IMPROVED INTEGRATION OF A 28M^3 SEASONAL THERMAL STORAGE IN THE HEATING AND DHW SUPPLY OF A SINGLE FAMILY HOME WITH A GEOTHERMAL HEAT PUMP AND FLAT PLATE SOLAR COLLECTORS

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Abstract:
The aim of an on-going study is to synchronise the rational use of alternative and eco-friendly energy generation in a single family home to reduce non-renewable energy consumption and overall domestic energy costs. Today, more and more buildings combine solar thermal with heat pumps and other heat sources. This project focuses on the optimisation of such combined installations with computer generated simulations and design of experiments with genetic algorithms.

Experimental tests have shown that short-term efficiency of the heat pump can be boosted considerably by using a seasonal storage (by adapting inlet temperatures). Validated simulations of the installation showed that poor efficiency is mostly due to bad regulation (a boiler reaching 95°C provides more energy than required and provokes thermal losses), but also because of inefficient use of available solar energy in summer.

After simulating the individual installations, the most important parameters influencing solar and heat pump efficiency were identified. A combination of these systems will later allow identifying important interactions between parameters. The results so far show that considerable improvement of regulation is possible, and will help develop a catalogue of optimisation tools for miscellaneous installations.

Key Words: seasonal thermal storage, efficiency, optimisation, IEA Task44

1 INTRODUCTION

Today many different approved and popular solutions exist to fulfil household energy demands without using fossil fuel resources. In Switzerland, these solutions mainly include solar thermal collectors, heat pumps or use of wood and pellets in domestic burners. Although commercial solar collectors and heat pumps sold nowadays reach high efficiency in test conditions, these performances are rarely achieved in field conditions due to poor system balance. Consequently, the payback time of the installation is extended, more non-renewable energy is consumed, and the end-user is punished with higher operation costs.
Based on building simulations with Matlab-Simulink (Jülich-Solar-Institut 2007) and Lesosai (E4Tech 2010), a pilot object was analysed to determine its thermal behaviour during operation, including DHW and heating demands. After validating the simulations with real values, the weak points of the installation were identified and the simulation models prepared

for the application of optimisation algorithms. For the optimisation, several objectives explained later in this document, respecting different levels of system boundaries, were defined:

- Minimise operation costs (costs of electricity), respecting local low and high local electricity tariffs
- Minimise overall non-renewable energy consumption
- Maximise operating time of the solar collectors leading to higher percentages of (free) solar energy to the system.
- Maximise efficiency of solar collectors and heat pump
- Maximise efficiency respecting different levels of comfort (see chapter 3.4 Objectives for optimisation)

Achieving all objectives is impossible, because of contradictory goals. However, once all the system parameters are known and active in the simulation, an optimisation respecting all objectives can be carried out with special optimisation tools. Usually, such optimisations are very time- and processor consuming, so fast converging genetic algorithms are applied, to reduce calculation time.

The project is integrated in the IEA Task 44, an international task focused on combined solar and heat pump systems (www.iea-shc.org/task44), which started in January 2010.

2 PILOT OBJECT

The main object of study is a single-family house inhabited by four persons (2 adults, 2 children). Situated in a village at 720 m above sea level, with an annual mean temperature of 9.2°C, the heating days (T < 12°C) according to SIA standards (SIA381/3 5.1984) are 232 days per year. The building was built in a sunny area (brief shading in the morning) with roof slopes of 30° oriented east, respectively west (see Figure 1). The installation and measuring equipment were sponsored by the local university of applied science (EIA-FR), and contain numerous temperature and mass flow probes on all possible pipes and connections. All monitoring data is recorded and analysed at the EIA-FR.

2.1. Thermal properties of building

According to latest Swiss building standards (SIA380/1 3.2009), the overall heat transfer coefficient (U-value in W/m^{2}K) to respect for the different elements of a newly built house with >20% of renewable energy sources for heating energy production are:

Table 1: Swiss building standards for U-values

construction element	surface of pilot object		heated space towards exterior	pilot object
opaque elements (roof, floor, walls, ground)	roof: walls: ground:	132m^2 160m^2 120m^2	0.20 W/m^{2}K	0.20 W/m^{2}K
windows, glass doors		40.3m^2	1.30 W/m^{2}K	1.10 W/m^{2}K
box for blinds		-	0.50 W/m^{2}K	0.40 W/m^{2}K
doors		7.7m^2	1.30 W/m^{2}K	0.90 W/m^{2}K

With the standard SIA verification simulation (SIA380/1 3.2009), these U-values lead to a heating energy consumption of 39 kWh/m^2 (140 MJ/m^2) per year for the analysed object.

2.2. Technical installation for heating and domestic hot water (DHW)

The heating and DHW demand for the house is entirely delivered by a heat pump (HP), a geothermal well, and solar collectors. The east oriented solar collectors (40m^2) are flat plate collectors from "Winkler Solarsysteme" and are directly integrated into the roof. The connecting pipes lie between the carrying brick structure and the insulation coat in the walls and underneath the tiles on the roof.

