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Optimization of pellet–solar combisystems for buildings using a DoE approach

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Abstract

A DoE investigation using factorial and response-surface designs to analyze a solar–pellet combisystem in Sweden to optimize the system based on energy cost was performed. The same approach was also used to examine collector output energy. Investigated parameters were: building heating load, hot tap water consumption, collector flow rate, tank size, collector area, and estimated wood pellet cost. Cost- and performance-based regression equations were derived for optimal collector area and tank size for a range of buildings, providing tools for individual building solar combisystem sizing and optimization. Tank set-point temperature and estimated future pellet price were subjected to sensitivity analysis, and the influence of solar collector parameters and tank insulation level on profitability was investigated. The results indicate that a larger than expected collector area would be profitable due to inflation and the future price of pellets, and that tank size is less important to system profitability. However, tank insulation and set-point temperature were highly significant.

Keywords: TRYNSYS, Solar, Combisystem, DoE, Cost, optimization

1. Introduction

The solar collector area for a building in Sweden is typically optimized by calculating the tap water load in summertime and translating that into the required area. Here, a multi-variable analysis of solar collector optimization based on energy cost using a design of experiments (DoE) approach is performed. The system is a solar–pellet combisystem for multiple buildings. Ghiaus et al (2012) in a recent study performed an investigation of what statistical/operational methods provided the best results when optimizing solar combisystems, finding that DoE produced the best results.

Sizing a solar heating system based on summertime tap water load is a way of avoiding over-dimensioning the collectors. This approach seems logical, as solar collectors are expensive relative to their heating output, and with this approach their energy output is never dormant. As Lund, P.D., (2005) notes, an oversized area may negatively affect the initial investment cost and may also entail the use of protection measures to avoid wasteful solar energy dumping. There are many collector optimizations based on solar collector energy output, for example, Gaddhar et al. (96) for Beirut and Atamaca (2003) for Turkey, and detailed mathematical models by Ardheali et al. (2007) and Joudi et al. (2002, 2003) are available for the Iranian and Iraqi climates, respectively.

The energy cost-based optimizations presented in the literature can be based on life-cycle savings, payback period, or a fractional savings indicator; Bales (2002) But these are much less frequent than collector output optimizations. Two investigations have presented collector output optimizations. Ghiaus et al. (2012) who used DoE to optimize cost as a function of solar collector area and tank size, found that surprisingly large collector areas increased profitability, and that tank size exerted little influence. Calise et al. (2010) applied DoE to a system in which collector slope, pump flows, set-point temperatures, and tank volume were optimized on collector output to a fixed collector area; the cost of the resulting system was then computed. An important cost optimization cited by Duffie and Beckman (2006) was performed by Tybout and Löf (1973). It considers factors not handled here, such as collector tilt and number of glazings on top of the collector. Their results for varying the tank size were similar to those of Ghiaus et al. (2012), indicating that massively increasing the tank size for a fixed collector area has a very small effect on system cost. Still, they recommended a tank size of 50–75 L m^{-2} for flat plate solar collectors.

Few cost studies have been performed, likely due to the uncertainties involved in estimating system cost. The cost of a solar collector–wood pellet combisystem can be calculated in numerous ways depending on what is included in the calculations. Uncertain factors are variations in government subsidies, taxes, loan costs, and the estimated future price of wood pellets, increase the potential error. Estimates of the future increase in the electricity price range from 0.7% (Elforsk 2012) to 5% (spot prognosis 2012) annually. Duffie and Beckman (2006) mention that small changes in economic assumptions greatly affect profitability, which of course is a major problem. Equipment costs are falling as production processes improve, and subsidies are changed frequently. Despite the uncertainties affecting the system's total lifetime cost, investigating cost dependency is still relevant, especially if the uncertainties can be quantified. The general objectives of the present paper are as follows:

1. to determine the optimal solar collector area and tank size for several types of buildings based on life cycle cost;
2. to quantify the effect of different estimated future pellet prices on the profitability of a solar-pellets heating system; and
3. to investigate what parameters and interactions significantly affect life cycle cost and energy output.

2. Method

2.1. The system

The investigated system consists of a building equipped with solar collectors, a tank, and a pellet burner. The system was modeled using TRNSYS, and a thorough explanation and experimental validation of the model is presented by Persson et al. (accepted for 2012). The radiators draw water into the building from two locations in the tank, through a bivalent shunt. Another bivalent shunt is used in the same manner for the hot tap water. A schematic of the examined system is shown in Fig. 1. The tank model consists of a cylindrical tank of varying size divided into five nodes to model temperature layers. The tank heat loss coefficient is 5 W m^{-2} K^{-1} at the top of the tank, and 3 W m^{-2} K^{-1} on the sides and bottom.

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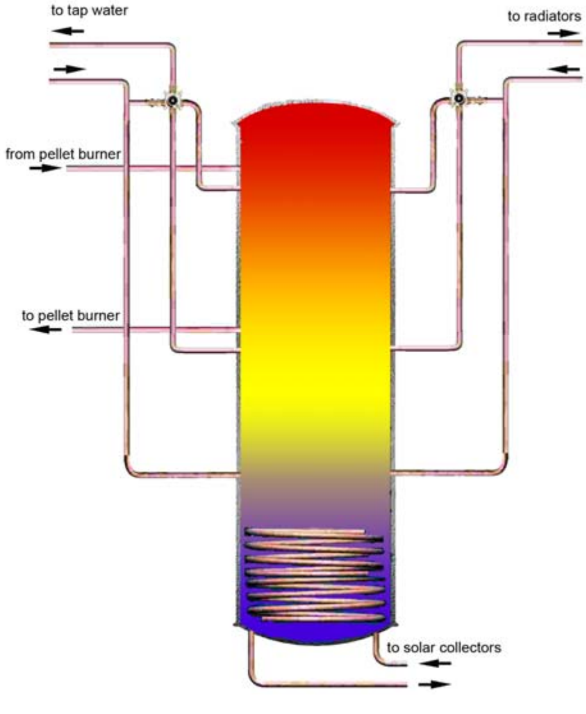

Fig. 1. Schematic of the examined system.

