into three parts of 2/5, 1/5, 2/5 was kept,
2.) the total load was set starting at 7 a.m., and
3.) starting at 12 a.m.

The flow rate and duration of draw-offs were varied as shown in table 3. For example, the lowest flow rate was 4 l/min, with the durations 20 min at 7 a.m., 10 min at 12 a.m, and 20 min at 7 p.m.

Table 3: Flow rates and durations of DHW draw-offs

flow rate/ (l/min)	**duration/** min	**distribution morning-noon-evening/** min
4.00	50	20 - 10 – 20
5.00	40	16 - 8 - 16
6.67	30	12 - 6 - 12
10.00	20	08 - 4 - 08
13.33	15	06 - 3 - 06
20.00	10	04 - 2 - 04

One-year-simulation results are shown in figures 12 and 13. In fig. 12 the curves at the top show results with the storage water flow regulation in operation, the bottom curves show simulation results for a system without flow regulation. The figure indicates: The maximum difference between the values of f_{save} is about 3.5%-points for the system without using a flow regulation device.

i) Flow Rate and Duration:

The fractional energy savings, f_{save}, are almost independent of the DHW-flow rate with operation of the flow regulation device. However, if the regulation is not in operation, f_{save} depends on the flow rate considerably: Applying three daily draw-offs as described in table 3, the maximum difference between the values of f_{save} is 2.2%-points. Related to the value of f_{save} with a flow rate of 10 l/min (as proposed in the prEN) f_{save} varies by about 12% for the morning profile and by about 9% for the other profiles.

These fairly high differences of f_{save} for simulations without a flow regulation device can be explained with the relation of the storage- to the domestic-water flow rate

$$r = \dot{V}_{store} / \dot{V}_{DHW} \ .$$

The value of r turns out to be higher for low than for high domestic-water flow rates during a draw-off for equal reference conditions. This is due to the fact that the pressure drop of the storage water flow depends strongly on the storage water flow rate, as shown in eq. 3. For this reason, a high storage water flow is slowed down to a higher extend than a small one. The higher the value of r, the higher the storage water outlet temperature $T_{store,out}$ of the heat exchanger and the more heat is delivered from the top to the bottom of the tank . For example, short term simulations with one morning draw-off and durations as listed in table 3, showed:

with flow regulation:

$$\bar{r} \approx 1 \text{ for } \dot{V}_{DHW} = 4 \text{ l/min and for } \dot{V}_{DHW} = 20 \text{ l/min;}$$

without flow regulation:

$$\bar{r} \approx 3.6 \text{ for } \dot{V}_{DHW} = 4 \text{ l/min and}$$

$$\bar{r} \approx 1.5 \text{ for } \dot{V}_{DHW} = 20 \text{ l/min.}$$

These values are not generally true, but depend strongly on the temperatures in the storage tank. Nevertheless they indicate the tendency that the value of the DHW-flow rate does not play an important role for the temperature stratification, if the system is designed with the flow regulation device. Without flow regulation, the design of the discharge unit is more suitable for high DHW-flow rates, whereas the pressure drop should be enhanced for small DHW-flow rates.

ii) Draw-off time of the day:

f_{save} depends on the time of the draw-off for both constructions. The values resulting from the noon profile are distinctly above the other values. With flow regulation, the values of f_{save} for the morning and evening load are about the same. Futhermore, if the DHW-load is taken at noon, the values of f_{save} are about 0.7%-points higher than the values for the loads taken in the morning or in the evening. Without flow regulation, the mean value of f_{save} resulting from the noon profiles differ from the one from the morning profiles by about 1.0%-pt.

In fig. 13 simulation results with one daily draw-off at different times of the day are shown. For all of the profiles shown, there is a maximum value of f_{save} around the early afternoon.

iii) Comparison of Simplified and Realistic DHW-Profiles:

The mean DHW-flow rate of the realistic profile is 6.9 l/min. As shown in fig. 12, the value of f_{save} for the realistic profile are slightly lower than the values for the simplified profiles with morning draw-offs and a DHW-flow rate of about 6.9 l/min. This is true, although an even distribution of draw-offs during the day has a positive impact on the fractional energy savings. The reason for the low values of f_{save} for the realistic profile is that the mean number of draw-offs per day is about 42 compared to one or three draw-offs/day for the simplified profiles. Since after a draw-off the thermosyphonally driven storage water flow does not stop instantaneously, warm water flows from the top to the bottom of the tank after every draw-off. This is also true with use of the flow regulation device due to the heat capacity of the expansible material.