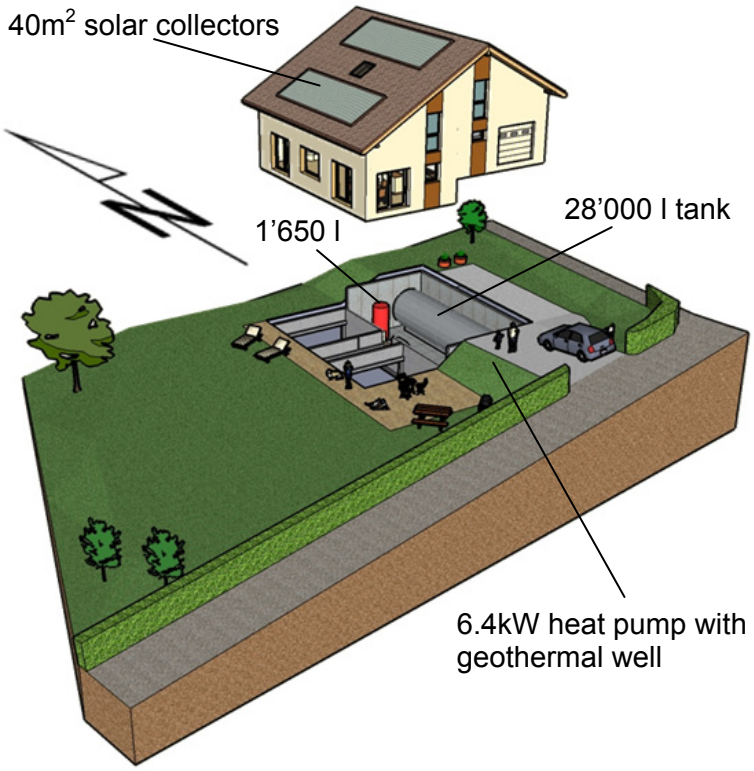


Figure 1: Pilot object with solar collectors, heat pump, stratified storage (red) and 28m^3 seasonal thermal storage

The heat pump is a NATURA WW106 from SATAG with 6.4kW power. Both sink and source side cycles are filled with water (no anti-freeze). The geothermal borehole is 150m deep and drives into sandstone (LMM: Lower Marine Molasse).

The stratified heat storage (1'650 l) is a "Geysir" from "Zeeh Heiztechnik" and contains a thermal separation disc as well as conducting sheet metal inlets and a heat exchanger with solar input stratification. Latter permits feeding the corresponding thermal layers in the stratification. The seasonal thermal storage is a 28'000 l water tank with 8 cm EPS insulation (U-value: 0.6 W/m^{2}K), but without an improved thermal stratification. The house has floor heating in all rooms (total heated area: 185m^2).

The complete connection of the different installations permits various operation modes. The different possible sources and sinks of each facility are listed below:

Table 2: Sources and sinks of all installations in pilot object

installation	sources	sinks
solar collectors	sun	stratified storage, seasonal storage
geothermal well	earth	heat pump
stratified storage	solar collectors, heat pump	DHW, floor heating
seasonal storage	solar collectors	heat pump, floor heating, stratified storage
heat pump	geothermal well, seasonal storage	stratified storage, floor heating

Every installation is equipped with temperature, mass flow and electricity meters, in order to record detailed and complete information of all processes.

3 OPTIMISATION

Before optimising the installation, the system boundaries and objectives were defined. Several contradictions actually prevent finding a simple solution for optimal operation conditions. Furthermore, not only direct installation parameters, but also interactions between parameters will play a major role for the overall system seasonal performance factor (SPF). Further optimisation of the systems performance will be achieved by introducing weather forecasts into the control algorithms and defining a risk factor for DHW production (risk of taking a cold shower due to degree of optimisation).

3.1. Efficiency in solar collectors

The efficiency of solar collectors depends mostly on the following factors: weather conditions, hardware efficiency, on-off temperatures of the pump and mass flow. Of course, the weather conditions are the most important factor; however, the user has no possibility to influence that part. The only parameters a normal user might be able to influence are the on- and off temperatures. A simplified formula (1) applied by many suppliers and scientists, for example G.Guihéneuf (G.Guihéneuf 2009) can be used to calculate the collectors efficiency.

$$\eta = \eta_0 - \left[\left(a_1 \cdot \frac{\Delta T}{G}\right) + \left(a_2 \cdot \frac{\Delta T^2}{G}\right)\right] \quad (1)$$

