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► **To cite this version:**

Gilles Fraisse, Yue Bai, Nolwenn Le Pierrès, Thomas Letz. Comparative study of various optimization criteria for SDHWS and a suggestion for a new global evaluation. *Solar Energy*, 2009, 83, pp.232-245. hal-00452757

HAL Id: hal-00452757

<https://hal.science/hal-00452757>

Submitted on 20 Nov 2018

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Comparative study of various optimization criteria for SDHWS and a suggestion for a new global evaluation

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Abstract:

This study compares various optimization criteria for a solar domestic hot water system (SDHWS). First of all, we present the various parameters used to evaluate a SDHWS. We consider the energetic, exergetic, environmental (CO₂ emissions) and financial (life cycle cost) analysis. Various optimization criteria of a standard solar hot water system are then proposed. The optimized solutions are compared with a standard hot water system. The most suitable criteria take into account both energetic (therefore environmental) and financial evaluations. The most powerful solutions tend to increase the collector area – increasing the solar fraction during the mid-season – and reduce the tank volume, thereby decreasing the thermal losses and financial cost.

Some of the usual evaluation criteria for SDHWS cannot be used as optimization criteria because they do not consider the auxiliary heater, resulting in inaccurate indications of the system's performance. Therefore, it seemed important to propose a new evaluation method which integrates the life cycle savings, primary energy savings and CO₂ emission savings with regard to a referenced solution based on a radar diagram of these three fractions. This mode of representation is particularly useful when various auxiliary heaters are compared.

Keywords: Optimization, SDHWS, simulation, global evaluation, mixed criteria

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1. INTRODUCTION

In addition to being a clean energy, solar energy has the advantage of being an energy source that is available throughout the globe, with no losses attributable to transport. On the other hand, its highly variable input requires storage systems auxiliary heaters and specific control systems. Optimally combining solar and conventional systems for the most advantageous control, sizing, etc. is essential to obtaining high efficiency.

Although there is an international standard defining the solar energy vocabulary (ISO, 1999), the performance parameters used to evaluate SDHWSs are numerous and it is never indicated clearly which value is the most relevant to evaluate or optimize a solar heating system: collector productivity, the solar fraction, efficiency, the fraction savings considering energetic, exergetic, environmental or economic criteria? The energy and economic criteria are most often used to optimize solar heating systems.

The economic criterion is often taken as the life cycle cost (LCC): it gives the financial cost of a domestic hot water systems over the life cycle (approximately 20 years) All the annual costs and savings are converted into present worth at a given interest rate and discount rate (Duffie and Beckman, 1991). Various types of SDHWS were thus optimized: thermosiphon systems (Lima et al., 2006) (Salazar et al., Web), forced-circulation systems (Kalogirou, 2004), direct-coupled photovoltaic and pump systems (Cardinale et al., 2003), and even a solar heating system combined with a wind power plant (Bakos and Tsagas, 2003).

The solar fraction (ISO, 1999) is widely used for both solar domestic hot water systems and combisystems. Numerous recent studies used this parameter as a reference: (Trillat et al., 2006; Badescu et al., 2006; Chow et al., 2006; Jordan and Furbo, 2005; Lund, 2005).

From an exergetic point of view, numerous studies have been conducted to optimize components (collector, storage tank) or the overall system (Singh et al., 2000; Torres-Reyes and Gortari, 2001; Torres-Reyes et al., 2003; Xiaowu and Ben, 2005; Gunerhan and Hepbasli, 2007; Fernandez-Seara et al., 2007; Zmeureanu and Wu, 2007; Hepbasli, 2007). Such systems generally have low exergetical efficiency because of the energy quality degradation of the incident solar irradiation incident on the collector (stemming from a solar source with a temperature greater than 5800 K) towards a quantity of heat close to the ambient temperature. Another definition can be used by taking into account the Carnot coefficient at the collector's temperature instead of the sun's temperature (Le Pierrès, 2005).

The objective of energy optimization is generally to minimize a function including energy consumption, solar production and a penalty when the water tap temperature is lower than the set-point (Prud'homme and Gillet, 2001):

$$J = \int_{time} [(P_{elec} + P_{pump} - P_{sol}) + \alpha \cdot (T_{s1} - T_{set})^2] dt \quad (1)$$

with P_{elec} the electrical consumption of the auxiliary heaters [W]; P_{sol} the solar energy collected [W], P_{pump} the power required by the pump to drive the fluid in the collector loop [W]; T_{s1} the temperature in the upper part of the storage tank [°C], T_{set} the set-point temperature [°C], α is a trade-off factor.

Mixed criteria are also used as criteria for optimization. For example, the ratio of the additional investment cost by the primary energy savings (€/kWh-ep) can be estimated and compared to a reference system. In the (Bales, 2002) study, the author compared the performance of a generic combisystem (space heating store with DHW load side heat exchanger and an external auxiliary), using several optimization criteria: the combisystem criterion and the fraction saving indicator, which includes the penalty function of the solar combisystem in the fractional energy savings. Up to ten parameters were optimized: e.g., the auxiliary heated tank volume, the thermostat setting for the auxiliary heated area, the position and size of the DHW heat exchangers, the insulation thickness and the collector area. Another study was based on the annuity of the overall investment (20 years of operation) over the annual solar heat delivered to the tank (Krause et al., 2002). Compared with the initial system (the estimated solar heat cost of this system is 9.7 c€/kWh), the best configuration reduced the ratio (18%), because it increased solar energy use and reduced the initial investment. One of the most widely used numerical tools to simulate solar heating systems is the TRNSYS software (Klein et al., 1996). As regards optimization, various software packages have been developed such as Optilib (Gabriele and Ragsdell, 1984) and Genopt (Wetter, 2004). Most optimization algorithms are adapted to the SDHWs: genetic algorithms, Hooke-Jeeves algorithms, etc. (Krause et al., 2002; Wetter and Wright, 2003). This study provides the various quantities necessary to evaluate a system considering energetic, exergetic, environmental and economic criteria. We considered a conventional installation (without a solar heating system) and a standard solar installation, and compared the optimized solar installations based on energetic, environmental, economic and mixed criteria. The optimization was carried out by combining TRNSYS and GenOpt simulation program. The TrnOpt component of the TESS library (www.tess-inc.com) was the interface between both software packages. The optimized parameters were the collector area, the tank volume and the flow rate in the collector loop. Finally, a global approach to evaluation based on the radar diagram of three kinds of savings (primary energy, CO₂ emissions and financial cost) will be proposed.

2. The evaluation criteria

The energetic and thermal quantities for a conventional domestic hot water system (without a solar heating system) and a standard SDHW with an integrated auxiliary heater (electric or heat exchanger) will be described first. On the basis of these values, the evaluation criteria of SDHWs will be presented.

