ON-SITE TRIAL OF HEAT PUMPS IN SWITZERLAND

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Abstract: The initial aim of the Field Analysis of Heat Pump Installations (short called FAWA in German and Anis in French) project was to document the energy efficiency of small heat pumps of up to 20 kW_{th} in the field using statistical methods and to demonstrate improvement potentials. The project was started in 1996 by the Swiss Federal Office of Energy as an accompanying measure within the framework of its heat pump promotion strategy. It soon became the largest on-site trial of heating installations in Switzerland (and worldwide?).
In the course of the FAWA project, it became apparent that the data collected could also form the basis of deeper analyses of plant behaviour over longer periods of time and allow recommendations on plant concepts to be made.
FAWA describes and analyses the present-day reality in the field and, therefore, can supply inputs for the planning process. On account of the statistical nature of the data, however, the results derived from it cannot generally be understood as being general planning guidelines.

Key Words: ***heat pumps, efficiency, seasonal performance factor, field test, on-site trial, costs, renewable***

1 INTRODUCTION

Since the project was started, 30 newly-built installations were included in FAWA every year until 2003, whereby those of 94/95 were subsequently also registered. From 2004 on, a sample of 121 installations was kept for long-term observation.
Seasonal performance factors (SPF) are known for 221 of the 236 installations monitored until 2003. According to the market, the sample covers the following plants: 105 air/water, 94 brine/water, 10 water/water and 8 ground loop/water, 3 energy piles and 1 with direct evaporation. The collected data now cover about 1.4 million hours of operation. This means that FAWA can probably be considered as the largest and best documented quality-control investigation of a heating system worldwide.
The SPF calculations are based on readings made by the plant owners of their power and heat meters. In addition to energy measurements, half of the plants were also examined with respect to their system temperatures. On the basis of this data, it was also examined to what degree the figures for real-life aggregates - as far as performance figures and heat production are concerned - differ from the results of EN 255 and EN14511 tests (Swiss Heat Pump Test Centre, WPZ) and values computed from manufacturer's specifications.
Since 2004, the project has focused on key long-term features such as availability, evolution of efficiency, refrigerant leakage and running costs including maintenance, trouble-shooting and repairs.

2 CRITERIA FOR PLANT CHOICE

At the beginning of the project, no measured data were yet available concerning the statistical distribution (SD, standard deviation) of seasonal performance factors (SPF) in the field. It was therefore not possible to define how many plants would be needed in order, for example, to obtain an annual SPF mean value with a particular degree of confidence. The number of the new plants to be included annually (30) was decided not least for budget reasons. When actually choosing the plant, the attempt was made to fulfil as many of the following criteria as possible:

- **Thermal rating**: The heat pump plants should not exceed a thermal rating of a maximum of 20 kW_{th} as this category of installations dominates the market in numerical terms.
- **Heat sources** : Air/water, brine/water or water/water plants, whereby priorities are set in accordance with the market – air/water is chosen as a first priority and brine/water as second.
- **Types of product**: Series-produced devices, no custom-built items.
- **Operating mode:** Monovalent, mono-energetic or bivalent with measurable secondary heat generation.
- **Site:** Various geographic locations, according to living population.
- **Objects**: The installations are to be used in new buildings and refurbishment projects. Refurbishment objects are defined as being older than the heat pump, i.e. the heat pump has replaced another heating plant.
- **Hot water:** Installations with hot water preparation via the heat pump should be represented in accordance with their actual share of the systems in operation.
- **Ownership:** Only privately-owned plants are considered, no publicly-owned objects.
- **Testing:** The heat pump aggregates are, if possible, to be tested according to EN 255.
- **Instrumentation:** The plants are, if possible, already furnished with electrical and heat metering so that power consumption and the amount of heat produced by the heat pump installation can be recorded. Otherwise, it must be ensured that the plants can be retrofitted with modest expenditure.
- **Hydraulic integration: This** is checked to respect the state of the art.