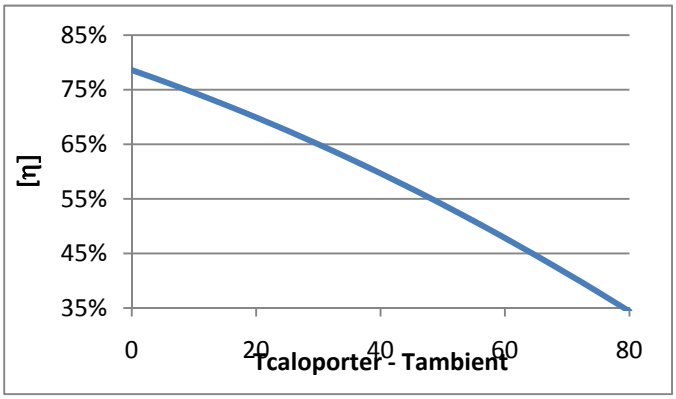


Figure 2: Efficiency of solar collectors in function of temperature difference

ΔT Caloporter fluid temperature minus ambient temperature ($T_{caloporter} - T_{ambient}$)
G global solar irradiation [W/m^2]
a_1 linear loss factor [W/m^{2}K]
a_2 quadratic loss factor [W/m^{2}K^2]
η_0 optical efficiency

The loss factors and optical efficiency are given from the solar collectors datasheet (SPF 2008)

The efficiency η is the solar energy captured divided by the solar energy globally available. If the ambient temperature during daytime is higher than the collector's temperature, a higher efficiency will result (see Figure 2 and 3). If the ambient temperature is lower, the efficiency is also lower, due to more thermal losses. The user must therefore try to adapt the collector's inlet temperature, in order to reduce losses and maximise efficiency.

For the analysed object, where mean ambient temperature between seasons varies a lot ($T_{ambient}$ winter: ~3°C, $T_{ambient}$ summer: ~18°C), the efficiency during summer and winter periods are completely different. This necessarily results in poor collector performance during the winter season (see Figure 3 below).

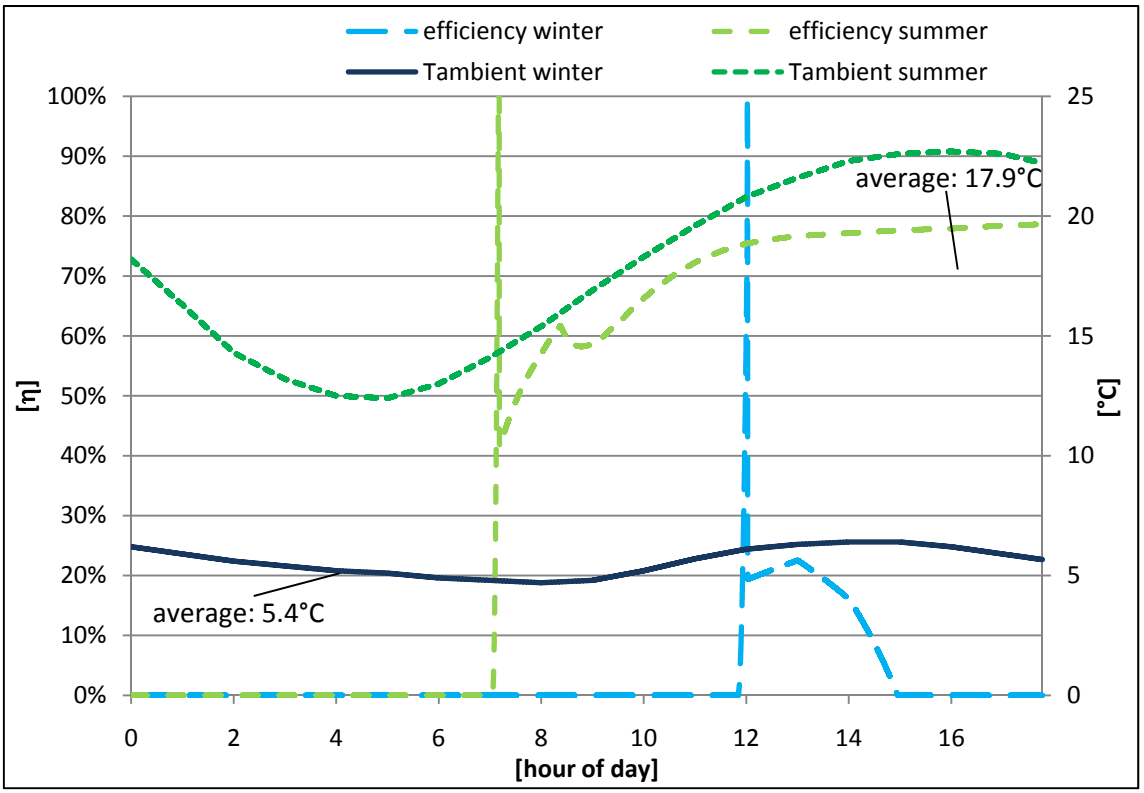


Figure 3: Efficiency curves for a typical day in June (summer), and December (winter) with a constant collector inlet temperature of 40°C and mean ambient temperatures of 17.9°C respectively 5.4°C (efficiency scale on left and temperature scale on right)