2.1. Description of a conventional installation

Fig. 1. shows the diagram of a conventional installation with an integrated auxiliary heater. The net energy demand for the tank set-point temperature $Tset_1$ is $Qnet_{conv}$. The tank thermal losses are Ql_{conv} . The energy supplied to the cold water between the inlet and outlet of the tank is Qd_{conv} . The tank energy balance is:

$$Qnet_{conv} = Ql_{conv} + Qd_{conv} \quad (\text{kWh}) \quad (2)$$

The final energy Qf_{conv} , which is the energy as the consumer receives it, is obtained from $Qnet_{conv}$ with the transformation efficiency $\eta f_{net_{conv}}$. Also, the primary energy Qp_{conv} is obtained from Qf_{conv} with $\eta p_{f_{conv}}$.

$$Qf_{conv} = Qnet_{conv} / \eta f_{net_{conv}} \quad (\text{kWh}) \quad (3)$$

$$Qp_{conv} = Qf_{conv} / \eta p_{f_{conv}} \quad (\text{kWh}) \quad (4)$$

The coefficient of performance of the conventional installation is:

$$COP_{conv} = Qd_{conv} / Qf_{conv} \quad (5)$$

To take into account periods when the water tap temperature Thw is lower than the set-point temperature $Tset_1$ (typically 55°C), penalty energy Q_1 needed to heat the water from Thw to $Tset_1$ is considered. The temperature Thw can be less than $Tset_1$ because of the off-peak hour and peak hour rates. The peak hour period forbids electrical water heating. We note $Qnet_{pen-conv}$ the expression of $Qnet_{conv}$ integrating the penalties Q_1 and Q_2 .

$$Q_1 = \max\left(0, \Delta t \cdot m_3 \cdot Cp \cdot (Tset_1 - Thw)\right) \quad (\text{kWh}) \quad (6)$$

With m_3 the water tap mass flow rate [kg/s]; Δt the time step [s]; Cp specific heat [J/kgK]

In addition, we added an equation that can penalize the installation when the water tap temperature Thw is lower than the set-point $Tset_2$ ($Tset_2 \leq Tset_1$):

$$Q_2 = \max\left(0, \Delta t \cdot m_3 \cdot Cp \cdot (Tset_2 - Thw)^X\right) \quad (\text{kWh}) \quad (7)$$

The temperature $Tset_2$ corresponds to the temperature limit below which the discomfort is penalized. The penalty level is expressed with the parameter X , representing the degree of discomfort. A value $X=4$ means almost forbidding the periods when $Thw \leq Tset_2$, whereas a value $X=2$ is much less penalizing. In that case, we accept some periods of discomfort as long as they are rare and it reduces the installation size.

Similarly, as in the study on solar combisystems (Weiss, 2003), we defined the heat demand penalty $Qd_{pen-conv}$, which integrates both quantities Q_1 and Q_2 . It compares several installations with the same loads and does not reach unacceptable solutions:

$$Qd_{pen-conv} = \Delta t \cdot \dot{m}_3 \cdot Cp \cdot \left\{ \max(0, (Tset_1 - Thw)) + [\max(0, (Tset_2 - Thw))]^x \right\} \quad (\text{kWh}) \quad (8)$$

The final energy $Qf_{pen-conv}$ was obtained from $Qnet_{pen-conv}$ (which is the sum of $Qnet_{conv}$ and $Qd_{pen-conv}$) by integrating the efficiency $\eta f-net_{conv}$. Also, the primary energy $Qp_{pen-conv}$ was obtained from $Qf_{pen-conv}$ with $\eta p-f_{conv}$.

$$Qf_{pen-conv} = Qnet_{pen-conv} / \eta f-net_{conv} \quad (\text{kWh}) \quad (9)$$

$$Qp_{pen-conv} = Qf_{pen-conv} / \eta p-f_{conv} \quad (\text{kWh}) \quad (10)$$

2.2. Description of the solar installation with an integrated auxiliary heater (Duffie and Beckman, 1991 ; Peuser et al., 2005)

The diagram of the solar installation is shown in Fig. 2. Since the outlet tank temperature can be greater than $Tset_1$, mixing with cold water (Tcw) is necessary, not to exceed $Tset_1$. The energy demand for the set-point $Tset_1$ is $Qnet_{aux}$. As previously, the heat demand penalty Qd_{pen} (same definition as equation (8)) is added to $Qnet_{aux}$. The tank's heat losses are QL . The energy supplied to the cold water between the inlet and outlet of the tank is QL .

The final energy Qf_{aux} (respectively $Qf_{pen-aux}$) is obtained from $Qnet_{aux}$ (respectively $Qnet_{pen-aux}$ which is the sum of $Qnet_{aux}$ and Qd_{pen}) by using the efficiency $\eta f-net_{aux}$. The additional electric consumption of the solar system (pump and controller) should be integrated into Qf_{aux} . Also, the primary energy Qp_{aux} (respectively $Qp_{pen-aux}$) is obtained from Qf_{aux} (respectively $Qf_{pen-aux}$) with $\eta p-f_{aux}$.

The incident solar energy on the collector (area: Ac) is H (kWh/m².year). The energy transmitted by the solar collector to the heat transfer fluid is $Qcol$. The heat losses from the collector loop are $QL,pipe$. The solar energy supplied by the collector loop to the tank is $Qsol$. The thermal balances are:

$$Qnet_{aux} + Qsol = QL + QL \quad (\text{kWh}) \quad (11)$$

$$Qd = QL \quad (\text{kWh}) \quad (12)$$

$$Qcol = QL,pipe + Qsol \quad (\text{kWh}) \quad (13)$$

We also defined the solar installation's coefficient of performance (COP):

$$COP = Qd / Qf_{aux} \quad (14)$$

2.3. The various evaluation criteria

2.3.1. Energetic quantities

The main quantities used to evaluate the energetic performance of SDHWs are shown as:

- Solar collector productivity:

$$Prod = Qcol / Ac \quad (\text{kWh/m}^2) \quad (15)$$

- Collector efficiency:

$$\eta_{col} = Qcol / (H.Ac) \quad (16)$$

- Solar fraction = “energy supplied by the solar plant of a system divided by the total system load” (ISO, 1999):

$$Fsol = Qsol / Qd \quad (17)$$

In the case of an integrated auxiliary heater, it is very difficult to determine the exact amount of energy supplied by the solar hot water system to the conventional part of the system. For this reason, we considered the energy supplied by the heat exchanger.

- Sometimes a different definition of the solar fraction $Fsol$ is used (e.g. in the Polysun software <http://www.solarenergy.ch> and T-Sol <http://www.solar design.co.uk>):

$$Fsol' = Qsol / (Qsol + Qnet_{aux}) \quad (18)$$

- Final energy savings:

$$Qf-sav = (Qf_{conv} + Qf_{pen-conv}) - (Qf_{aux} + Qf_{pen-aux} + Qpar) \quad (\text{kWh}) \quad (19)$$

with $Qpar$ the parasitic energy for the collector loop (pump, the control unit, and possibly the boiler pump)

- Primary energy savings:

$$Qp-sav = (Qp_{conv} + Qp_{pen-conv}) - (Qp_{aux} + Qp_{pen-aux} + Qpar * 2.58) \quad (\text{kWh}) \quad (20)$$

(The term 2.58 is usually used in France to convert electrical energy into primary energy)

- The final energy fractional rate:

$$Fsav-f = Qf-sav / (Qf_{conv} + Qf_{pen-conv}) \quad (21)$$

- The primary energy fractional rate:

$$Fsav-p = Qp-sav / (Qp_{conv} + Qp_{pen-conv}) \quad (22)$$

2.3.2. Exergetic quantities

Exergetic efficiency not only takes into account the quantities of energy used, but also their quality. The exergetic efficiency η_{ex} of the solar system with an integrated auxiliary heater is obtained with the equation:

$$\eta_{ex} = \frac{\int \dot{m}_3(t)[h_{Thw} - h_{Tcw}(t) - Ta(t) \cdot (S_{Thw} - S_{cw}(t))]dt}{Qf_{aux} + Qf_{pen-aux} + Qpar + \int G(t) \cdot Ac \cdot (1 - \frac{Ta(t)}{T_{abs}(t)})dt} \quad (23)$$

with Ta the ambient air temperature [K]; T_{abs} the absorber temperature [K]; h the water specific enthalpy [J/kg]; S the water entropy [J/(kg.K)]; G the solar radiation [W/m²]

The numerator of this equation represents the exergy gain of the water supplied to users (Gunerhan and Hepbasli, 2007). The denominator is the exergy entering the system: the electrical energy is pure exergy but the heat transferred to the solar panel is weighted by the Carnot factor (Stitou et al, 2000; Sorin et al, 2002).