The collector properties used in the simulations are shown in Table 1. The same collector was used for all investigations except in section 3.6, in which the collector parameters were varied. The weather data consisted of meteonorm files from Stockholm (Meteonorm 2012).

Table 1
Solar collector parameters

	a_1 [W m^{-2} K^{-2}]	a_2 [W m^{-2} K^{-2}]	η_0
Collector parameters	1.23	0.0082	0.755

2.2. *Tank set-point temperature: control strategy*

The set-point temperature of the tank refers to the temperature at the top of the tank at which the pellet burner is shut off. The collector provides heat to the tank as long as the tank water is at least 4°C lower than the return flow in the collector, or as long as the temperature in the tank remains below 90°C.

2.3. *Cost calculations*

The cost of each system is the sum of the operation, maintenance, and capital costs. In this study, the total system cost was calculated using the same approximate tank and pellet burner costs as used in Task 26 (2003), as the prices had changed little since then, as seen in Table 2. The collector cost was set to € 400 m^{-2}, as shown in Table 2, and taxes and subsidies were not included in the calculations. The solar–pellet combisystem was expected to remain functional for at least 25 years (Persson, T 2008); the pellet burner was expected to be changed once in this period. Estimates of the future increase in the electricity price range from 0.7% (Elforsk 2012) to 5% (spot prognosis 2012) annually. Persson.T (2004) argues that an increasing wood pellet price cite the increasing use of, and therefore lack of, biomass. Arguments for a less dramatic increase in the wood pellet price claim that the pellet price generally tracks the electricity price, which might remain low in Sweden for a long time (Elforsk 2012). The present authors feel unqualified to decide which scenario is the most probable, so energy cost is first presented as a two-level problem in the initial screening, and then as a five-level parameter in the central composite design. The used pellet price is the average price from today to 25 years in the future, assuming that the price will increase by a certain percentage each year; the resulting prices are shown in Table 3. The maintenance cost for the solar collector was estimated by Carlsson et al (submitted) at € .015 kWh^{-1} of solar heat collected under Swedish conditions. The yearly inflation rate was assumed to be 2.5%.

Table 2
Initial cost estimate

	Min. value	Max. value	Unit
Solar collector	400		€ m^{-2}
Pellet furnace + storage	9000		€
Extra pellet burner	2000		€
Storage tank	2300	4000	€

Table 3
Assumed price of wood pellets

Estimate	€ kWh^{-1}
Today's pellet price	0.0826
0.7% annual rise [12]	0.0899
2.5% annual rise	0.113
5.0% annual rise [13]	0.158

The capital cost includes: the initial investment cost of a pellet–solar heating system comprising a tank, collectors, piping to and from the collectors, a pellet stove with a burner, pellet storage, and installation costs. The radiators and their piping were assumed to be already present. The capital cost as described by Duffie (2003) also includes the time value of money, described as the cost of borrowing or the loss of positive interest accrued if the money used for the investment were held in a bank; this interest rate is set to 5%. The total cost is called present value and can be described as presented in eq. 1

$$C = r \cdot K + D \qquad (1)$$

where *K* is the initial cost, *D* is depreciation (described by eq. 2), and *r* is the real nominal rate (described by eq. 3) and n is the number of years.

$$D = \frac{r \cdot K}{(1+r)^n - 1} \qquad (2)$$

r = interest – inflation = 5% - 2.5% = 2.5% (3)

2.4. DoE: parametric runs

This study used a statistical method known as design of experiments, described among others by Walpoe et al. (1993). DoE is commonly used for systematically investigating effects and interactions, i.e. when the response to one factor depends on the setting of another, in systems with many variables. Two DoE methods were used. A half-factorial design was used for the initial screening to identify the relative strength of each variable and of each variable–variable interaction. This design has the advantage of requiring fewer runs and is good at identifying the variables that can be excluded from further investigation, but has the disadvantage of being unable to identify any non-linear in variable behavior. Consequently, a more complex central composite design was also used to investigate possible non-linear and provide a more accurate regression.

2.5. Initial screening

To determine the variables' impact on the response variables, an initial screening was conducted using a two-level six-variable half-factorial design with 16 runs. An iterative process was made where factors and factor–factor interactions with very low impacts were removed, and the factorial analysis was rerun with fewer factors/interactions. The factors and their maximum and minimum values are presented in Table 4; the responses are shown in Table 5.

Table 4
Factorial analysis variables

	Min. value	Max. value	Unit
Tank size	500	5000	l
Solar collector aperture area	10	40	m^2
Solar collector max. flow	0.1	2.5	$l\ min^{-1}\ m^{-2}$
House load	20,000	100,000	$kWh\ year^{-1}$
Tap water load	60	600	$l\ day^{-1}$
Tank set-point temperature	65	80	°C

Table 5
Output variables

	Unit
Solar collector energy output	$kWh\ m^{-2}\ year^{-1}$
Energy cost	€ $kWh^{-1} year^{-1}$

Fig. 2 presents the initial screening for energy cost and solar collector energy output. The left diagram of Fig. 2 presents a Pareto plot showing the effects of each variable and the interaction effects on solar collector energy output. The line in each pareto plot is the significance line, showing that it is less than 5% chance to find an effect where no effect exist. The middle diagram of the image presents a Pareto plot showing the effects of each variable and the interaction effects on total energy cost with a low pellet price, while the right diagram presents a Pareto plot based on a higher pellet price. An interesting observation is that the tank size–tank temperature interaction greatly affects energy cost but not collector energy output. The tank size–tank temperature interaction determines the heat loss from the tank. As this was an initial screening, only two conclusions were drawn from Fig. 2. First, the maximum flow in the solar collector insignificantly affects both total energy cost and collector energy output, and can be excluded from further investigation. Second, the pellet price significantly interacts with the other parameters, as can be seen from the change in the order of the parameters of the two price levels shown in Fig. 2, indicated by darker and lighter shades of grey; price is therefore included as a parameter in further investigations.