While one option to improve solar collector efficiency is to adapt inlet temperatures, the other option is to store unused thermal energy when the heat production exceeds the demand (typical situation for oversized installations or during sunny periods in summer). Summarising, the objectives for an optimisation of the solar collectors are:

- increase solar energy storage possibility (when production exceeds demand)
- keep efficiency high by controlling inlet temperature with seasonal storage
- maximise solar harvest (sun power is free) during year

3.2. Efficiency in Heat pump

The heat pump performance also depends on multiple factors, which influence its operation efficiency. The source temperature (T_{cold}) and the sink temperature (T_{hot}) are the most important. Luckily, these parameters can easily be adapted within the analysed installation. The source circuit of the heat pump is a geothermal well with the following variables:

Table 3: Parameters for the geothermal well

parameter	value	units
depth	150	m
tube Ø	0.026	m
borehole Ø	0.126	m
earth	LMM (sandstone)	-
lambda earth	3.1	W/m*K
T gradient	0.03	K/m
T at surface	16	°C
brine	normal water	-

A simulation with the given values (Table 3) shows the temperature dependence of the efficiency (COP). Although T_{cold} is quite steady (T_{cold} = 12±2°C), the COP is changing considerably because of T_{hot}. The "real COP" (see definition and curves in Figure 4) of the heat pump varies between 6.7 and 3.2.

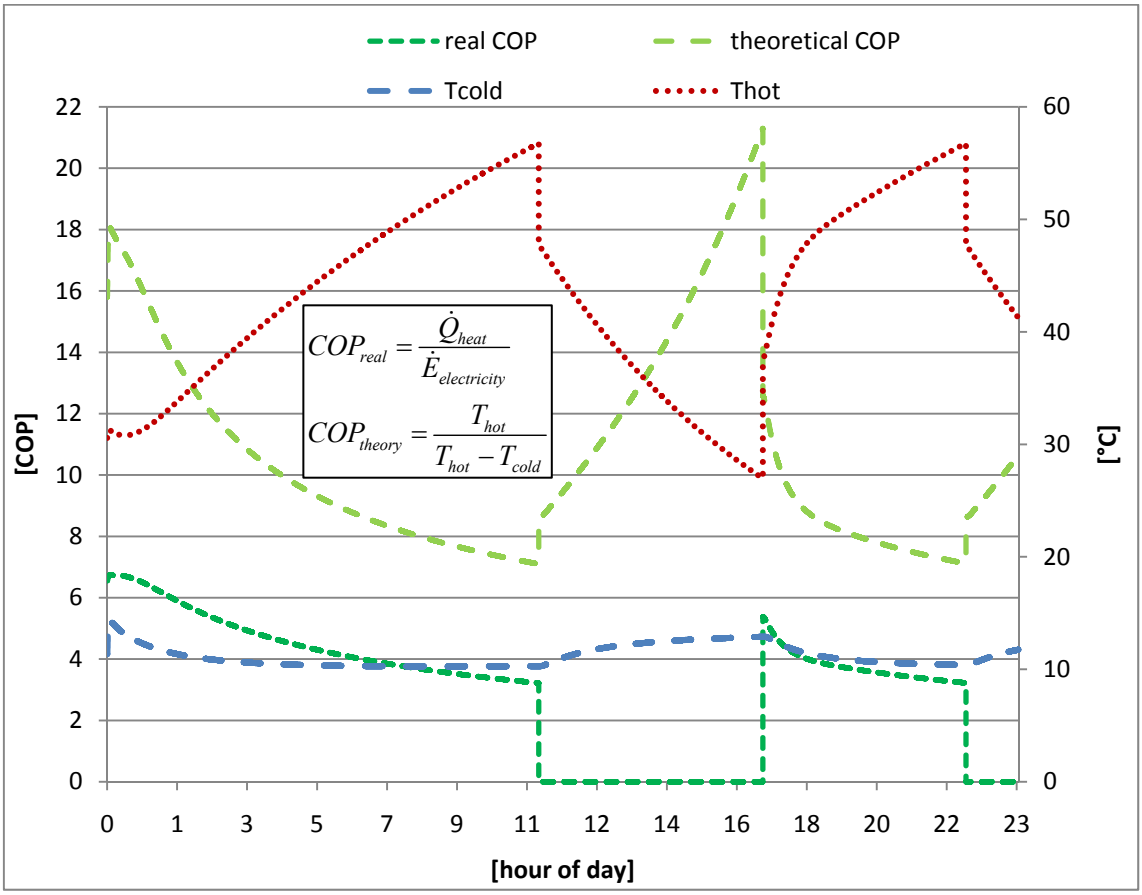


Figure 4: The left-hand scale shows the COP and the right-hand scale the temperatures. Note: the pump was turned off between 11h15 and 16h45.

