“Solar fitness and wellness” – A unique design for sustainable wellness technologies

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Abstract. A spa facility with two saunas and a steam bath aiming at a primary energy demand reduction by a factor of 6 with reference to a conventional system was designed and built into the NEST innovation platform. For performance analysis, simulations over the course of a year were performed and calibrated with available measurement data. It was found that the efficiency goal along with the targeted annual net zero energy balance could be achieved. For an in-depth performance analysis in the future, a more stable operation and optimized control is needed along with measurement data for a full year of operation.

1. Introduction
The current Swiss energy strategy is targeting a clean and secure energy supply for the future by increasing energy efficiency and gradually substituting fossil and nuclear fuels with renewables. This shall drive a CO₂ emission reduction in Switzerland of 20% to 2020 with reference to 1990 [1]. An acceleration of the emission reduction targets beyond 2020 is foreseen in order to meet the Paris goal of limiting atmospheric temperature rise to 1.5°C with reference to pre-industrial era and will be implemented in the future Swiss CO₂ Act currently under negotiation.

Focusing on the service sector, reduction measures taken today will not be sufficient anymore to fulfil the more ambitious targets of tomorrow, especially given that in some sectors energy consumption is expected to rise in future. This is for instance true for the wellness industry including hotels with spa facilities. In 2001, Swiss hotels were responsible for 8.4% of final energy consumption and respective CO₂ emissions in the service sector [2]. Not only in Switzerland but globally, the spa economy is on the rise and reaches in 2017 an estimated market size of 119 billion USD and a growth rate from 2015-2017 of 6.4%, corresponding to twice the growth rate of the global economy [3].

In contrast to regular space heating in buildings, the operation of spa facilities and respective services such as sauna, steam bath, etc. requires heat to be provided at relatively high temperatures, well above 60°C. For simplicity and cost reasons, direct electric heating is typically used to provide this heat. Furthermore, the saunas and steam baths built today often hardly implement any energy saving measures such as high levels of thermal insulation. Consequently, there is a great and unused potential in this domain for energy demand and CO₂ emission reduction by increasing energy efficiency, reducing the share of high-grade energy and integrating renewables.

In view of this fact, Empa launched a building project within the research and innovation platform NEST (www.nest.empa.ch) under the name "Solar Fitness and Wellness" (SFW) with the declared goal to design, implement and operate a spa facility that shows a reduced high-grade energy demand by a
factor of 6 with reference to standard technologies being implemented. This paper gives an overview on
the energy system concept, component design, experiences from commissioning and first operational
results of this novel facility.

2. Design and Implementation
In the SFW unit, a fitness and spa facility for up to 12 persons was built with the aim of reducing primary
energy consumption by a factor of 6 compared to a similarly sized conventional system with a yearly
energy demand of 121 MWh/a. Furthermore, the energy demand of the entire unit shall be covered by
on-site solar energy such that a net zero energy balance over the year is achieved. An ideas competition
was launched to identify appropriate spa technologies along with their integration into a convincing
architectural design. The selected project features a fitness area, two saunas and a steam bath along with
a restroom, showers and dressing rooms. It focuses on a well-insulated building envelope with high
window fraction for passive heat gains, large building-integrated PV areas combined with some
evacuated tube collectors. The fitness equipment was selected based on energy efficiency with an
additional requirement on energy recovery, where available. The saunas have been equipped with high
levels of thermal insulation in order to minimize heat demands as well as the cooling loads of
the surrounding space. The energy system of the SFW unit was designed in the frame of a research project
funded by the former Swiss Commission for Technology and Innovation CTI with Empa, NTB Buchs
and HSLU as research partners and Scheco, suissetec, fit & wellness concept gmbh and Migros as
industrial partners. The heat supply for the saunas and steam bath, the sanitary hot water (SHW) and the
space heating is provided by a transcritical CO\textsubscript{2} heat pump, which additionally covers the space cooling
demand in summer [4]. A dedicated controller operates the saunas and the steam bath, not continuously
but on demand, based on a reservation system.