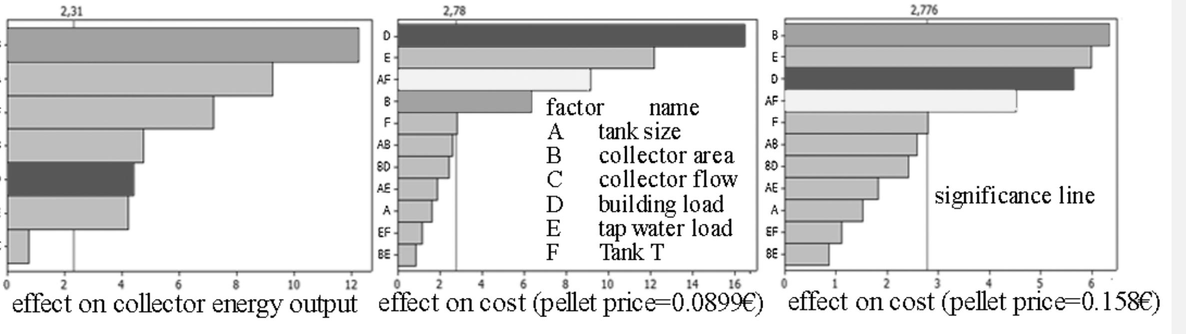

Fig. 2. Pareto plots from the initial screening. Left: collector energy output; middle: energy cost based on a low pellet price estimate; right: energy cost based on a high average pellet price estimate.

A very important observation from Fig. 2 is that tank size (parameter A) has very little impact on energy cost, but a large impact on collector output energy. This low impact means that, as Duffie and Beckman (2006) also note, tank size is not an important parameter in energy cost calculations. It is included in the next step in the calculation however, due to the significant interaction effect between tank size and tank temperature.

2.6. New parametric runs: the central composite design

When insignificant variables had been identified and removed, a central composite response-surface design with 90 runs was implemented. In the response-surface design, pellet price was added as a parameter. The factors included in the response-surface design, as well as their maximum and minimum values are presented in Table 6; Table 5 shows the output for both designs.

Table 6
Response-surface variables

	Min.				Max.	Unit
Tank size	500	500	3000	5000	8000	l
Solar collector aperture area	0	5	22	40	64	m^2
House load	0	20,000	60,000	100,000	150,000	kWh $year^{-1}$
Tap water load	0	240	720	1200	1900	l day^{-1}
Tank set-point temperature	30	50	65	80	100	°C
Average pellet price	0	0.0899[1]	0.1129[1]	0.158[1]	0.238[1]	€ kWh^{-1}

[1] Average price over 25 years

3. Results

3.1. The regression equations

The central composite DoE design results consist of two regression equations for the two output variables, i.e. energy cost and solar collector output. Tables 7 and 8 present the regression equations for energy cost and solar collector energy output, respectively. These are equations of the second degree and consist of the coefficients of the linear, square, and interaction variables in the form:

$$y = C + c_1x_1 + c_2x_2 + \cdots + c_{11}x_1x_1 + c_{22}x_2x_2 + \cdots + c_{12}x_1x_2 + c_{13}x_1x_3 + \cdots \qquad \text{Eq. 4}$$

where y is the energy cost/collector output, c_n represents the coefficients listed in Tables 7 and 8, and x_n represents the factors listed in Tables 7 and 8.

Table 7
Regression constants for energy cost

Factor	Coefficient	Unit
Constant	0.126396	
TS = Tank size	–1.99533E-06	l
SA = Solar collector area	–0.00114061	m^2
B = Building load	–1.33768E-06	kWh $year^{-1}$
W = Tap water	–4.85405E-05	l day^{-1}
TC = Set-point temperature	–8.15673E-04	°C
PP = Estimated pellet price	0.609409	€ kWh^{-1}
TS*TS	4.04690E-10	
SA*SA	1.33593E-05	
B*B	1.09930E-11	
W*W	1.43242E-08	
TC*TC	5.21035E-06	
PP*PP	1.26148	
TS*SA	–1.39248E-07	
TS*B	–3.84266E-11	
TS*W	–1.26007E-09	
TS*TC	8.98279E-08	
TS*PP	5.47892E-06	
SA*B	5.00112E-09	
SA*W	1.03851E-08	
SA*TC	1.55349E-05	
SA*PP	–0.00757211	
B*W	5.21849E-10	
B*TC	–7.62649E-09	
B*PP	1.37750E-06	

W*TC	–8.85598E-08
W*PP	–4.83866E-05
TC*PP	0.0024344

Table 8
Regression constants for collector energy output

Factor	Coefficient	Unit
Constant	727.493	
TS = Tank size	0.0382579	l
SA = Solar collector area	–10.1006	m^2
B = Building load	0.00181777	kWh $year^{-1}$
W = Tap water	0.152871	l day^{-1}
TC = Set-point temperature	–2.30912	°C
TS*TS	–6.42473E-06	
SA*SA	–0.0304526	
B*B	–1.00982E-08	
W*W	–6.28868E-05	
TC*TC	–0.0181963	
TS*SA	0.00105704	
TS*B	–4.52691E-08	
TS*W	–3.37818E-07	
TS*TC	0.000103727	
SA*B	2.24877E-05	
SA*W	0.00214146	
SA*TC	0.00881250	
B*W	–2.63387E-07	
B*TC	–2.33464E-06	
W*TC	–5.88650E-04	

The energy cost and energy output models have R^2 values of 96% and 98%, respectively. For flexibility, the regression equations were inserted into MATLAB.