2.3.3. Environmental quantities (CO₂ emissions)

A solar installation can save energy that would have been supplied by a conventional heating system and that would have produced greenhouse gases. This quantity of greenhouse gases depends on the quantity of the conventional energy saved. By calculating the energy saved, we can calculate the reduction in greenhouse gases. In France, the quantity (kg) of CO₂ per kWh-PCI avoided for the DHWS is (ADEME, 2005):

Natural gas	0.234
Fuel oil	0.300
Calor or butane gas (LPG)	0.234
Electricity	0.040

The electricity value is very low because of the huge proportion of nuclear energy used in France. We calculated the mass of non-emitted CO₂ (m_{CO_2}) and the fractional savings of CO₂ with regard to the conventional solution F_{sav-CO_2} .

2.3.4. Economic quantities (life cycle cost) (SAE, 1995; Fuller and Petersen, 2002)

The life cycle cost (LCC) method considers the costs and savings over the life cycle of the system, which is roughly 20 years for a SDHW. Optimizing the system means obtaining the lowest LCC or the highest life

cycle savings (LCS). The annual costs and savings are converted into present worth values at a given interest rate and discount rate.

The calculation of the solar heating system cost includes (see Annex 1):

- Initial investment: calculated according to the cost of the equipment and manpower associated with the installation of the system, and the tax reduction allowed (50% on the equipment in France, after having deducted the grants available)
- Annual maintenance and operation costs

The cost of a conventional installation consists in costs relating to the hot water tank, manpower, and annual operation and maintenance.

The annual savings (*Sav*) is the difference in maintenance and operation costs between the conventional and the solar installation. The additional investment cost between the solar and conventional installations are noted as *AI*.

By assuming equal yearly payments *YP*, the life cycle cost is calculated using the follow equation:

$$LCC = I + K * YP \quad (\text{€}) \quad (24)$$

with *I* the investment [year 0]; *YP* the annual payments

$$K = \frac{r \cdot (r^n - 1)}{r - 1} \quad (25)$$

$$r = \frac{1 + i}{1 + d} \quad (26)$$

with *i* the interest rate (0.02 in France); *d* the discount rate (0.04 in France); *n* is given as 20 years (life cycle of the system)

The inflation rate corresponds to the increase in the cost of living. The discount rate makes it possible to return financial streams that are not directly comparable, because they occur at different dates, on the same basis. It can not only compare them but can also make arithmetic operations on them. The life cycle savings (*LCS*) over the life cycle can be calculated.

$$LCS = K * Sav - AI \quad (\text{€}) \quad (27)$$

with *AI* the additional investment[€];*Sav* the annual savings (€)

It is also possible to calculate the pay back time:

$$N = \frac{\text{Ln} \left(1 + \frac{AI}{Sav} \cdot \frac{r-1}{r} \right)}{\text{Ln}(r)} \quad (28)$$

Finally, we define the financial fractional savings compared with a conventional solution (without a solar heating system):

$$F_{sav-LCC} = LCS / (LCC)_{\text{conventional}} \quad (29)$$

3. Optimization based on various criteria

3.1. Description of the cases studied

3.1.1. The installations studied

The characteristics of the conventional and solar installations are described in Annex 2. Only the electric auxiliary heater was studied. The energy demand for hot water was 3450 kWh per year (200 l at 55°C). The weather conditions corresponded to the city of Lyon. The cold water temperature varied between 9 and 19°C over the year. The price of electricity was 0.1074 €/kWh with the auxiliary heater functioning during the periods 2h–6h, 12h–14h and 20h–24h. This price was applied to $Q_{f_{conv}}$, $Q_{f_{pen-conv}}$, $Q_{f_{aux}}$, Q_{par} and $Q_{f_{pen-aux}}$. The manpower cost of the solar installation was set at 1688 € (taxes included) for reasons of simplification. On the other hand, the cost of the equipment depended on the size of the collector and the tank (see Annex 1).

The efficiency coefficients of the conventional and solar installations (electrical auxiliary heater) were:

$$\eta_{f-net_{conv}} = \eta_{f-net_{aux}} = 0.95 \quad (30)$$

$$\eta_{p-f_{conv}} = \eta_{p-f_{aux}} = 1 / 2.58 \quad (31)$$

The tank set-point temperature was $T_{set1} = 55^\circ\text{C}$ and the comfort penalty was calculated from the temperature $T_{set2} = 40^\circ\text{C}$ ($X=2$).

The mass of non-emitted CO₂ was calculated by using the 0.089 kg value per kWh of electricity saved (this value was much lower than the European average).

3.1.2. The optimization criteria studied

The optimized parameters were the collector area, the tank volume and the collector loop flow rate. We limited the number of parameters to be optimized so as to simplify the comparisons. Various optimization criteria were used. The performance quantities were the following:

- Energetic criterion (to be minimized): $Q_{f_{aux}} + Q_{f_{pen-aux}} + Q_{par}$ (kWh)
(optimizing in terms of F_{sav-f})
- Exergetic criterion (to be maximized): η_{ex} (-)
- Financial criterion (to be minimized): LCC (€)

- Mixed criterion 1 (to be maximized): $F_{sav-f} * F_{sav-LCC}$ (-)
- Mixed criterion 2 (to be minimized): $(Q_{net_{aux}} + Q_{d_{pen}} + QI) / Q_{sol}$ (-)
- Mixed criterion 3 (to be minimized): AI / Q_{f-sav} (€/kWh)

Mixed criterion 1 was designed to reflect the highest financial savings combined with the final energy savings to obtain a compromise between these two criteria. The second mixed criterion was the ratio of the energies to be minimized (tank losses, auxiliary heating and comfort penalties) divided by the energy to be maximized (the solar energy supplied to the tank). Therefore, mixed criterion 2 will be noted Q_{min} / Q_{sol} . The third criterion was used in the (Bales, 2002) study; it reduced the additional investment with regard to the energy saving.

The optimization was carried out using the Hooke-Jeeves method (Wetter and Wright, 2003). We used the default values of the interface TrnOpt, which combines TRNSYS (Klein et al., 1996) and GENOPT (Wetter, 2004) software. The optimization algorithm makes it possible to set the minimal and maximal values for each of the optimized parameters. The following values were considered:

- Collector area: 2–10 m² (initial: 6 m²)
- Tank volume: 0.2–0.6 m³ (initial: 0.4 m³)
- Flow rate in the collector loop: 5–65 l/h.m² (initial: 35 l/h.m²)

We did not consider the initial values of these three parameters identical to the solar standard installation (see Annex 2) so as not to be too close to an a priori high-performance installation. The tank was modeled with the TRNSYS TYPE 140 considering 20 temperature nodes. The tank exit temperature was mixed with the cold water temperature using a three-way valve, noted Thw . Annual simulations were carried out with a 12-min time step.

3.2. The optimization results

The objective of the optimization was not to look for a common solution because the results depended directly on the hypotheses. These vary widely considering the SDHWS design (we assumed, for example, a relative height of the auxiliary heater in tank of 0.5), financial costs (interest and discount rates, energy price, the grants, etc. (see Annex 1)). On the other hand, comparing the solutions obtained can indicate which optimization criteria are the most relevant.

3.2.1. Improvements obtained on each of the optimized criteria

The improvement on the optimized solar installations compared to the standard solar installation with each of the criteria is shown in Table 1. The improvement on each criteria ranges from 10% to 256%.

Figure 3 shows the variation of each of the optimized parameters and the performance values during the iterations in the case of the *LCC* optimization. It can be seen that *LCC* performance decreased during the iterations. The variations in *LCC* did not decrease continuously because of the optimization method retained. The Hook-Jeeves method tests new parameters based on the preceding parameters by considering an increase or a decrease, which explains the discontinuous progression of the *LCC*. The optimization stops automatically depending on the parameter defining the maximum number of step reductions. The performance values do not change much after 22 iterations. The minimum *LCC* value was obtained at the 40th iteration; the parameter values were then 8.3 m², 313 l and 17.2 l/(h.m²). These sizing parameters do not necessarily correspond to the material made available by manufacturers. Ideally, one would vary each parameter during the optimization phase by taking into account the data for each of the components actually available.