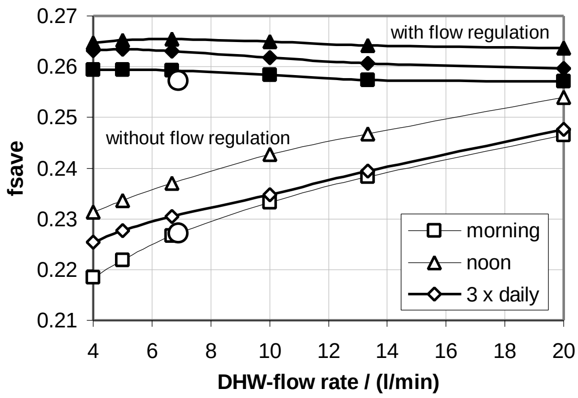


Fig. 12: Fractional energy savings. One year simulations with one or three draw-off during the day. The DHW flow rate was varied in the range between 4 and 20 l/min.
Circles: Values resulting from realistic load profile.

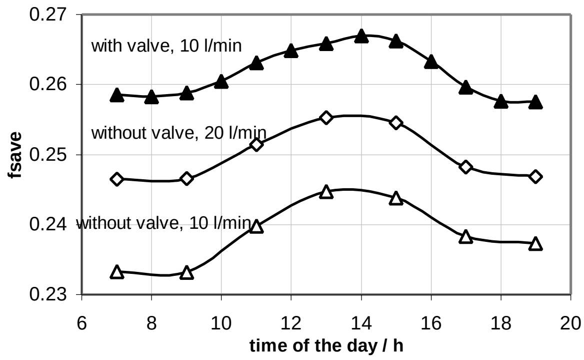


Fig. 13: Fractional energy savings. One year simulations with one draw-off during the day. The draw-off time was varied between 7 a.m. and 7 p.m.

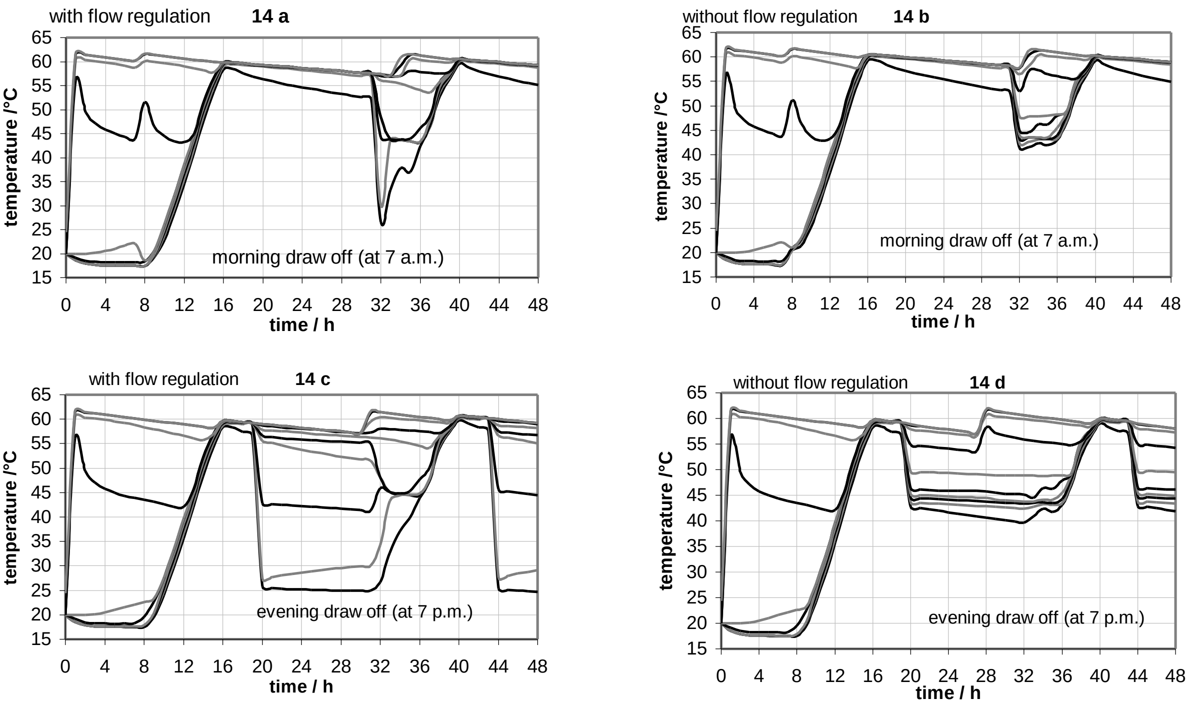


Fig. 14a – d: Two-days simulations with morning or evening draw-offs. Ten temperatures in the storage tank are shown at the normalized heights: 0.05, 0.15, .. 0.95. Initial storage temperature: 20°C. During the first hour, the three top layers are heated by auxiliary.
Fig. 14a and 14c: simulations with flow regulation, fig. 14b and 14d: without flow regulation.