3.2. Optimizing tank size and collector area for one building

In Fig. 3, the equations from section 3.1 were used to optimize the solar collector area and tank size for a building. The building had a heating load of 30,000 kWh $year^{-1}$, a tap water consumption of 120 l day^{-1}, an estimated pellet price of € 0.11 kWh^{-1}, and a tank set-point temperature of 70°C.

One difficulty in optimizing solar collectors with respect to maximum energy output can be seen in the right diagram of Fig. 3. Maximum energy output per collector area is achieved with as small an area as possible, preferably 0. The left diagram of Fig. 3 shows the same optimization performed for energy cost. It indicates that an optimal solar collector area would be approximately 22 m^2, larger than a tap-water-optimized area of approximately 8 m^2, and considerably larger than an output-optimized area of 0 m^2. The optimum solar area stretches over a rather large range of areas, showing that there is an optimum, around 22m^2 as mentioned, but that the optimum is rather flat, accepting areas from 7m^2 to 39 m^2. This means that the increase in capital cost from an increase in solar area is close to the increased gain from the added m^2 of collectors. This in turn shows us that it is not the actual collector area that is the most important factor when installing a solar combisystem.

The sizing of the storage tank also differs depending on if the system is optimized based on energy cost or collector efficiency. In the right diagram of Fig. 3, the general rule of thumb of approximately 100 L m^{-2} of collector area is shown as a solid black line. This line seems to advise a smaller tank than the calculations suggest. The left diagram of Fig. 3 presents the energy cost optimization for the same building. The minimum energy cost has a very flat valley-like behavior. The tank size does not seem to have a great impact on energy cost: for a collector of 20 m^2, using a tank of 500 or 3500 L barely affects the energy cost. This tank size behavior may seem strange, but was previously observed by several authors, such as Duffie (2006), Ghiaus et al. (2012) and Calise et al. (2010).

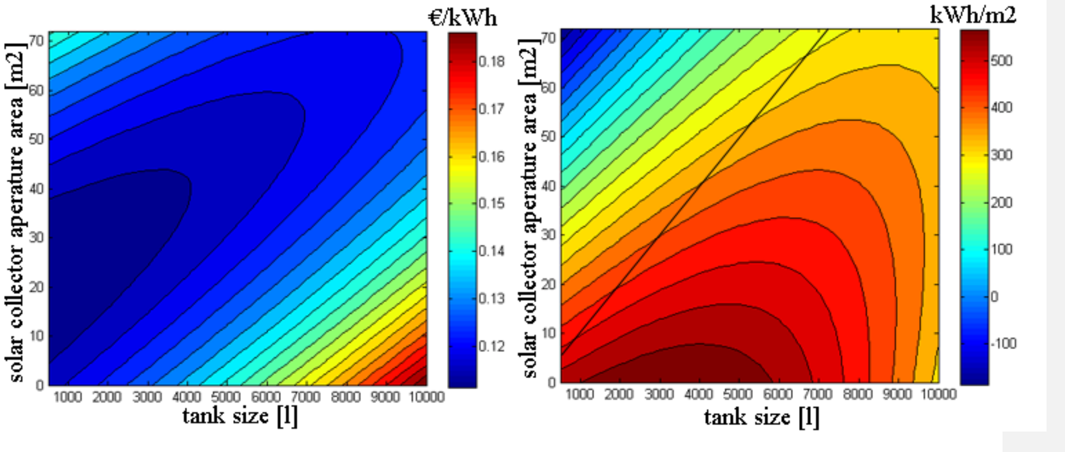

Fig. 3. Left: energy cost as a function of collector area and tank size; right: energy output as a function of collector area and tank size.

3.3. Optimizing tank size and collector area for several buildings

The left diagram of Fig. 3 shows the optimized collector area as a function of energy cost for one building. Fig. 4 shows the energy cost-optimated solar collector area and tank size for all buildings with a load within the range of 500–80,000 kWh $year^{-1}$ and a tap water consumption of 0–2000 L day^{-1}. The solar collector/tank size combination from Fig. 3 providing the lowest energy cost for the building was considered that building's optimal setting. This optimal collector area/tank size was then calculated for all combinations of tap water and building loads, as shown in Fig. 4. In Fig. 4, the pellet price was kept at € 0.11 kWh^{-1} and the tank set-point temperature at 70°C. Fig. 4 provides a quick way to determine the collector area and tank size for a building that draws tap water from the tank, and the pellet price is estimated conservatively based on a net increase of 2.5% annually. The results in Fig. 4 show that, as in Fig. 3, a fairly large collector area is preferred. The tank is smaller than would generally be recommended but, as was shown in Fig. 2, the tank size has little impact on total energy cost. Therefore, the tank sizes presented in Figs. 3–6 are not highly significant. The collector area has a much stronger impact, as also shown in Fig. 2. In Fig. 4 we see that the tap water load has a larger impact on optimal collector area than does the building load. The low impact of building heating load observed in Fig. 4 may be surprising, but has been demonstrated by others, for example Ghaius (2012), Bales (2002) and Persson (2004).