3.2.2. Presentation of all the results

Table 2 shows most of the evaluation criteria for the standard solar installation, the conventional solution (last column) and all the solar solutions obtained after optimization. The values of the parameters are indicated at the top of the table.

Optimizing a single criterion is not necessarily judicious in that because there is a risk of obtaining lower performance for the non-optimized criteria. The energy savings (F_{sav-f}) is always greater than the financial savings ($F_{sav-LCC}$) considering the low price of electricity and the additional investment for the solar plant. A substantial increase in the price of energy could balance both savings rates.

If only these two criteria are relevant, it is easy to classify the optimized solutions with Fig. 4. A solution will provide greater performance in terms of these two criteria the farther the point is from the origin of axes, i.e. the higher the product $F_{sav-LCC}$ by F_{sav-Ef} is (mixed criterion 1). Mixed criteria 1 and 2 offer the best performance, followed very closely by the *LCC* and energy criteria. The last two criteria are $AI/Qf-sav$ and exergy. The exergy criterion favors energy performance, whereas the $AI/Qf-sav$ mixed criterion seems to benefit financial performance. Therefore, the most helpful criteria are the four criteria: mixed criteria 1 and 2, energy and *LCC*. The performance thus obtained for this group is approximately $F_{sav-LCC} = 14\%$ and $F_{sav-Ef} = 67\%$. The standard solar configuration seems much less attractive ($F_{sav-LCC} = 6\%$ and $F_{sav-Ef} = 47\%$).

This demonstrates the potential of performance improvement based on combining an optimization tool with an energy system simulation tool.

It is important to note that energy and mixed criteria 2 do not directly take the cost of the installation into consideration. Consequently, one risks obtaining the collector's oversize area if a large variation is brought into play. Moreover, the collector's area obtained with these two criteria corresponds to the maximum value authorized in our study (10 m²). This value corresponds to double the standard sizing (approximately 5 m²) and can be considered to be oversized. A larger variation range was not used so as not to penalize the calculation time. The *LCC* and mixed criteria 1 integrate both installation cost and energy consumption. It will be necessary to consider the *LCC* if we wish to encourage reducing the installation pay-back time, and mixed criterion 1 to obtain an energy and financial compromise. Even if the progression in energy prices is an unknown over the life cycle of the installation, it seems necessary to take cost into account. Knowing that the price of energy can only increase, the pay-back time of the installation will actually be lower.

Other mixed optimization criteria were studied, but not presented in this study, for example mixed criterion 4, which consists in minimizing the cost and the final energy with regard to a reference solution (solar installation or not) in the following way:

- Mixed criterion 4 : $(LCC / LCC_{ref})^2 + ((Qf_{aux} + Qf_{pen-aux} + Qpar) / Qf_{ref})^2$ (32)
- Solar Fraction: $Fsol'$

These criteria are very successful because they provide results that are very close to mixed criterion 1. The optimization criterion $Fsol'$ presents the problem of not integrating the financial cost. The solution obtained therefore risks being oversized (moreover, the maximum collector area was obtained in this case). Nevertheless one should not lose sight of the technological feasibility of the optimized solution. For example, over-sizing the solar collector requires a specific device that can prevent the risks of deterioration caused by over-heating (with an additional cost that should be taken into account).

The disadvantage of Fig. 4 is that it does not integrate the environmental issue (primary energy and greenhouse gas emissions). The following will illustrate how to define a global evaluation.

- **Energy issue**

The high solar fraction $Fsol$ is obtained in the summer period (roughly 150%), providing the best solutions because the areas are high (9.9 m² for mixed solution 1), providing an incentive to over-size the collector area so as to increase solar gains during the mid-season. Nevertheless, monitoring the system for over-heating during the summer period will remain necessary (technological systems are used with combisystems).

For all the solar installations, the parasite energy used by the pump and controller is not low since it accounts for approximately 5.7% of the final energy from the auxiliary heater Q_{aux} when LCC is optimized (flow rate, 17.2 l/h.m²) and 7.7% for the exergetic optimization (flow rate, 65 l/h.m²). It is therefore normal that the energy optimization tends to reduce the fluid flow rate compared to a standard solar installation. A direct coupling of a photovoltaic module with the pump would save parasite energy.

The coefficient of performance (COP) of the best solution is approximately 2.5, 1.4 in the standard solar installation and only 0.7 in the conventional solution.

High collector efficiency is not necessarily synonymous with optimal performance. The efficiency in the standard configuration is 43% versus 28% in the optimized solution with mixed criterion 1. This result is not surprising because by decreasing the thickness of the tank insulation, we can expect to increase the collector efficiency.

- **Exergy issue**

The solution obtained with the exergy optimization shows very high efficiency ($\eta_{ex}=97\%$). The exergy criterion made the collector work with a high flow rate and a large tank volume so as to reduce the collector temperature. The quality of the input exergy is therefore very low. In addition, the exergy criterion tends to minimize the use of the auxiliary heater, which means a large collector area and high solar energy Q_{sol} supplied to the tank. The maximum values authorized by the three optimized parameters (flow rate, area and volume) were determined by the optimization. On the other hand, the tank's thermal losses and the initial investment are penalized and the pay-back time is the highest. Furthermore, the large tank volume leads to high Q_l losses but limits the over-heating in spite of the large collector area.

If we consider the mixed criteria, the most advantageous solutions do not have the highest exergy efficiency ($\eta_{ex} = 33\%$ in mixed criterion 1), making it difficult to classify the solutions solely on the exergetic criterion.

It would be necessary to mix the exergetic and financial criteria.

We have also considered a modified exergy parameter taking into account not the exergy of the heat entering the solar panel as in equation (23), but rather the exergy of the incident solar radiation, following the Petela expression (Petela, 2003). This criterion presented low values between 17% (using equation (23) for optimization) and 25% (using the Petela expression for optimization), because solar radiation has a high exergy content. The optimization also leads to a large solar collector (9.75 m²), a large storage tank (587 l) and operation at a high flow rate (65 l/hm²).

- **Environmental impact**

To reduce greenhouse gas emissions, optimized solutions with mixed criterion 1 can save 309 kg of CO₂ per year compared to the conventional solution, corresponding to 94 kg more (309–215) compared to the standard solar heating installation. Concerning the fossil and fissile resources, the annual primary energy savings is 10,548 kWh-ep with solar energy according to mixed criterion 1, and 7386 kWh-ep in the standard solar installation.

- **Cost**

The pay-back time of the basic solar installation is 15.2 years, and 12.9 years for the solution obtained with the optimization using mixed criterion 1. The annual savings (auxiliary heater, pump and controller) thus obtained is 288 € (taxes included); the annual cost of electricity consumption in the conventional installation being estimated at 553 €. The payoff period is relatively high given the current cost of electricity in France. This is not the case in all European countries such as Denmark, where the price of electricity is twice as high. Even if energy prices continue to increase, thus reducing the payoff period, it is crucial to attempt to reduce the investment cost of a SDHWS installation using, for example, polymer materials.

- **Comfort**

All the solar solutions (standard or optimized) present a more advantageous distribution of hot water temperature Thw in terms of comfort than the conventional solution (see the temperature distribution when Thw is below 50°C in Fig. 5). The Qd_{pen} penalty integrated into the various optimization criteria makes it possible to optimize the solutions with a high comfort level (Thw is close to the set-point 55°C).

The conventional solution is penalized by thinner tank insulation. Moreover, the solar energy supplied to the tank increases its temperature during the day, tapping being defined in an unpredictable way according to the method described in (Shah, 2002). It can be seen that solar energy provides both energy savings and improved comfort.