For the Finnish sauna a peak temperature of 120°C is required, resulting in very high pressures of
the refrigerant (CO\textsubscript{2}) in the heat pump. Due to the missing phase change and the non-linear behavior of
the specific heat capacity of CO\textsubscript{2}, the optimal load structure was determined by means of a pinch
analysis. In particular, it should be noted that high COPs of the heat pump can only be achieved if the
consumption can be organized in a temperature cascade (see figure 1) and the return temperature to the
heat pump is as low as possible. Since a demand-driven operation of the saunas was foreseen, a stratified
heat storage with a temperature spread from 20°C - 120°C was implemented (figure 2).

Besides the energy system design there were different components that were developed at Empa in
the frame of this project. These included all heat emission systems in the saunas as well as the low
temperature steam generator in the steam bath replacing conventional, direct electricity based systems.
Further, all saunas were equipped with CO₂-controlled ventilation and heat recovery units. In the bio sauna and the steam bath, dedicated enthalpy exchangers were used, which were developed and tested by HSLU. These allow for a 60% humidity recovery.

During the implementation and construction phase various practical challenges were encountered. Heat recovery in the spa area can lead to hygiene problems. Supply and exhaust air ducts and the enthalpy exchangers condense water vapor at a temperature close to 40°C favoring Legionella growth. In order to prevent a potential contamination, various thermal disinfection measures were implemented. The use of CO₂ sensors to control ventilation turned out to be difficult as they are neither temperature nor moisture stable. Further, low-temperature steam production with the newly developed evaporator was successful, but led to a strong thermal stratification in the steam bath, such that comfort was severely affected. This problem was alleviated by forced air convection.

3. Measured results
Initial commissioning of the SFW unit took place from November 2017 to January 2018, with remaining technical and regulatory challenges for some parts of the energy system. For safety reasons, final commissioning of the technical system did not take place until January 2019. The high storage tank temperature and hence system pressure made extra on-site inspections necessary. During this time, testing was possible only under laboratory conditions and unattended public use was not allowed. Nevertheless, in order to be able to characterize the load behavior of the whole system, the measured energy consumption of the different consumers (saunas, steam bath, storage, SHW production, space heating, and cooling) was analyzed, subdivided into typical sections and assembled by simulation into an annual load profile.

3.1. Analysis of preliminary measurements
The energy demand of the SFW unit had to be covered by PV, vacuum tube collectors and electricity supplied by the gym equipment (bicycles, etc.). A comparison of expected and measured annual values for demand and supply are presented in table 1.
Table 1. Energy gains of the year 2018

|                              | Measured  | Planned  | Comments                                           |
|------------------------------|-----------|----------|---------------------------------------------------|
| PV electric yield            | 21439kWh  | 18395kWh | Good solar year                                   |
| Vacuum tube collector        | 1020kWh   | 2500kWh  | Due to overheating of the storage, partially out of service |
| thermal yield                |           |          |                                                   |
| Gym equipment electricity supply | -877kWh  | 500kWh   | Available capacity unexploited, standby losses higher than expected |

In order to assess and to compare the efficiency of the implemented spa technologies to conventional ones, standard electrical resistance heaters have also been installed. Energy demand was measured for novel and standard system types. With the measured data, it is possible to determine typical demand patterns for each sauna/steam bath. Individual load profiles were divided into typical and recurring sections (heating-up phase, operating phase, drying phase (only steam sauna) and hygienic phase (bio sauna and steam sauna)). Time-averages were formed for each of the different measured sections and therefrom regressions were calculated and used in the simulation. As an example, the Finnish sauna in figure 3 can be considered. The red line represents the Matlab simulation which was carried out by NTB in the planning phase. It was used to determine the level of insulation and to design the heat exchanger of the sauna. The blue solid line is the mean curve of 57 operations with the electrical equipment (averaged over 5-minute time intervals). The blue dotted line is the regression used in the EnergyPlus simulation. For the bio and steam sauna, regressions were determined in the same way, with 82 and 11 operations, respectively.

The measurements show that the energy demand of the heat exchangers fed by the CO₂ heat pump is slightly higher than the one of the electrical equipment due to the losses in the distribution lines. However, the consumption of the entire production chain - from the CO₂ heat pump to the storage tank to the heating of the saunas - is of interest. This value cannot be measured directly as the heat produced by the heat pump is distributed to different consumers and the split is not easily visible. Therefore, the loads and losses of the different consumers are determined by means of simulation.