A very important criterion is the heat source, i.e. air, soil (brine) and water. In the course of the project it was established that, with an annual sample size of 30 plants, it is impossible to make statistically relevant statements on all three groups as far as their seasonal performance factor is concerned. Therefore, at the end of 2000, the accompanying group decided not to include any further water/water and ground-loop systems in the test programme, as these only represent a very modest share in the Swiss market. From this point in time onwards, only 15 each of air/water and brine/water installations were selected. Today, we also know that the SPF spread of the brine/water installations is far higher than that of the air/water plants. The situation regarding air/water and brine/water plants established by the FAWA project is represented in figure 1. If, for example, a CI for the SPF of $\pm$ 10% should be attained for every installation year, 9 new A/W and 14 new B/W plants would have to be introduced into the programme every year.

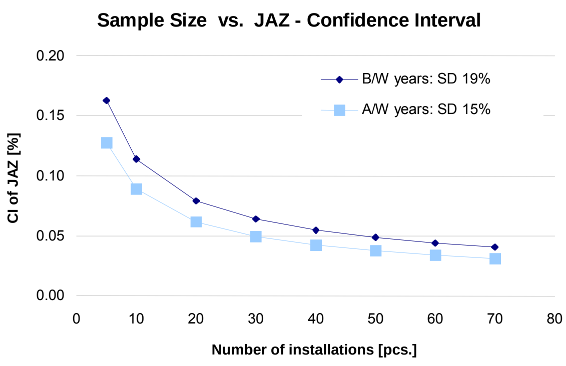


Figure 1: Standard deviation SD and confidence interval CI in function of sample size. "JAZ" stands for "SPF"

2.1 Measuring methodology

First step: To record data that do not change during operation, or that only change as a result of manipulation (e.g. automatic controller settings). They also include parameters concerning the building, the heating demand and the parameters of the heat pump installation itself. Second step: To record values during operation. Ideally, these meters are read and the measured values are noted by the property owners on a weekly basis, but at times it can also be that this is only done every three to four weeks.

Electricity consumption: An electricity meter registers the power consumption of the heat pump installation. Depending on the system boundary, the registered amount of energy is mathematically corrected. If the meter also monitors electrical supplementary heating, for example, its share in consumption can be determined using its power rating and running time and thus, if required (system boundary), be subtracted.
Measuring instruments: Usually, Ferraris-type induction meters with an accuracy class of 2 (not calibrated) and a measurement accuracy of +/-2% are used, but modern induction meters (Electrex, Ulrich Matter AG) with +/-0.5% are also employed.

Heat production: A heat meter (ultrasonic device) registers the amount of heat generated by the heat pump. If a storage boiler is installed and circumstances allow, the heat meter is placed between the heat pump and the storage tank. Computational corrections concerning specific system boundaries are carried out in the same manner as described for the electricity meter.
Measuring instruments: With a few exceptions, heat meters are in use that measure flow using an ultrasonic sensor. The temperature sensors are directly in the medium (no sleeves). In addition to the amount of heat produced, the heat meter also provides data on the volume flowing through the condenser. In 75% of cases, the heat meter was provided and installed by FAWA. Neovac (Siemens) 2WR3 to 2WR5 series devices are employed. They were chosen in such a way that the pressure drop caused by them caused no relevant reduction in the volume flow. The measurement uncertainty of these meters is +/-2.2% at most as determined by error calculations.

Running time and starts: Unless otherwise already registered by the heat pump control system, the running time and the number of compressor starts are counted using a mechanical counter. For installations with two compressors, this data is registered separately for both.
Measuring instruments: Analogue devices from EHS Schaffhausen (model 920) are employed. These include a counter for operating hours and an impulse counter. No information is available on their accuracy of measurement.