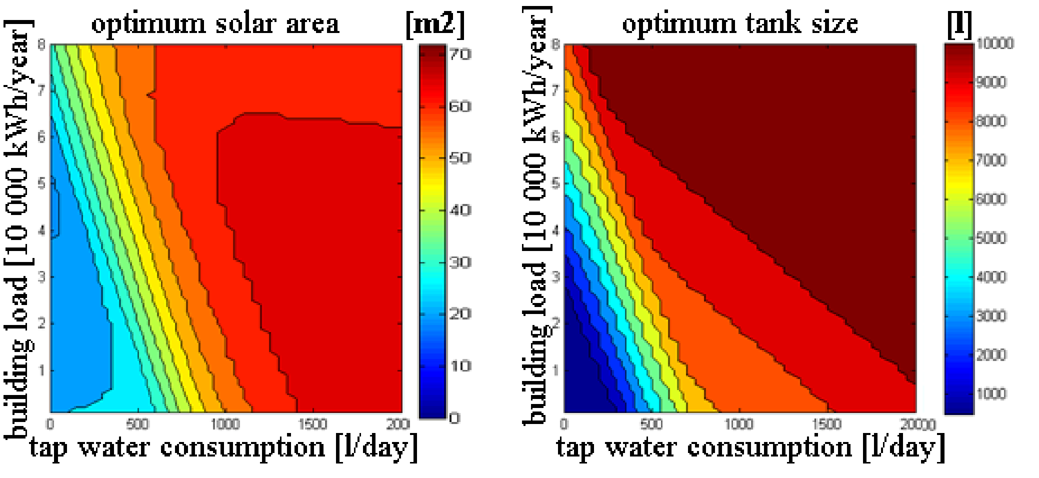

Fig. 4. Optimum for building load and tap water consumption. Left: Collector area Right: Tank size

Initially, we felt that the energy cost-optimized collector areas seemed unreasonably large, but other authors have obtained similar results when performing energy cost optimizations. For example, Ghaius et al. (2012) found that the recommended collector area for a building with a heating load of approximately 9000 kWh year^{-1} could be as large as 33 m^2. This result corresponds well to what we see in Fig. 4.

Fig 5 is similar to Fig 4 but shows the actual cost per kWh for a cost-optimized solar area system. The cost per kWh decrease with increasing load which is not surprising as an increased load generally means a larger building, and a larger building has less wall area as compared to inner volume, meaning less losses per required kWh. As we see in Fig 5, the cost per kWh decrease both for building load and tap water load, but more intensely for building load which is most likely due to this phenomenon. This investigation does not vary the insulation level of the house. It could be theorized that such a variation might have shown results where the tap water load has a larger impact than heating load for buildings with good insulation, and vice versa.

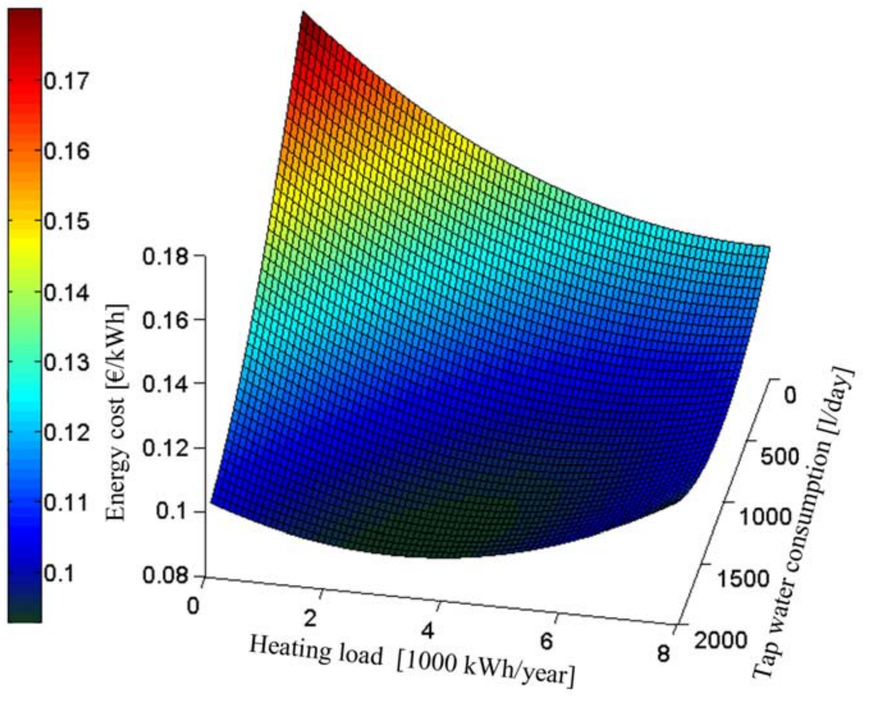

Fig 5. The energy cost in €/kWh for buildings with varying heating load and tap water consumption. The solar collector area for each building was determined by the cost-optimization in Fig 4.

3.4. Sensitivity analysis

The optimization shown in Fig. 4 does not include the effects of pellet price development or set-point temperature in the tank, both of which strongly affect system profitability. Fig. 6 shows the optimum solar collector area and tank size, as in Fig. 4, for three tank set-point temperatures. Fig. 7 shows the energy cost-optimated solar collector area and tank size for three probable scenarios of pellet price development.