4. Simulation results

The simulations were performed with EnergyPlus (8.9.0) and Design Builder (4.7.0.027). Models implemented were validated with the help of measured values (from 1.1.2018 - 22.6.2018). In all simulations a DRY weather file created with Meteonorm 7.0 for the NEST site (Duebendorf) was used, a stratified water storage with 2000 liters was assumed and night cooling was considered.
Five different cases were simulated.
1. Sauna operation 12 hours daily, saunas electrically heated. Generic heat pump (COP 4.3) used for heating, cooling and SHW production.
2. Sauna operation 12 hours daily, saunas heated with CO$_2$ heat pump. Heating, cooling and SHW production with CO$_2$ heat pump.
3. Sauna operation 1 hour daily, saunas electrically heated. Generic heat pump (COP 4.3) used for heating, cooling and SHW production.
4. Sauna operation 1 hour daily, saunas heated with CO$_2$ heat pump. Heating, cooling and SHW production with CO$_2$ heat pump.
5. No sauna operation. Generic heat pump (COP 4.3) used for heating, cooling and SHW production.

The two cases with 12-hour non-stop operation correspond to typical operation schemes of spa facilities. The 1-hour operation case considered is more likely for private spa/sauna owners.

![Figure 4](image_url)

Figure 4. 5 different cases are simulated for one year with EnergyPlus. Energy demands for solar collector, PV, fitness devices, ventilation, light and building control are measured values (compiled from data by [5]).

When considering the results (figure 4), the following observations can be made:
- In the 12 hour case, the energy demand of the saunas is reduced by a factor of 2.9 with the use of the CO$_2$ heat pump instead of using direct electric heating
- In the 1 hour case, the proportion of storage losses compared to the heat output of the saunas is relatively high, though still achieving an efficiency gain by a factor of around 2.1 when using a CO$_2$ heat pump
- Cooling is already guaranteed when using the CO$_2$ heat pump (especially in 12 hours operation), which would need to be provided on top in an direct electricity based system design
- The goal of the annual net zero energy balance is missed in the case of the 12 hours operation by about 10% only, but is easily reached for the one-hour case.

Measured heat demands of the Finnish sauna and steam bath show a good agreement with planned values whereas heating demand of the bio sauna is around 35% higher than expected. In the heating-up
phase, much more water vapor is needed than expected due to absorption by the dry wood of the wall and the benches. The annual COP of the heat pump is measured to be 2.92 for the year 2018 vs. the design value of 3.15.

5. Conclusion
Based on the measurements combined with simulations, it can be stated that the original target of a net zero energy balance of the SFW unit was almost reached for the case of 12-hour operation. Demand-based control leads to considerably shorter operating times, from today’s perspective, to max. 4 hours a day. This would suffice for a net zero energy balance. If one looks only at the spa operation, the originally targeted energy efficiency improvement (with reference to a standard system through increased thermal insulation and the use of heat pump) by a factor of 6 could be reached. However, direct comparison with a standard spa facility is difficult as in the SFW unit auxiliary energy demands for space heating, cooling and SHW production are also included.

Even today (14.05.2019), the SFW spa facility is not yet fully operational. Some individual prototype components must be further improved. In addition, the control of the system is already highly complex and demand-based control is not yet being optimized. Furthermore, the entire unit is struggling with overheating problems in summer such that additional cooling demand could threaten the achievement of net zero energy balance.

6. Outlook
Future work concerns the operational reliability of the system and the optimization of control. In the above described project, the integration of a CO$_2$ heat pump and energy demand reduction were investigated. However, in order to make the system marketable, a subsequent project has to investigate possibilities for using fragrances in saunas and steam baths while avoiding clogging of the membranes in the enthalpy exchangers.

The CO$_2$ heat pump relies on consumers with heat loads at all temperature levels simultaneously. For the integration into existing spa facilities, it has to be clarified how to carry out component replacement. In such a case, not all temperature levels can necessarily be served in parallel. As the market for renovation projects is much bigger than for new systems, this question also has to be addressed in future.

7. References
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