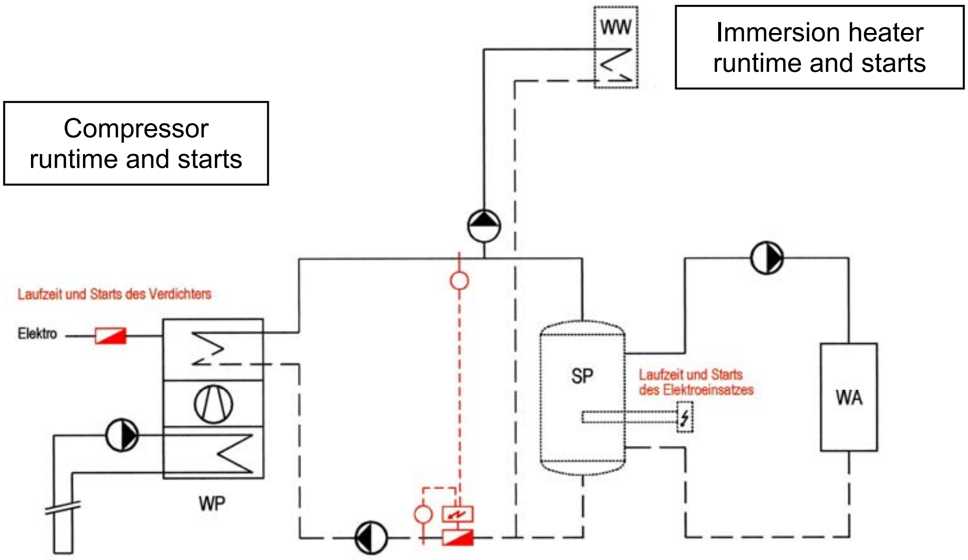


Figure 2: FAWA measurement diagram for long-term investigations. Heat and electricity meters, runtime counters and starts are read periodically by the plant operators. WP is heat pump, SP is accumulator, WA is distribution, WW is tap water

2.2 Definitions, boundary and models

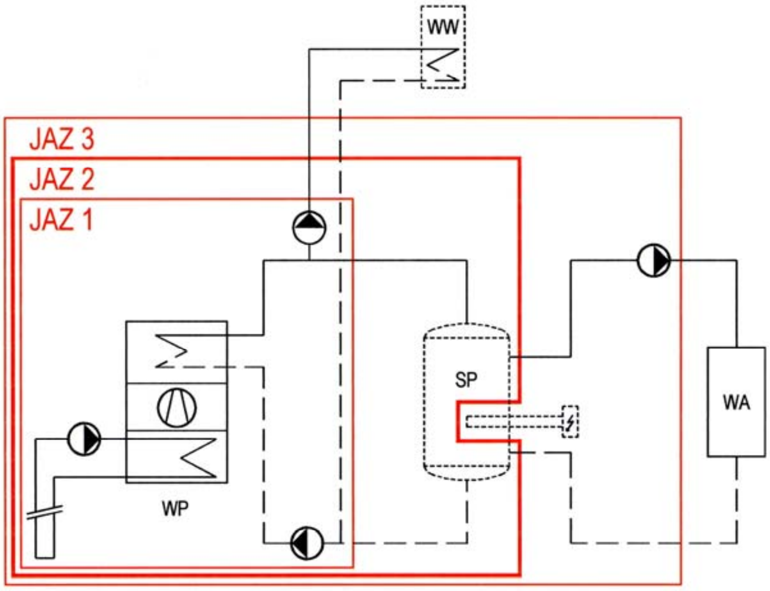
The heating season employed in the FAWA project begins on October 1st and ends on April 30th This period was chosen since, on the one hand, it covers the largest part of space-heating demand and, on the other hand, only in rare cases can periods without space-heating demand be found during this period. In this way, it can to a large extent be ensured that periods (data points) are excluded that are dominated by the power consumption of auxiliaries (circulation pumps) and storage losses.

The average outdoor temperature during the period between two readings made by the owners is calculated on the basis of data from the nearest meteorological station. A correction is made with respect to the difference in height between the object in question and the meteorological station. This is calculated using a height correction factor of around 0.5°K per 100 m.
The performance factor (PF) is the ratio between heat produced and power input over a specific period of time. If this ratio is calculated over a whole year, the resulting value is called the seasonal performance factor (SPF). In the FAWA project, three system boundaries were defined, resulting correspondingly in three different PF and SPF figures (cf. figure 3.):

SPF 1 Relationship between the amount of heat provided by the heat pump, without storage losses (if installed) and the heat pump's own specific power requirements, including auxiliary equipment such as circulating pumps and Carter heating. On the consumer side, only the power needed to overcome the pressure drop over the condenser is included (volume flow as measured by the heat meter). In the particular case of installations with storage tanks connected in parallel, the whole power consumption of the charging pump is included. For the remaining installations, the pumping power consumption for the condenser is estimated using its pressure-drop characteristics, the actual volume flow and an assumed value for pump efficiency (15%).