3.2.3. Relations between the energetic criteria

We estimated three important energetic criteria (F_{sol} , F_{sav-f} and COP). Improving these three criteria requires an increase in collector area (which reduces the productivity of the collector and increases the investment cost). The criterion, that seems a priori the most valuable is fractional savings F_{sav-f} compared to an equivalent conventional installation. The relation between this criterion and the two others needs to be calculated for better comparison.

It is easy to determine the relation between F_{sav-f} and COP from the equations. Assuming a water tap temperature of 55°C ($Q_{f_{pen}}$ equals zero):

$$F_{sav-f} = 1 - (Q_d / COP + Q_{par}) / Q_{f_{conv}} \quad (33)$$

The function $F_{sav-f} = f(COP)$ increases as long as Q_d and Q_{par} remain fairly constant and $Q_{f_{conv}}$ is fixed. It is thus possible to replace the F_{sav-f} optimization criterion with the COP criterion. The relation between F_{sav-f} and COP is easily defined in the following conditions:

- when $F_{sav-f} = 0$: $COP = Q_d / (Q_{f_{conv}} - Q_{par}) \quad (34)$

- when COP increases, F_{sav-f} becomes $1 - Q_{par} / Q_{f_{conv}} \quad (35)$

Fig. 6 shows how this function evolves.

The solar fraction F_{sol} gives important information on the installation sizing: how much of the energy supplied by the system is solar? Nevertheless, the solar fraction F_{sol} is not representative of the installation's global energy performance because the solar energy supplied to the tank can be useless (high solar production during summer) or lost (high tank losses because of large volume or insufficient insulation). The solar fraction F_{sol} determined in summer contributes additional information on the sizing of the installation for high solar radiation.

Qualitative considerations allow one to study the function $F_{sav-f} = f(F_{sol})$:

- When F_{sol} tends towards 0, the solar energy supplied to the tank becomes very low. We thus approach the conventional installation and we can consider that F_{sav-f} tends towards 0. It is actually a bit more complicated because the standard solar and conventional installations are very different (for example, there is more tank insulation in the first case).
- It is relatively easy to obtain $F_{sol}=100\%$ by over-sizing the collector area and the tank volume (we could even reduce its insulation) so as to supply a large amount of solar energy and thus obtain $Q_{sol} = Q_d$. On the other hand, obtaining $F_{sav-f} = 100\%$ is unrealistic because of inadequate solar energy incident at certain times during the winter.
- The various solutions studied are presented in Fig. 7. The maximum for F_{sav-f} is slightly lower than 70%, which corresponds approximately to $F_{sol} = 90\%$.

Since the function is not monotonic, we cannot use F_{sol} as a criterion for optimization.

3.2.4. Comparison of the various optimization methods

We also used the Hooke-Jeeves method and the Nelder-Mead-O'Neill and Coordinate Search methods to compare *LCC* optimization (the same initial values are used). We used the Hooke-Jeeves method with initial penalizing values (2 m², 0.2 m³ and 65 l/hm²) for the *LCC* as well. The *LCC* values obtained at the end of the optimization are very close for all the methods.

3.3. Global evaluation approach

The most advantageous optimization criteria have been shown through the financial and energy savings. Here we study a global evaluation of an installation based on a radar diagram of savings with regard to a reference installation compared to the conventional installation. The radar diagram indicates three fractional savings that we believe to be essential in savings relative to the *LCC* (*Fsav-LCC*), primary energy (*Fsav-p*) and greenhouse gas emissions (*Fsav-CO₂*). The first evaluation criterion is important for the installation owner and the last two are important from an environmental point of view (limitation of greenhouse gas emissions and conservation of fossil or fissile resources). For readability, the best performance corresponds to the outside triangle (and conversely).

Fig. 8 shows that the standard solution is the least beneficial. The lines relative to the various solutions are parallel between *Fsav-p* and *Fsav-CO₂* because these two criteria are equivalent in terms of the electricity choice for the auxiliary heater (it would obviously be interesting to compare installations with various auxiliary energies).

4. Conclusion

We have compared various optimization criteria for a SDHWS with an electric auxiliary heater. It is important to consider criteria integrating both energy and financial aspects. The *LCC* optimization criteria, mixed 1 and mixed 4, are the most indicative. The solutions obtained after optimization show that it is better to oversize the collector area than the tank volume (the thermal losses and financial cost are high).

Even if the results obtained are closely related to conditions in France through the parameters selected, a number of general conclusions can be drawn. For example, the evaluation criteria used for the solar installations are often not representative of actual performance because they are often based on the solar energy supplied to the tank (solar fraction and productivity) without considering the auxiliary heater. In addition, the current environmental problems require that the greenhouse gas emissions and the consummate

primary energy also be considered. This is the reason why we developed a new representation of global evaluation in the form of radar diagram based on fractional savings F_{sav-p} , F_{sav-CO_2} and $F_{sav-LCC}$.

The highest-performance solutions obtained should not be considered ideal because they are not necessarily realistic given, on the one hand, the sizing restrictions related to the materials available, and, on the other hand, the simplifying hypotheses advanced. For example, only three optimization parameters were considered and we did not take into account the technological precautions necessary when the collector is oversized. Nonetheless, this article proposes a starting point for studies that are more complete (taking other countries into account, etc.) and more realistic.

Substantial work remains to be done to obtain a reliable tool for evaluation and optimization of the numerous SDHW configurations. It would be particularly necessary to:

- integrate the various design possibilities: direct coupled photovoltaic and pump, the energy choice for the auxiliary heater.
- modify the hypotheses so that countries other than France could be studied. Nevertheless, the price of a kWh of electricity is relatively low in most European countries (on average approximately 14 c€/kWh). The payoff period therefore risks being relatively long in general. Even if a rise in price can be expected in the coming years, it is important to design new, less expensive SDHWS using, for example, polymer materials and simplifying the systems.
- evaluate more precisely the financial cost: manpower depending on the component sizing (collector area, etc.), the price of the devices to prevent over-heating during summer, the cost of the insulation (tank and pipes), etc. It would also be necessary to integrate various changes in the price of energy.
- add parameters to be optimized: height of the auxiliary heater in the tank, the thickness of insulating material, etc.
- integrate other optimization parameters related to the production of primary energy. For example, the availability of water in certain arid areas poses the problem of producing electricity based on a cycle vapor power plant.

Nomenclature

Symbols

A_c	collector area (m ²)
AI	additional investment between non-solar and solar DHWS (€)
COP	coefficient of performance
d	discount rate

F	solar fraction
F_{sav}	fractional saving
G	solar radiation (W/m^2)
H	solar irradiation incident on the collector over the year and per unit area ($kWh/(m^2.y)$)
h	water specific enthalpy (J/kg)
i	interest rate
LCC	life cycle cost ($€$)
LCS	life cycle savings ($€$)
m	mass (kg)
N	pay back time (year)
$Prod$	productivity of the solar collector ($kWh/m^2.y$)
Q_{col}	energy removed by the heat transfer fluid over the year (kWh/y)
Q_d	heat demand over the year (kWh/y)
Q_f	final energy demand over the year (kWh/y)
Q_L	energy delivered at the outlet of the solar heating system over the year (kWh/y)
Q_l	store heat losses over the year (kWh/y)
$Q_{l,pipe}$	pipe heat losses of the collector loop over the year (kWh/y)
Q_{net}	net energy demand over the year (kWh/y)
Q_p	primary energy demand over the year (kWh/y)
Q_{par}	parasitic energy for the collector loop pump and the control unit (kWh/y)
Q_{sol}	energy delivered by the solar loop to the store over the year (kWh/y)
S	water entropy ($J/(kg.K)$)
Sav	annual savings ($€$)
T_a	ambient air temperature (K)
T_{abs}	absorber temperature (K)
T_{cw}	cold water supply temperature (K)
T_{inC}	inlet collector temperature (K)
T_{inHX}	inlet temperature of the solar heat exchanger (K)
T_{outC}	outlet collector temperature (K)
T_{outHX}	outlet temperature of the solar heat exchanger (K)
T_{set}	set-point temperature (K)
X	comfort penalty parameter
η_{f-net}	transformation efficiency between final and net energy
η_{p-f}	transformation efficiency between primary and final energy
η_{col}	collector efficiency
η_{ex}	exergetic efficiency
\dot{m}	water mass flow rate (tank) (kg/s)
\dot{m}_1	
\dot{m}_2	propylene-glycol / water mixture mass flow rate (kg/s)