In order to get higher COP, two possibilities are available. Either T_{cold} must be higher, or T_{hot} lower. Unfortunately, the value for T_{hot} can hardly be adapted, because of the necessary heat energy for DHW and heating demands. However, thanks to the seasonal storage, T_{cold} can be adapted with temperatures higher than the usual 12°C coming from the geothermal well. The COP will thus be optimised, and the otherwise unusable temperature range between 15-35 °C from the seasonal storage can be efficiently exploited. Summarizing, the objectives for an optimisation of the HP are the following:

- keep source temperature as high as possible
- keep sink temperature as low as possible (if no DHW is needed, only heating demand must be fulfilled→45°C instead of 60°C)
- keep operation time low and during low electricity tariff hours (electricity consumption)
- keep cycles low (effect on life-time of heat pump)

3.3. Thermal storage

One major problem with solar collectors is, that solar energy is often available when there is no demand, and that the efficiency of the solar collectors sinks, when the temperature differences increase (temperature between mean collector temperature and ambient outside temperature). An additional large-scale thermal storage permits storing excess heat in

summer and “doping” solar collector and heat pump inlet temperatures in order to achieve higher efficiencies. To optimise the behaviour of the seasonal thermal and the stratified storage, the following objectives were defined:

- minimise thermal losses (keep temperature gradients low)
- the minimal temperature at the DHW storage outlet should be raised to 60°C once a week to reduce hygienic risks from Legionella (BFE 2007).
- reduce peak demands: DHW and heating demands should not consume energy simultaneously
- maximise solar collector efficiency by “doping” inlet temperatures with seasonal storage
- maximise heat pump COP by “doping” inlet temperatures (source circuit) with seasonal storage
- maximise solar energy harvest in summer (don’t waste free solar energy)

3.4. Objectives for optimisation

The optimisation of the whole installation is inevitably a compromise between highest efficiencies, high comfort levels for the inhabitants and lowest operating costs. After analysing each subsystem individually, the following optimisation objectives were defined:

Table 4: Summary of optimisation objectives

description	units	criteria	evaluation
main objectives			
non-renewable energy	[kWh]	minimum	annual consumption
operation costs	[$]	min costs, min cycles	overall operating times of pumps and installations, average length of cycles, number of cycles per installation
second order objectives			
maximum thermal comfort	[hr, °C]	heating period: 21.5±2.5°C	number of hours above/below comfort temperature per day (SIA180 1999)
DHW demand	[hr, °C]	40°C for 5min	number of hours per day not covering demand (risk factor)
maximum solar energy harvest	[%]	maximum	percentage of available solar power captured
maximum efficiency in solar installation	[%]	maximum	system boundary around solar installation
maximum efficiency in HP installation	[%]	maximum	system boundary around HP installation

3.5. Optimisation with genetic algorithms

For the optimisation, adaptable system variables (on-off conditions, temperature levels, mass flows and switch conditions) are defined in input blocks (see Figure 5) and linked to the simulation (Matlab-Simulink) with the optimisation software ModeFrontier (ESTECO 2010). The simulation is then run using random choices inside given boundaries for the input variables and bringing out the values for the chosen optimisation objectives. According to the defined objective tendency (for example: minimise costs), and after several consecutive simulation runs, the genetic algorithm will start analysing the output values and making more intelligent choices for consecutive simulations. Unpromising combinations can thus easily be skipped to reach faster convergence towards the objective goals (FMOGA: Fast converging

Multi Objective Genetic Algorithm). The higher the number of input variables and output objectives for the optimisation, the more time is saved with the fast-converging Multi Objective Genetic Algorithms compared a conventional design of experiments (DOE) setup.