SPF 2 Relationship between the amount of heat delivered by the heat pump or from the storage tank (if fitted) and the heat pump's own specific power requirements, including the auxiliary equipment such as circulating pumps (on the consumer side only pressure drop over the condenser) and Carter heating. Therefore, for installations without storage tanks, SPF 1 is the same as SPF2.

SPF 3 Relationship between the amount of heat delivered by the heat pump or from the storage tank (if fitted), including electrical supplementary heating (for space heating and hot water preparation, the latter only if hot water preparation is integrated in the heat pump system) and the heat pump's own specific power requirements, including all auxiliary equipment such as circulating pumps (total) and Carter heating.
The current evaluations are based on SPF 2. The SPF 1 system boundary is only used as the basis for calculating expected values.



JAZ3 is SPF 3

JAZ2 is SPF 2

JAZ1 is SPF 1

Figure 3: System boundaries employed in the FAWA project for the calculation of SPF 1, 2 and 3. In the most cases, SPF 2, which takes any storage losses into consideration, is employed. For plant with no storage, only the power consumption of the circulation pump on the consumer side needed to overcome the pressure drop over the condenser is considered when calculating SPF 1 and SPF 2.

3 BUILDINGS AND SYSTEMS

Of the 236 plants examined by the FAWA project, 60% are in new buildings and 40% in refurbished objects. The number of refurbishment objects was chosen so that there were sufficient plants in this group to be able to draw statistically sound conclusions.

As far as the refurbishment objects are concerned, it should be noted that half of them were built after 1970 and that in 70% of them, energy-relevant refurbishment was carried out at the same time. In 25% of the cases, a total refurbishment of the building was carried out before the heat pump was installed.

The planned values for the Energy Index (EI is the yearly thermal energy consumption divided by the heated floor surfaces of the building) of the objects examined show a large spread. On average they lie around the 270 MJ/m^2 mark (SD 40%).

As far as the heat distribution and delivery systems are concerned, the refurbishment objects and new buildings examined in the FAWA project differ quite clearly. In 92% of the new buildings, floor heating predominates which, in part, is complemented by radiators. In refurbishment objects, the share of floor heating systems is about 53%.

Seasonal performance factors are currently available for a total of 221 plants. These cover 105 air/water (A/W) plant, 94 brine/water (B/W), 10 water/water (W/W), 8 ground-loop/water, 3 energy pile plants and one installation with a direct evaporation system.

In 50% of the plants, the heat pump is at least partly involved in hot water preparation. In 22% of the cases, hot water is heated solely by the heat pump. The remaining 50% of the plants have separate electric hot water boilers.

4 FINDINGS AND RECOMMENDATIONS

4.1 Customer satisfaction

In 1997, a survey showed that 78% of heat pump owners questioned indicated that they were very satisfied. A further 17% were rather satisfied. Only 3% had reservations and 2% were not satisfied at all with their heat pump. It is worth noting that half of those who stated that they were not satisfied at all were in fact complaining about the high price of electricity. This result which was nevertheless highly positive was almost certainly to do with the high figure of 99.5% for heat pump availability determined by the FAWA project. Heat pump plants have very few faults. Brine/water installations and installations without technical heat storage come out on top in this respect.

4.2 Availability

The problem is when a heat pump does not run when it is supposed to. Availability is defined as the ratio of time with defects divided by the operating time to cover the heat. Example: heat pump idle for one day out of 100 heating days means availability of 99%.
The data were collected on 121 plants over the past 13 years.
Problem occurred in definition of the kinds of faults due to different interpretations. Most of the time, it was necessary to call the owner and ask for further details.
The figure below shows the analysis of the data representing over 1.36 million operating hours.

Faults	All	New	Retrofit	Air/Water	Brine/Water
Operating time total [h]	1'360'580	702'430	658'150	333'886	713'336
Fault [h]	5'279	1'701	3'578	3’988	1'291
Availability [-]	0.9961	0.9976	0.9946	0.9882	0.9982
Plants with faults					
Number	31	15	16	13	18
Share	0.25	0.21	0.30	0.37	0.29

Figure 4: operating time, availability and faults of measured installations.

Availabilty was over 99.5%. No data are available on furnaces, but this value is very high. Retrofit plants have slightly more faults than new ones.