\dot{m}_3 water tap mass flow rate (kg/s)

Subscripts

aux auxiliary heater

f final energy

p primary energy

pen penalty energy due to water tap temperature (comfort)

ANNEX 1: the financial costs

a) conventional installation (taxes included)

- Tank (200 l, vertical): 550 €
- Manpower: 300 €
- Annual maintenance = 20 € / year

Annual operation costs:

- Final energy consumption (electricity): 0.1074 €/kWh

b) standard solar installation

Grants and VAT:

- grants: 800 €
- Tax reduction: 50 % on the equipment (grant have to be deduct)
- VAT: 5.5 %

Equipment costs (tax free):

- collector: 360 €/m²
- tank: 3500–4500 €/m³
- pipe: 10 €/HT/m

Other equipment cost: 575 € (tax free)

- Manpower: 1600 € / installation
- Maintenance: 100 € / year

Determination of the solar investment (taxes included)

- Tax reduction = 50% * (equipment – grants * equipment / (equipment + manpower))
- equipment € = $c1 + c2 * Sc + c3 * V + c4 * Lpipe$

$c1 = 600 \text{ €}$

$c2 = 380 \text{ € / m}^2$ (collector)

$c3 = 4220 \text{ € / m}^3$ (tank)

$c4 = 10 \text{ € / m}$ (pipe)

- manpower = 1688 €

Annual maintenance cost: 105 € / year (taxes included)

ANNEX 2: description of the installations

a) conventional installation

- Volume: 200 l
- Tank insulation: 3.3 cm
- Auxiliary heater: 3000 W
- Diameter: 0.434m
- Tank height: 1.35m
- Tank losses: $UA=4 \text{ W/K}$

b) standard solar installation

Clipsol TGD solar collector (X=6, Y=2)

- area: 5.963 m²
- collector efficiency: $\eta = 0.73$
- collector loss coefficients $a_1=4.26 \text{ W/m}^2\cdot\text{K}$ and $a_2=0.0047 \text{ W/m}^2\cdot\text{K}^2$

Pipes:

- Diameter 16/18 mm
- Insulation thickness: 2.2 cm (conductivity: 0.04 W/mK)
- Total length: 28 m
- Fraction of glycol (propylene-glycol / water mixture): 20 %

Tank:

- Volume: 400 l
- insulation: 6 cm (conductivity: 0.037 W/mK)
- Auxiliary heater: 3000 W
- Tank height: 1.811 m

- Tank losses: 3.5 W/K
- Heat exchanger tube inside diameter / area: 1.5 cm / 1.69 m²
- Auxiliary heater relative height: 0.5
- Heat exchanger input / output relative heights: 0.27 / 0.07

pump: 10 W (10 l/hm²), 35 W (50 l/hm²), 60 W (90 l/hm²)

Controller: 5 W

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Table 1. Improvement obtained for each optimized criterion

Criterion	Performance function	Standard	Optimized	Improvement
Energy	F_{sav-f}	47.0%	68.1%	45%
Exergy	η_{ex}	39.9%	97.4%	144%
Cost	LCC	9653 €	8729 €	10%
Mixed 1	$F_{sav-f} * F_{sav-LCC}$	2.7%	9.7%	256%
Mixed 2	Q_{min} / Q_{sol}	1.8	0.8	54%
Mixed 3	AI / Q_{f-sav}	0.94 € / kWh	0.82 € / kWh	13%

Table 2. Evaluation criteria for the installations (standard solar, optimized solar and conventional systems)

		standard	OPTIMIZATION CRITERIA						
		(solar)	energy	exergy	LCC	mixed 1	mixed 2	mixed 3	
		4	10	10	8.3	9.9	10	5	Ac (m ²)
	EVALUATION	0.400	0.400	0.600	0.313	0.313	0.313	0.300	Vtank (m ³)
	CRITERIA	50	20.0	65.0	17.2	17.2	19.1	23.8	Q (l/hm ²)
ENERGY	H	1177	1177	1177	1177	1177	1177	1177	
	$prod$	512	342	357	368	330	327	472	
	η_{col}	43	29	30	31	28	28	40	
	F_{sol}	54	90	95	80	86	86	62	
	F_{sol} (summer)	110	163	183	145	151	151	122	installation (non solar)
	F_{sol}'	44	69	67	66	69	70	53	
	COP	1.39	2.35	2.04	2.28	2.51	2.53	1.75	0.73
	QL	3385	3418	3438	3371	3378	3379	3333	3162
	Q_{sol}	1816	3076	3273	2693	2893	2910	2071	
	QI	749	1051	1450	788	844	850	630	952
	QI_{pipe}	342	532	495	511	542	543	414	
	$Q_{net-aux}$	2319	1384	1601	1406	1279	1270	1810	4138
	Q_{d-pen}	160	102	35	259	241	237	365	749
	Q_{par}	115	78	117	76	75	76	87	
	Q_{f-sav}	2420	3503	3305	3316	3470	3481	2768	
Q_{p-sav}	7386	10650	10066	10083	10548	10584	8426		
F_{sav-f}	47.0	68.1	64.2	64.5	67.4	67.7	53.8		
F_{sav-p}	47.4	68.3	64.6	64.7	67.7	67.9	54.0		
EXERGY	η_{ex}	40	40	97	30	33	36	26	
CO2	m_{CO2}	215	312	294	295	309	310	246	
	$F_{sav-CO2}$	47.0	68.1	64.2	64.5	67.4	67.7	53.8	
COST	manpower	1688	1688	1688	1688	1688	1688	1688	300
	equipment	3920	6200	7000	5185	5803	5850	3900	550
	tax credit	1680	2786	3178	2291	2591	2615	1671	
	grant	800	800	800	800	800	800	800	
	AI	2278	3452	3860	2932	3249	3273	2267	
	annual maintenance	105	105	105	105	105	105	105	20
	annual operation	293	176	198	196	180	179	255	553
	annual Sav	175	291	270	271	288	289	212	
	LCC	9653	8920	9677	8729	8775	8778	9031	10247
	LCS	594	1327	570	1518	1472	1469	1216	
	N	15.2	13.6	16.9	12.3	12.9	12.9	12.1	
$F_{sav-LCC}$	5.8	13.0	5.6	14.8	14.4	14.3	11.9		
MIXED 1	$F_{sav-f} * F_{sav-LCC}$	2.73	8.82	3.57	9.55	9.69	9.70	6.39	
MIXED 2	Q_{min}/Q_{sol}	1.78	0.82	0.94	0.91	0.82	0.81	1.35	
MIXED 3	AI / Q_{f-sav}	0.94	0.99	1.17	0.88	0.94	0.94	0.82	