5.3 Stratification in the Storage Tank: Two-day Simulations

The following considerations will not give final explanations for the results shown in section 5.2, but illustrate some tendencies that are induced by different draw-off patterns and by the implementation of a flow regulation device. For this kind of investigations, reference conditions play an important role. As an example, extreme reference conditions, a cold storage tank and fairly high insolation, were chosen.

In figures 14 a-d the temperature stratification in the storage tank is shown for two-day simulations for a warm weather period in the spring. The initial temperatures in the store were 20°C. The auxiliary heater deliveres a set temperature of 62°C when the temperature at a sensor, placed at a normalized height of 0.8, sinks below 57°C. Ten temperatures in the store in an equal vertical distance are shown. The calculations were done with 100 temperature nodes, with the one dimensional multiport storage TRNSYS-type 140.

The store is heated up in the first day until about 4 p.m. to a temperature of 60°C. Therefore, at the first day much more auxiliary energy is needed in the simulations shown in fig. 14a and 14 c (morning), and some more solar energy gets into the store than for the evening draw-offs. At the end of the day, the store is hot in the cases of the morning draw-offs. For the evening draw-offs, the lowest temperature in the store is about 25°C with flow regulation, and it drops to about 40°C without flow regulation. During the night, the stores for cases c and d are much cooler. The temperature at the bottom of the store is below 30°C during the night with flow regulation compared to above 40°C, without. Therefore, the store losses are reduced considerably. At the second day again the store is heated to 60°C at 4 p.m. Until then, there is much more solar energy gain for the morning profiles.

For morning draw-offs more solar energy is delivered into the store, however the overall heat losses are much higher than for evening patterns. Therefore the solar system gain (Q_{hx}-$Q_{store,l}$) turns out to be almost exactly the same for the morning as for the evening draw-offs in this example as well.

5.4 Variations of the Realistic Load Profile

The influence of assumptions made for the distributions of the DHW-consumption for the realistic load profile, described in section 2 was investigated. In figure 14 one-year simulation results are shown for realistic load profiles **without** taking into account the distributions for the DHW-consumption

a) during the weekday (see fig. 3)
b) during the day (see fig. 4)
c) during the year (sine function with minimum in the summer time)
d) during the holiday season
e) of any of the distributions a - d.

For simulation b and e it was assumed, that there were no DHW-consumption between 11 p.m. and 5 a.m. During the rest of the day the probability for DHW-consumption was assumed to be equally distributed.

All of the distributions had a negative impact on the fractional energy savings. If none of them were applied, the fractional energy savings increased by 0.9%-points (simulation e) compared to the profile described in section 2. According to the results shown in fig. 15, taking into account the holiday season had the highest influence (0.4%-points), followed by the yearly sine-distribution (0.2%-points), and the daily distribution (0.2%-points), respectively. Almost no difference was found neglecting the distribution for different weekdays.

The load profile was further simplified, defining only one category of draw-offs with flow rates distributed around a mean value by a gaussian-function (fig. 16b). In fig. 16a the values of f_{save} are shown for different flow rates and draw-off durations. They turn out to be in the same range as the ones for the conventional load patterns. The values do depend on the DHW-flow rates and on the draw-off durations as well, however not uniformly. If the flow regulation device is applied, f_{save} varies by more than 1.3 %-points.

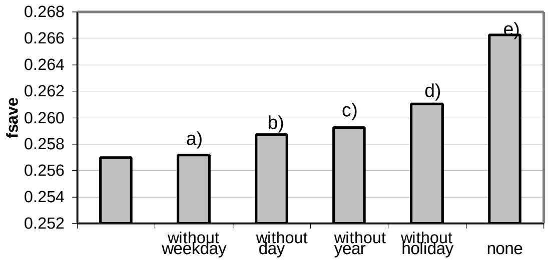
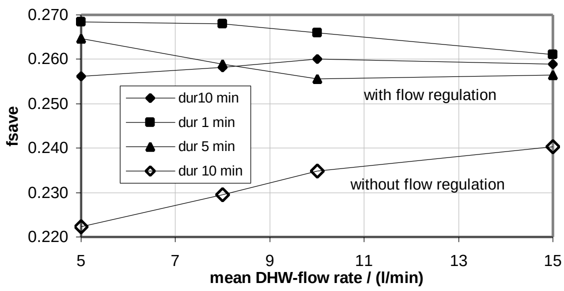


Fig. 15: Fractional energy savings calculated with realistic DHW-load profiles. In simulations a – d only one distribution was neglected (weekday, day,..), in e none of the distributions was taken into account.