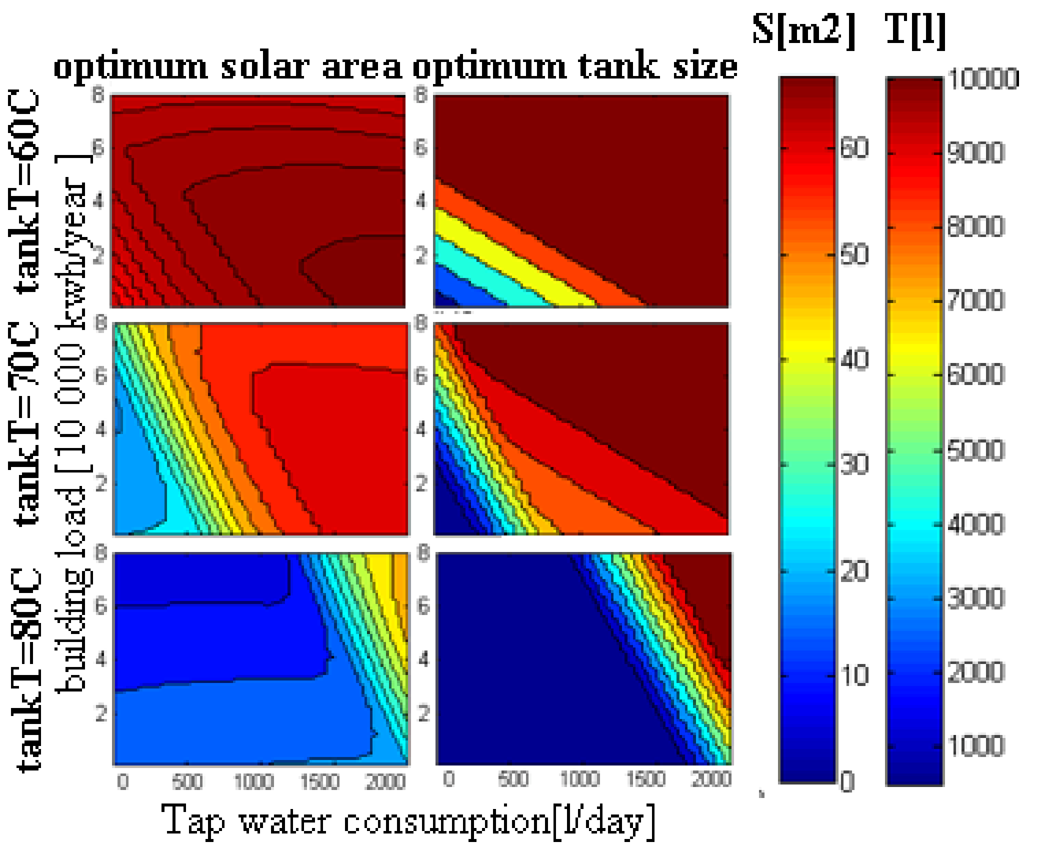

Fig. 6. Optimum configuration for building load and tap water consumption. Left: collector area; right: tank size (right-hand vertical scale: tank set-point temperature).

Fig. 6 shows the profitability optimization with three tank set-point temperatures, i.e. 60, 70, and 80°C. The large impact of set-point temperature can be observed. The upper section of Fig. 6 shows a system with a tank set-point temperature of 60°C. With this set-point temperature, energy cost-optimized solar collector areas will be as large as 50–70 m^2. At such low temperature, the heat losses from the tank are also less than with a higher temperature, which further increases savings. The middle section of Fig. 6 shows a system with a tank set-point temperature of 70°C, while the bottom section shows a tank set-point temperature of 80°C.

Much has been written about how to achieve a low tank temperature (e.g. Persson (2004), Andrén (2007) and Kovács (2010)). Some appropriate techniques for achieving this are correct connections between tap water and the solar loop, an external tank for tap water heating, and tank-in-tank systems.