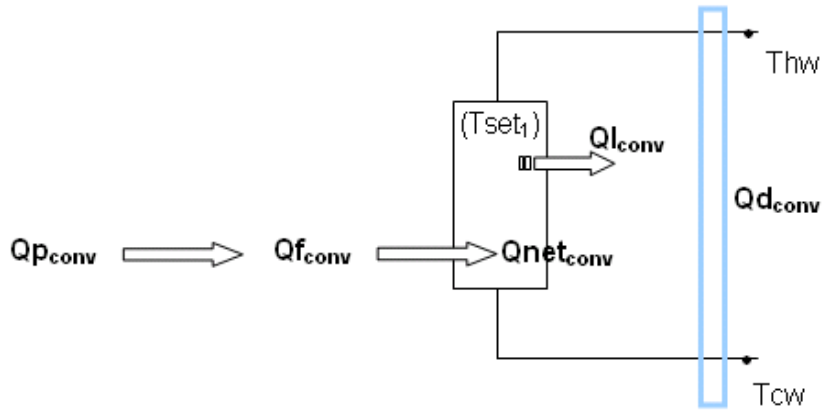


Fig. 1. Conventional domestic hot water system

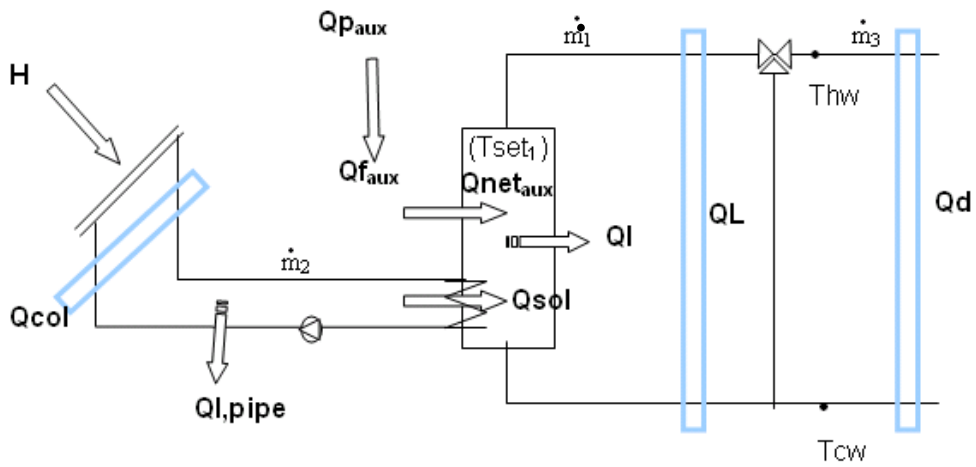


Fig. 2. Solar installation with integrated auxiliary heater

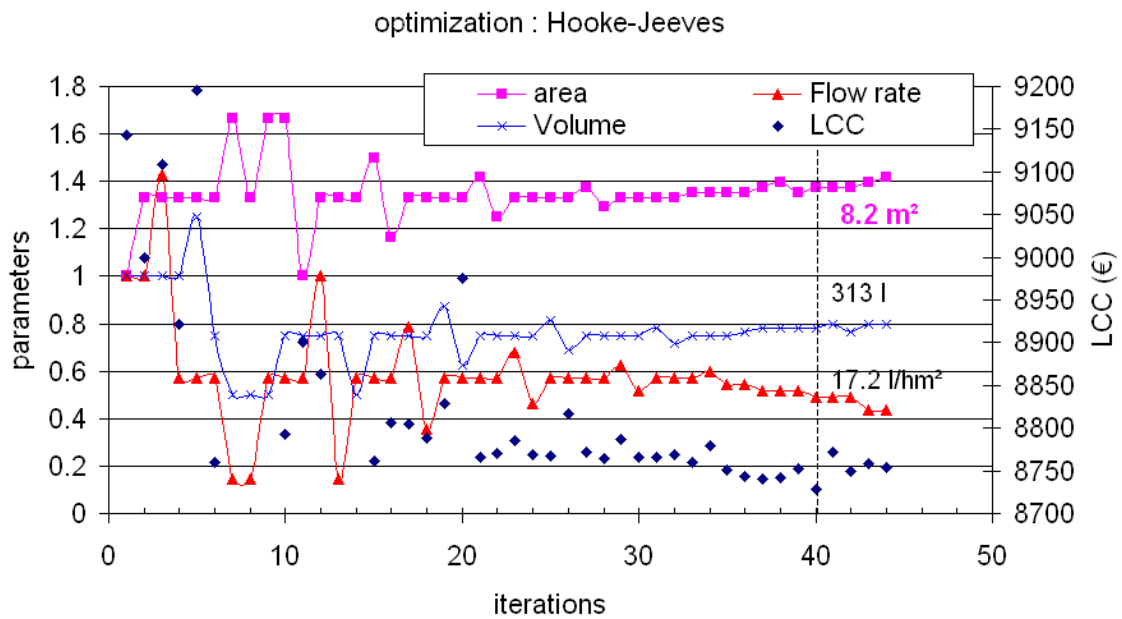


Fig. 3. Example of LCC optimization results

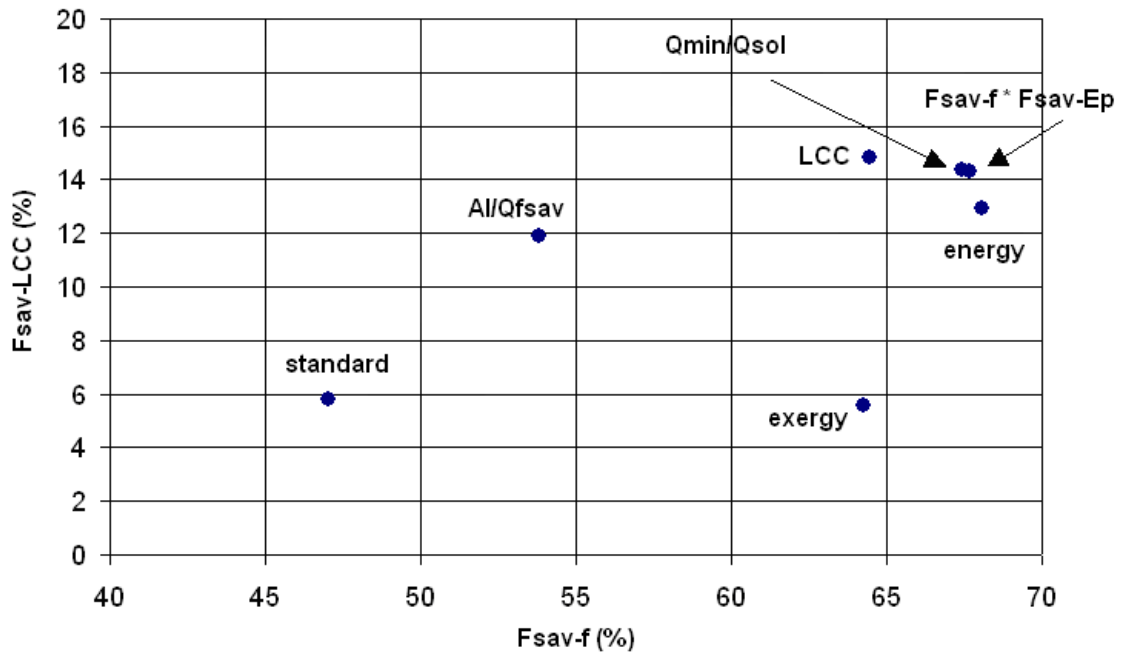


Fig. 4. Energy and financial evaluation