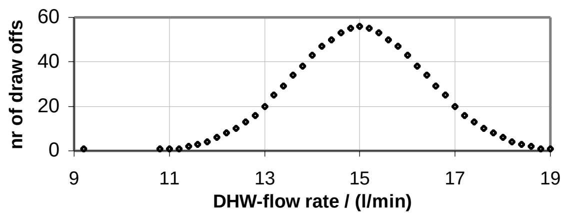


Fig. 16a: Fractional energy saving calculated for different load profiles, with one category of draw-offs with a given duration (1, 5, or 10 min).

Fig. 16b: The flow rates were distributed around a mean value (15 l/min) with a gaussian function; s = 2 (see eq. 1).

6. CONCLUSIONS

A realistic DHW-load profile with a one minute time step was generated with statistical means. Although the differences between the values of f_{save} for the realistic and the conventional DHW-profile are rather small for the investigated system, some severe influences were found depending on the DHW-flow rate and on the draw-off time of the day if the design of the discharge unit is changed.

1.) A comparison between a conventionally used and a more realistic load profile showed that the differences in the fractional energy savings for the investigated system were less than 0.8%-pt. During the summer less solar energy is delivered applying the realistic DHW-profile.

2.) If the discharge unit is not designed properly, f_{save} varies by 2.2 %-points, depending on the DHW-flow rate, applying three daily draw-offs similar to the DHW-load pattern proposal by prEN 12977. For a system with a proper flow regulation device, no marked dependence on the flow rate was found.

4.) Variing the draw-off time of the day for simplified DHW-load patterns with one or three draw-offs per day, the highest values of f_{save} were found for draw-offs in the early afternoon. The differences of f_{save} for morning and noon profiles differ between 0.5%-points and 1.1%-points. For morning draw-offs more heat losses occur during the night, more solar gains are delivered into the store due to lower temperatures in the store during the daytime than for the evening draw-off.

5.) Variations of the realistic DHW-profile concerning distributions of the DHW-consumption showed, that the highest influence was obtained by taking into account a holiday period during the summer, followed by a yearly distribution of the DHW-consumption described by a sine-function, and by the daily distribution. The influence of taking into account the different probabilities at different weekdays could be neglected. If the flow regulation device and only one category is applied, f_{save} varied by more than 1.3 %-points, depending on the mean DHW-flow rate and on the draw-off duration.

It can be concluded that the influence of the DHW-load profile may not be disregarded, for a comparison as well as for optimization of combistores. This is especially true if the durations and flow rates of the DHW draw-offs have a severe influence on the temperature stratification in the storage tank. Therefore, it can be expected that the presented profile also has an impact on SDHW-systems. An optimization for only one flow rate and a small number of draw-offs may lead to non optimal solutions for realistic reference conditions.

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NOMENCLATURE

c_p	specific heat capacity, J/gK
C	heat capacity, J/K
d	diameter, m
f_{save}	fractional energy savings
g	gravity constant, m/s^2
h	storage height, m
$\dot{M}$	mass flow rate, kg/s
P	power (of burner and el. pump) /W
$prob$	probability
Q	energy (heat) / kWh
T	temperature, K
UA	heat transfer coefficient*area, W/K
$\dot{V}$	volume flow rate, m³/s
Greek	
a	transfer coefficient, 1/K
r	density, kg/m^3
j	angle of the valve, °
n	velocity, m/s
t	time constant of the expansible material, s
V	pressure drop coefficient
h	efficiency
Indices	
aux	auxiliary energy of the solar system
b	begin of the regulator temperature interval of the valve
$conv$	conventional sytem
DHW	domestic hot water (system)
dom	domestic water
$Hx1$	heat exchanger, primary cycle
i	nr. of node, describing temperature layer
l	heat losses
m	max. nr. of nodes in the vertical tube
n	max. nr. of nodes in the heat exchanger
out	outlet (temperature)
$store$	storage water in the heat exchanger nodes
SH	space heating water (system)

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