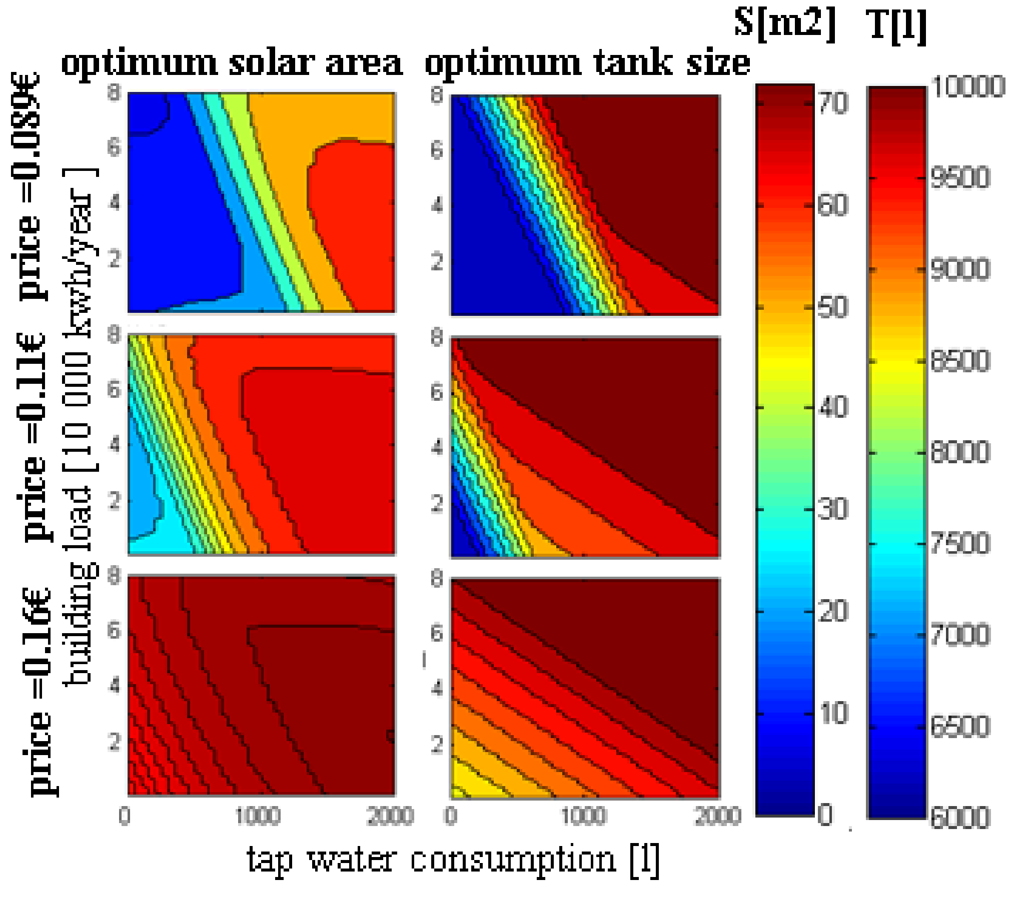

Fig. 7. Optimum for building load and tap water consumption. Left: collector area; right: tank size (right-hand vertical scale: estimated future pellet price).

Fig. 7 is similar to Fig. 6 but with a fixed tank set-point temperature of 70°C and three different estimated pellet prices. The top part of Fig. 7 shows a conservative estimate with a 0.7% annual increase in pellet price for the next 25 years, leading to an average price of € 0.089 kWh^{-1} over 25 years. The middle part of the image shows the profitability with an annual pellet price increase of 2.5% leading to an average price of € 0.11 kWh^{-1}, and the bottom part an annual increase of 5% leading to an average price of € 0.16 kW^{-1}. The price likely at least tracks the rate of inflation, i.e. approximately 2.5%, in a sense staying the same in real terms. In that case, fairly large collector areas will be profitable if the tank set-point temperature can be held below 70°C.

3.5. The profitability of a system with regards to pellet price

To further analyze the sensitivity of solar heating system profitability to estimated future pellet price, the effect on four different buildings is shown in Fig. 8.

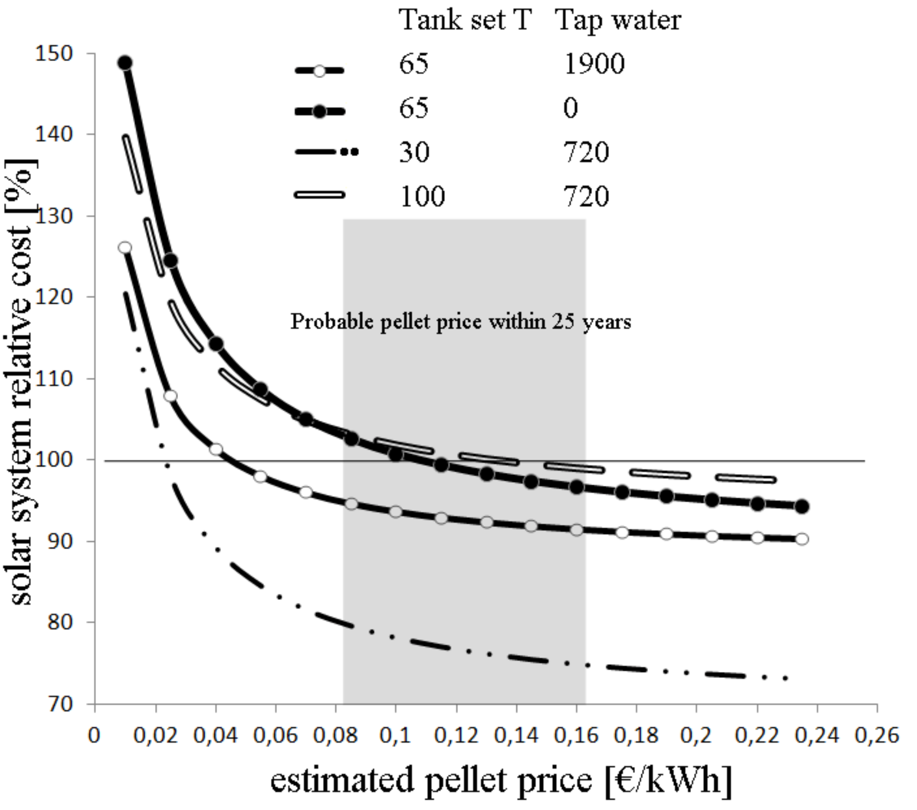

Fig. 8. Profitability of solar collector systems vs. pellet price.

Fig. 8 shows the relative energy cost of a solar heating system versus that of a solar-pellet combisystem in percent, as a function of future pellet price. The graph values on the *y*-axis are determined by dividing the energy cost of heating the building using only pellets by the energy cost of a heating system using both pellets and solar collectors. If the curve is below 100%, this means that the solar collectors are profitable. The four buildings each have a heating load of 20,000 kWh year^{-1}, 40 m^2 of solar collectors, and a tank size of 1000 L. The tank set-point temperature is 65°C. This is not an optimized system; it is created solely to demonstrate that even a large collector area can be profitable. The tank set-point temperature and tap water consumption vary as shown in the figure. The two solid curves with superimposed dots show the difference between a tap water consumption of 0 and 1900 L day^{-1}. The difference is fairly large: the larger water consumption curve crosses the profitability line at € 0.04 kWh^{-1}, whereas the building without water consumption needs a price of € 0.1 kWh^{-1} to be profitable. The profitability varies even more with tank set-point temperature, by € 0.1 kWh^{-1} between the two levels.