Statistically, the average for one plant is one fault every 4 years. Note that 71% of the plants did not have any trouble at all. The mean duration time of a failure was 40 hours (from callout by owner until heat pump runs again).

These results show the high standard of quality now achieved by small heat pump units.

4.3 Evolution of seasonal performance factor

The SPF values for brine/water plants (B/W) are, at an average of 3.5, about 32% higher than the values for air/water plants (A/W) with 2.7. It was also found that the SPF of B/W plants show a much greater spread than those of the A/W plants, no doubt because of the greatly different performance of individual geothermal heat probes. As far as improvements since 1994/95 are concerned, the two groups show an improvement of approx. 15%. The annual performance figures, when projected onto the Swiss plant park, with 59% A/W- and 41% B/W plants, have been seen to increase by 20% from 2.5 to 3.0 since the project was started. This increase corresponds very well with the results of the Heat Pump Test Centre WPZ. Also, the FAWA results, which show that the SPF has hardly changed since 1999, correspond to the WPZ data too. The average SPF of the plants measured has improved over the years. The improvements noted at the WPZ are also reflected in experience made in the field. The improvements measured in the field can be traced back primarily to better machines being used.

On the basis of test-bed measurements, a forecast of the efficiency of B/W machines was made and compared with measurements made in the field. These calculations showed on average a deviation of only minus 4% in comparison to the test-bed data. This shows that improvements in the aggregates observed at the WPZ have a direct effect on the energy-efficiency of the installations. This further confirmed that the machines presented to the WPZ for testing correspond to average products taken from the production lines of the manufacturers.

Thus, in everyday operation, the energy-efficiency of heat pump aggregates is as to be expected from test bed measurements (WPZ or manufacturer's specifications according EN255 or EN14511).

4.4 Ageing

The plants have also done unexpectedly well with respect to ageing. The first year is set as 100%. During the ten years of operation monitored, no significant reduction in the SPF could be found, either for the A/W or for the B/W plants. The soiling of evaporators and over-cooling of geothermal heat probes has therefore not been a topic of discussion up to now.

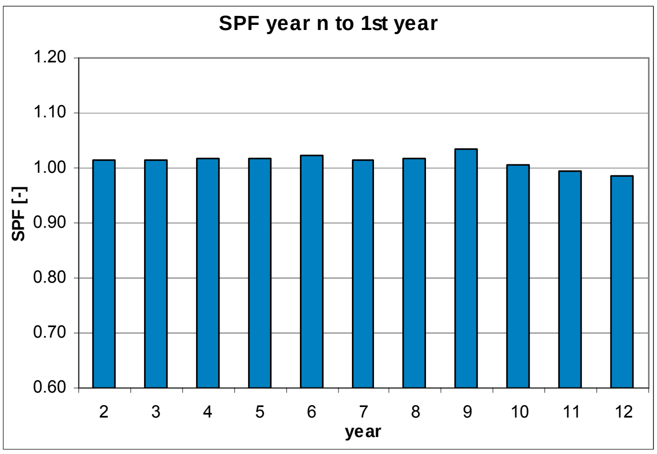


Figure 5: Aging of installation figured as SPF of year n divided by SPF of 1st year.

Standard deviation is 0.011 to 0.016 also more due to the accuracy of the measurements as to ageing effects.

4.5 Electrical supplementary heating

Real-life operation of A/W plants has shown that electrical supplementary heating is not required for normal heating operation and, therefore, that the entire heat requirement can be covered by the heat pump, even at low outdoor temperatures, down to -10°C. However, electrical supplementary heating can nevertheless be useful during the commissioning and drying-out of buildings. On the basis of measured capacity utilisation under design conditions, it was established that the aggregates are often oversized, in particular in B/W installations. The resulting disadvantages are primarily of an economic nature.

Air/water heat pumps can be operated in monovalent mode (without electrical supplementary heating) in the Swiss lowlands without incurring problems as long as there is an outside air temperature for dimensioning of above -10°C. No electrical supplementary heating is required for normal heating operation. The use of an electric heating element can be useful during the commissioning and drying-out of buildings. Brine/water heat pumps are often oversized, which has a negative effect on costs. When designing brine/water heat pump installations, the planning-in of capacity reserves is to be avoided. An electrical heater for the drying of a new building is better and more efficient than the over-dimensioning of the heat pump and/or an overloading of the earth probe.