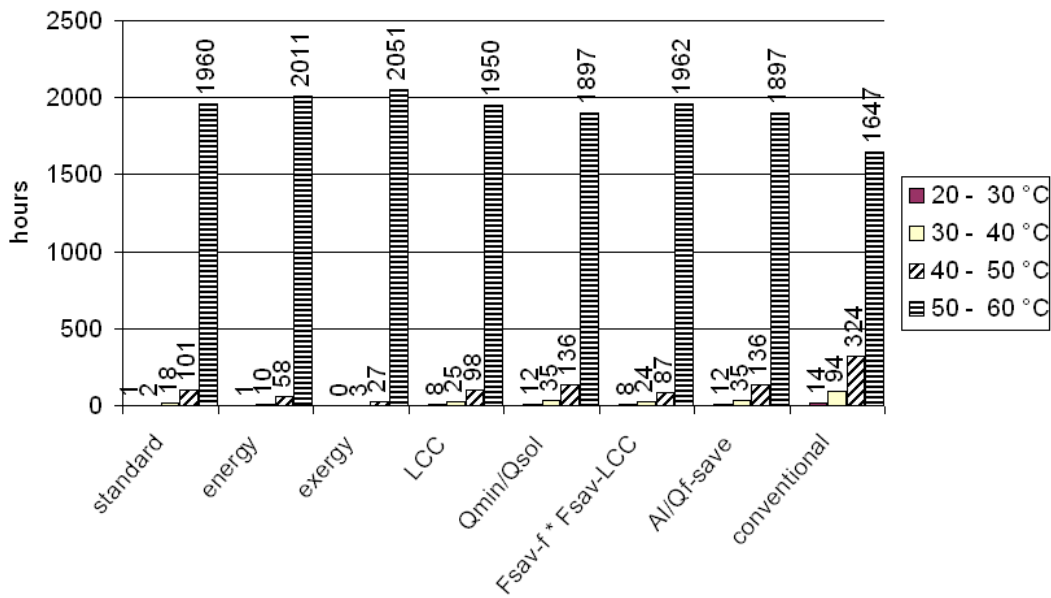


Fig. 5. Hot water temperature distribution (when water is tapped)

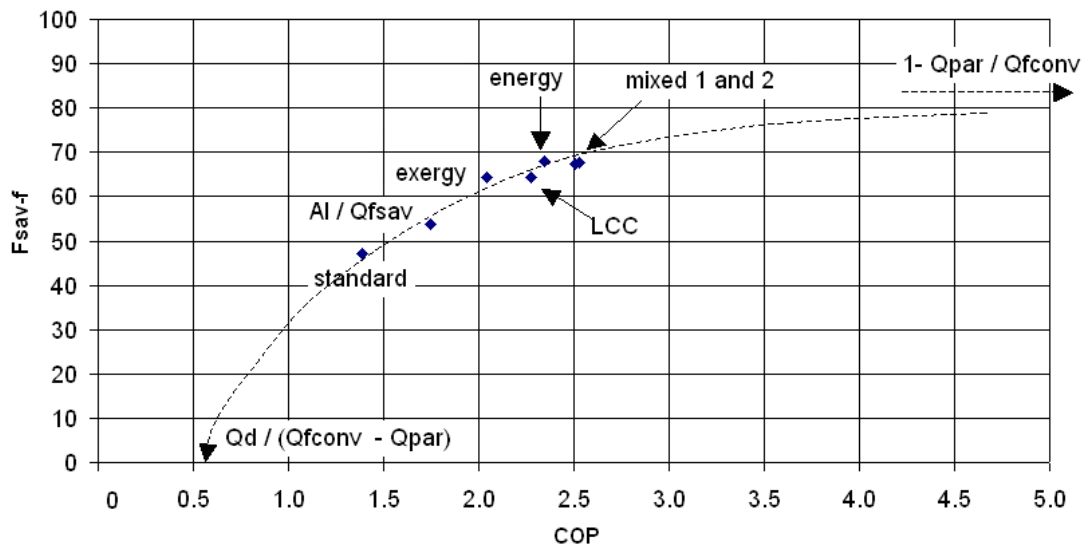


Fig. 6. Relation between F_{sav-f} and COP

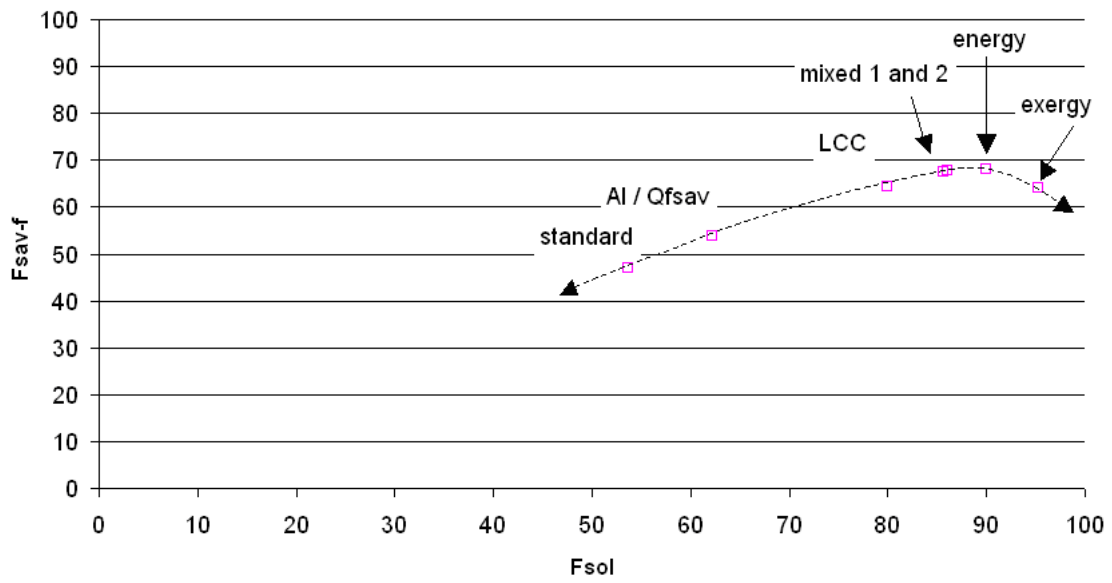


Fig. 7. Relation between F_{sav-f} and F_{sol}

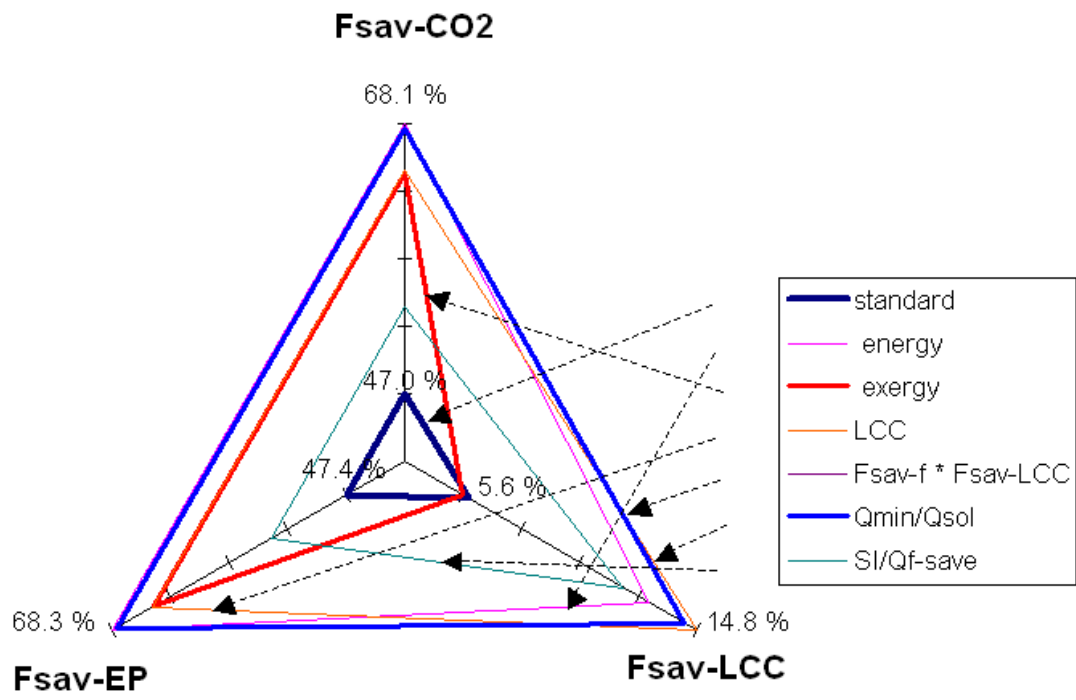


Fig. 8. Performance for a global evaluation