3.6. The impact of tank insulation level and solar collector parameters

To further investigate why the influence of tank set-point temperature is so strong, another sensitivity analysis was performed. The authors recognize two explanations for this strong influence: first, solar collectors are more efficient when working against a low inlet temperature and, second, tank heat losses increase with increasing tank temperature. The explanation could be a combination of both factors. If the increase in energy cost is due mainly to lower collector efficiency when working against a higher inlet temperature, it is a costly and difficult problem to solve. If the increase in energy cost is instead due mostly to tank losses, the tank and pipes could be insulated more thoroughly at a relatively low energy cost. To investigate the relationship a full-factorial analysis with three factors, i.e. collector parameters (supposing that with "better" parameters, the collector is less sensitive to increased inlet temperature), tank heat loss coefficient, and tank set-point temperature was performed. We are mainly looking for a strong interaction between tank set-point temperature and either the collector parameters or tank heat loss coefficient. The varied factors and the original values used in the above simulations are shown in Tables 9 and 10.

Table 9
Collector parameters

	a_1 [W m^{-2} K]	a_2 [W m^{-2} K^{-2}]	η_0
Collector parameters, original	1.23	0.0082	0.755
Collector parameters, low performance	2.2	0.01	0.79
Collector parameters, high performance	1	0.0052	0.7

Table 10
Tank insulation parameters

	Heat loss coefficient [W m^{-2} K]
Collector parameters, original	3
Collector parameters, low setting	1
Collector parameters, high setting	5

Fig. 9 shows the Pareto plot describing the effects of collector parameters and tank insulation on energy cost.

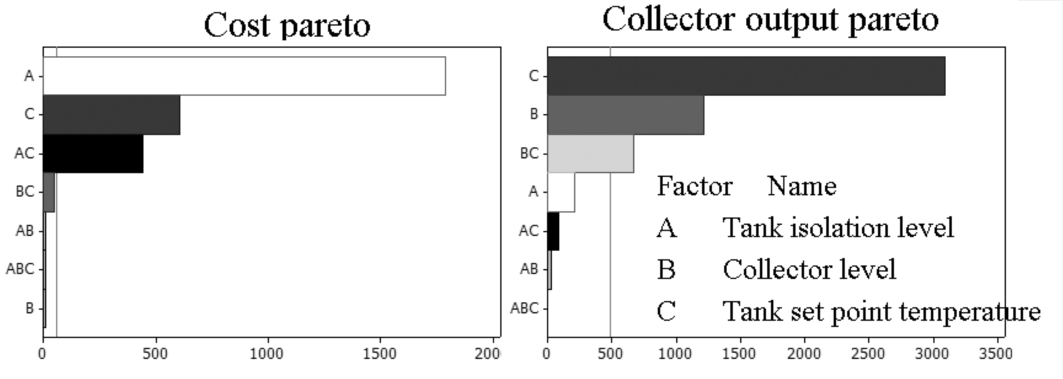

Fig. 9. Cost-dependence variables affected by tank set-point temperature.

In the right diagram of Fig. 9 (parameter "C") we see that for collector output, the set-point temperature is a very important factor, as expected. The next two influences, i.e. the collector parameters (parameter "B") and the interaction between collector parameters and tank set-point temperature, indicate that for collector output, the collector parameters are far more important than are tank properties. In contrast, when observing the left diagram of the figure, which shows the influence on cost, another scenario can be observed. From a cost perspective, whether or not we have a good collector (parameter "B") is not even significant. The most important factor is tank insulation, and the interaction between insulation and set-point temperature is also significant. This means that relatively simple steps can be taken to increase the profitability of a solar heating system, by carefully insulating the tank and piping. The interaction between tank insulation level and tank set-point temperature is expected, as a warmer body transfers more heat.

4. Conclusions

In view of factors such as inflation, increasing pellet prices, and long collector lifetime, solar collectors are profitable for a large range of buildings. Even conservative estimates of pellet price indicate profits for a system using both solar collectors and pellets as opposed to one using only pellets. Results indicate that surprisingly large collector areas can be profitable. Initially, we felt that the cost-optimized collector areas seemed unreasonably large, but other authors have obtained similar results when performing energy cost optimizations. For example, Ghaius et al. (2012) found that a recommended collector area for a building with a heating load of approximately 9000 kWh $year^{-1}$ could be as large as 33 m^2. This result corresponds well to what we see here. The optimum for collector area is rather flat, indicating that the conditions in which the solar system is installed is more important than a change in collector area. Another aspect not taken into account here is the possibility of an increase in building value, which would further increase profitability.

Generally, it is considered that a building with a low heating load and large tap water consumption, possibly a passive house or a well-insulated rental property, is best suited for a solar collector system. However, a collector system could easily be adapted to buildings with high heating demand and very low tap water consumption, such as office buildings, churches, or commercial buildings, as low tap water consumption allows for low temperature in the tank. With low tap water consumption, especially if using in-floor heating, the required tap water could be heated in a secondary heater, allowing the tank to stay at a very low temperature. As seen in both Figs. 6 and 8, a low tank temperature is even more important to system profitability than is tap water consumption. From a profitability perspective, collector energy output is not an important factor; more important is a well-insulated tank and pipes.

5. Recommendations for a cost-optimized system

The regression equation presented in Table 7 can be used for buildings within the limits of the maximum and minimum values presented in Table 6. Extrapolation beyond these limits is not recommended. If the reader wishes to use these equations to find a suitable solar collector area for a specific building, the energy cost-based equation is recommended. As the tank size has a low impact on cost, as shown in Fig. 2, choosing a reasonably large tank is recommended, for example, 100 L per expected m^2 of collector area, and inserting this value together with the building properties to find the optimum solar collector size. General recommendations to minimize cost are as follows:

1. insulate the tank thoroughly;
2. insulate the pipes thoroughly;
3. do not spend money on “top-of-the-line” collectors;
4. keep the tank temperature as low as possible; and
5. install a large collector area, as it will be profitable in view of inflation and increasing pellet prices.

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