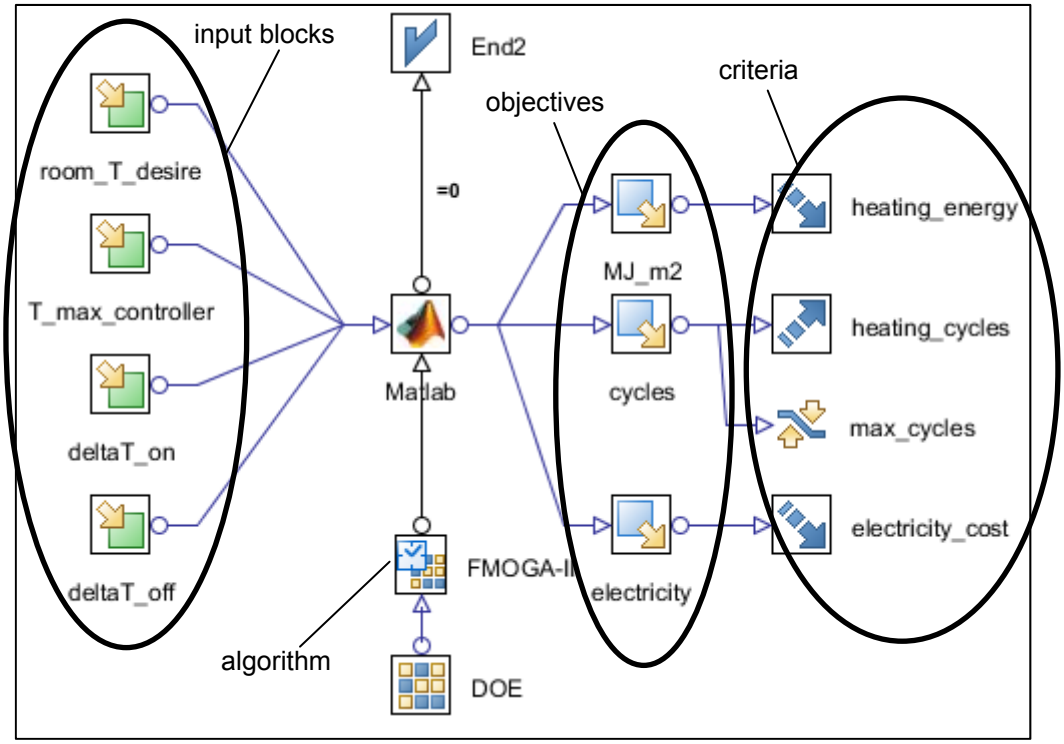


Figure 5: Optimisation model with genetic algorithms for fast convergence to objective goals

As mentioned earlier in this document, the optimisation will be a compromise between the different “best” conditions for each installation. It is therefore important to identify interactions between input variables, as well as sensibilities between objectives and variables.

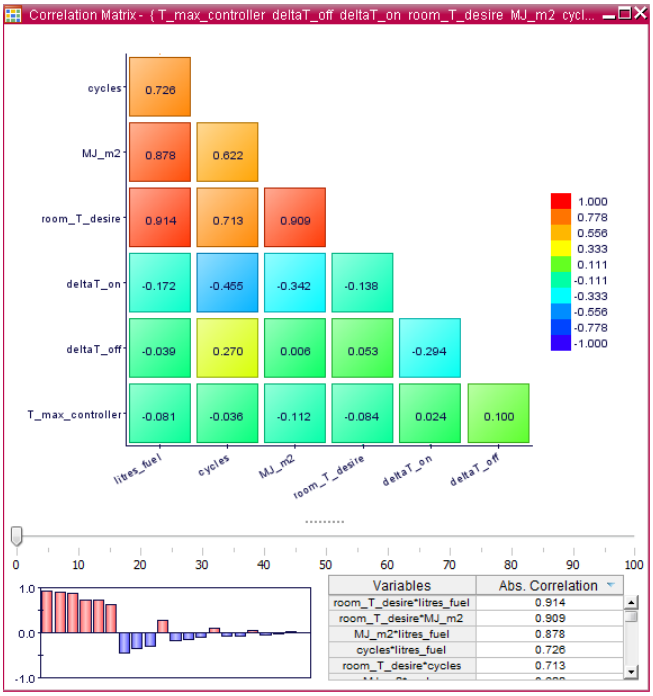


Figure 6: Interactions between input variables and objectives in visualised with a “correlation matrix” in ModeFrontier (ESTECO 2010)

In Figure 6, the correlation matrix points out the interactions between variables. This evaluation method helps decide if an adaptation of values will improve the system a lot or only insignificantly. For this small-scale simulation, a short manual calculation could also have proved that the heating demand per square meter (MJ_m^2) depends mostly on the desired room temperature (room_T_desire), and that the litres of fuel required depend on the heating cycles (cycles), the room temperature, and the heating demand. However, with a growing number of variables, a manual overview of the interactions between variables becomes complex and requires the help of visual presentation methods to better understand dependencies and relations.

After the optimisation, the variables with the most important influence on the system performance are identified and strategies can be developed to adapt them to their optimal temperature.

4 SIMULATIONS

Prior to simulating the entire system, each sub-system was simulated and validated with measured values. The solar collectors and the thermal storages were simulated first during a diploma work (Tenconi 2010). The thermal inertia of the building itself was calculated according to Swiss engineering norms (SIA380/1 3.2009) and simulated with Lesosai (E4Tech 2010) and Bsol (HEVs 2002). The weather conditions for the simulation originate from a weather station 5km west of the building (Marsens) and were generated from the official Swiss weather database (Meteotest 2011).

4.1. Simulation of building

The simulation of the building shows the overheating in summer and the thermal inertia of the massive elements of the house (see Figure 8 below). Selected measured mean values coincide with the mean temperatures of the simulation; a long-term measurement is on-going and will deliver more precise validation possibilities.

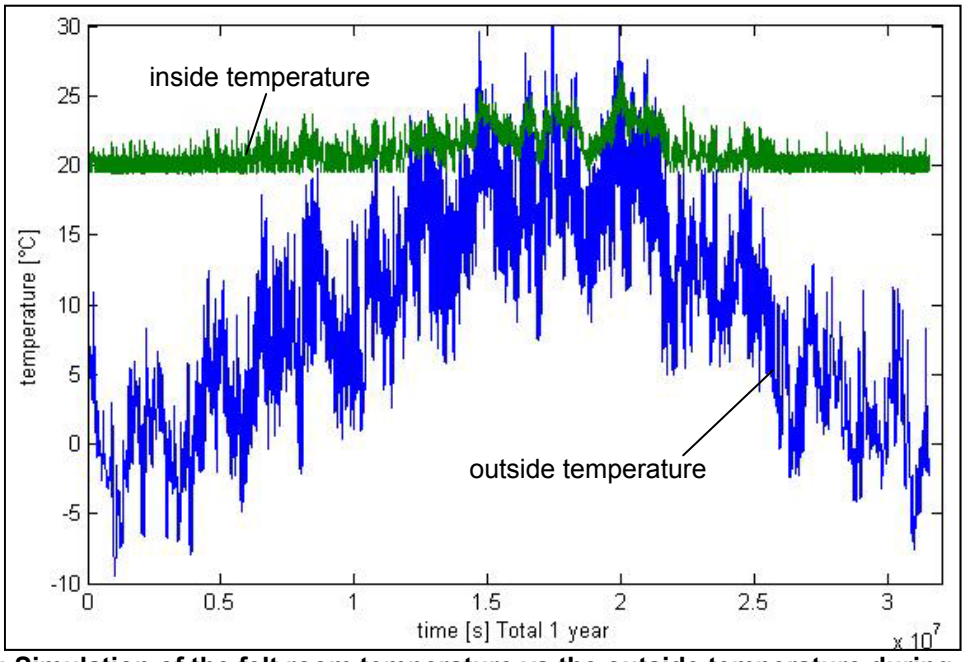


Figure 7: Simulation of the felt room temperature vs the outside temperature during one year

The graph of the temperatures shows that the inside temperature has a sharp boundary towards temperatures below 20°C, but varies when reaching temperatures above 20°C. Therefore, the following conclusions can be made:

- heating system reacts rapidly to temperatures below 20°C
- every excess of the comfort temperature (20°C) is an unnecessary energy consumption and therefore represents a potential to reduce energy consumption
- the heating period covers approximately three quarters of the year. This corresponds to the SIA standard for heating days for that region (SIA381/3 5.1984)

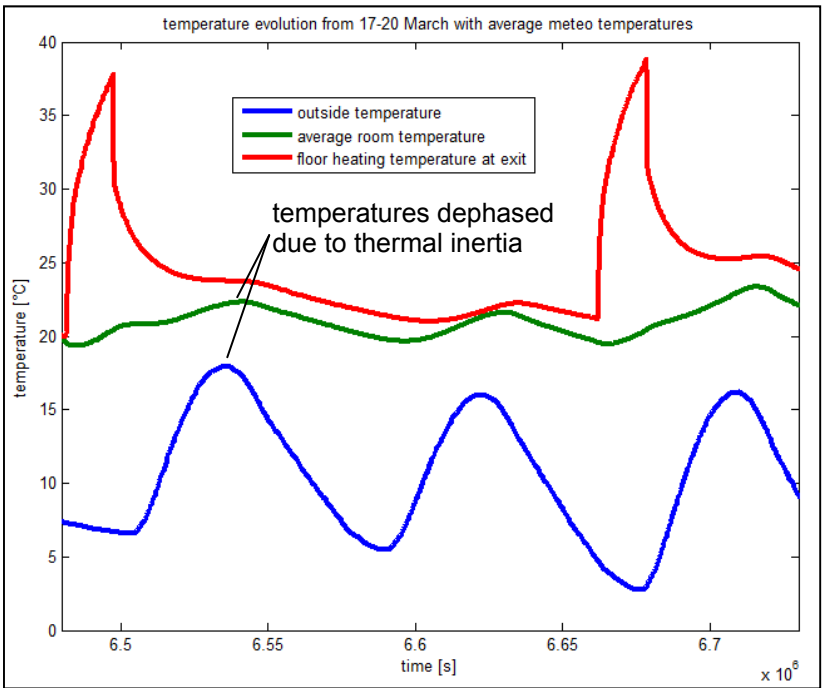


Figure 8: Comparison between outside temperature, perceived temperature and floor heating outlet temperature

The thermal inertia of the building causes an offset (Figure 8) between outside and inside temperature. This behaviour is convenient in summer, because the building stays cool during the day despite hot outside temperatures. During the heating period however, the offset may provoke unnecessary heating activation, leading to higher than necessary temperatures.

4.2. Stratified storage (1'650 litre)

For the simulation of the stratified heat storage a 1D calculation model based on (E.M.Kleinbach, W.A.Beckman and S.A.Klein 1993) was used. The model was tested and validated with real measurements (Tenconi 2010).

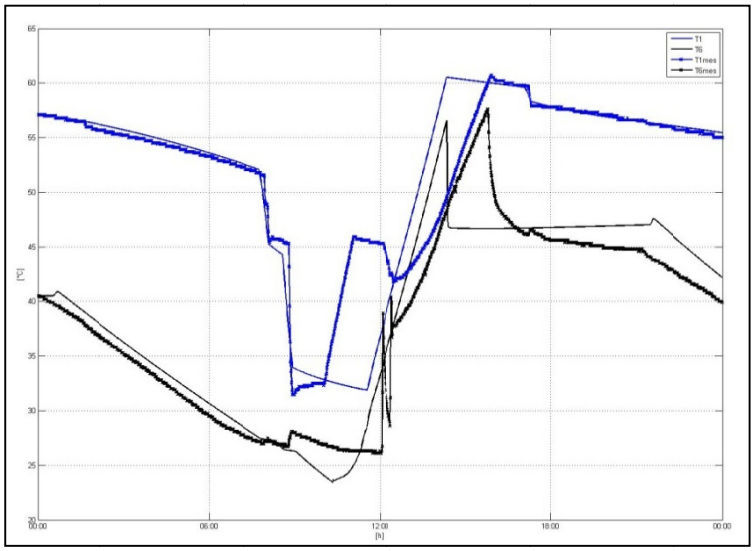


Figure 9: The simulation of the temperatures (thick lines) in the top and bottom layers correspond very well to the measured values (thin lines)

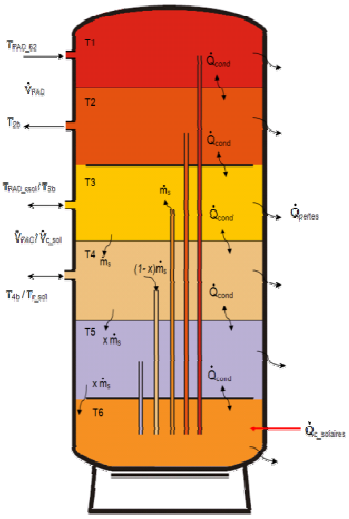


Figure 10: The storage was separated into 6 layers for the simulation

4.3. Seasonal storage (28'000 litres)

The simulation of the seasonal storage is similar to the stratified storage. However, due to the missing stratification discs and stratified charging, a stronger free convection movement reduces temperature differences between the top and bottom layers (1-4°C difference). Measurements in the tank have validated these simulated values.

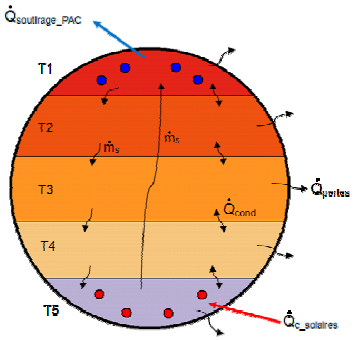


Figure 11: The seasonal storage was divided into 5 layers for calculation

The main question is, what control strategy is the cleverest:

- continuous storage of solar energy (even in summer, when the heat is not instantly needed)?
- a temperature dependant feeding of the stratified storage, DHW, the heating system, or the source side of the heat pump?
- a complete shut-down of the solar circuit when no energy is needed, thus saving standby energy from circulation pumps?

5 RESULTS AND FORECAST

After the first year of operation, a seasonal performance factor of 3.8 (SPF according to the FHBB Method (C.Wemhöner and T.Afjei 2003)) was achieved. This value is very low and several reasons were found to explain the disappointing result:

- humidity in the new building provoked more heating energy than calculated
- several malfunctioning controls and valves prevented optimal operation (teething troubles no solved)
- seasonal storage was filled up only after main solar harvest period (September), and therefore could not be used like planned in the first heating season

The technical installations and the thermal properties of the building were simulated individually using different software tools (Lesosai (E4Tech 2010), Bsol (HEVs 2002), Carnot

Blockset (Jülich-Solar-Institut 2007) and other small applications). The simulations for the solar collectors, the seasonal and stratified storage, as well as the building were simulated with weather data recorded throughout the year and compared to monitoring data with good correlation (see Figure 7, 8 and 9). The heat pump with the geothermal well was only grossly validated and will be compared more precisely prior to linking all components together.

5.1. Project forecast

The optimisation of the system will be carried out in three steps:

1. identification of most important variables and interactions between system variables influencing system performance with genetic algorithms
2. experimental tests on pilot object with most promising setups from optimisation algorithms
3. validation of results on two additional buildings with similar technical installations

The development of an intelligent control system, which monitors the resident's energy consumption habits and automatically chooses an optimal regulation, is on target as well as the use of simple weather forecasts for anticipated energy production. Additionally, the introduction of risk-based building control (% of risk that DHW is available) is planned and will allow a further reduction of operating costs and primary energy consumption for household energy demands.

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