4.6 Hot water heating

FAWA shows that, when compared with electrically heated boilers, clear environmental and energy-relevant advantages can be gained through the integration of domestic hot water heating, see figure 6.

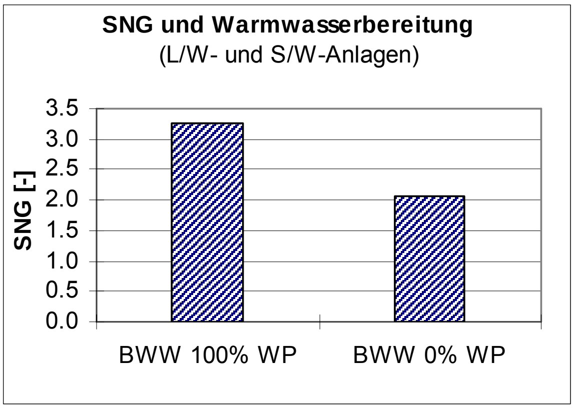


Figure 6: Comparison of the seasonal performance factor SPF of plants making hot water with the heating heat pump ("BWW 100% WP") or with a electrical boiler ("BWW 0% WP")

Considerable differences were also found concerning the different ways of integrating domestic hot water heating. Please note: the tap water temperature of 55°C or 60°C alone does not determine the COP of the boiler. The key value is the mean temperature during the heating of the tap water. Loading the hot water tank from 35°C to 55°C gives a mean temperature of only 45°C, which determines the COP. This explains why there is no significant difference in the SPF of plants making only heating or making heating and warm water.

As far as energy efficiency is concerned, separate, slightly undersized boilers (for one day's requirements) with internal heat exchangers have proved to be the most effective and most reliable. Multi-purpose boilers should only be employed when combined with other sources of energy (sun, wood).

4.7 Technical accumulators

Technical accumulators have no positive influence on the SPF. They cost money, however, take up space and complicate an installation and should, therefore, only be used where they are really necessary. Technical accumulators have no influence on the Seasonal Performance Factor. Technical accumulators make plants more expensive and complicated and, therefore, should only be employed where they are absolutely necessary. Best example: to get two independent hydronic systems, one for heat production around the heat pump and one for heat consumption. An accumulator is recommended when the mass flow of distribution is not well known (retrofit) and/or variable (radiators with valves).

4.8 Geothermal heat probes

As already mentioned, large differences are to be found in the SPF of B/W plants. The presumption that an important reason for this was to be found in the strongly differing characteristics of the complex sub-system soil - geothermal heat probe - heat probe circuit was confirmed. Although the brine temperatures measured lie quite high – at almost 5°C on average – their spread is quite large, however. The brine temperatures measured could only be explained in part by geological data. The rule of thumb currently employed of 50 W/m for probe design could not be confirmed as being a guarantee of good results. The energy extracted annually per probe length, 100 kWh/meter/year should instead be recommended as a basis for design. A factor with high potential for optimisation and which can be implemented relatively simply was discovered in the circulation pumps in the brine circuit. Over-sizing the brine pumps has a clearly negative effect on the SPF of the B/W plants. Brine/water heat pumps are mostly over-sized. If the geothermal heat probe is laid out in accordance with the heat pump rating, it is usually too long, too. The brine temperature is influenced by various factors, particularly of a geological nature. If no detailed information is available in this area, a considerable potential for uncertainty remains.
Brine circuit pumps are often over-sized, which has a clear, negative influence on the energy-efficiency of the installations

Only the better and more appropriate design of the geothermal heat probes can lead to economically and energetically optimal results. Drilling companies should become more involved in this task. Attention should also be paid to the correct sizing of the brine circuit pumps.

4.9 Costs of maintenance and repairs

We carefully collected data on maintenance and repairs. Maintenance costs are part of the normal operation of the plant. Example: change of used part after normal lifespan/operation time, controlling and refilling refrigerant as requested by law, normal change of filters, cleaning of heat-exchanger. We consider these as maintenance as far as they are defined in the buying contract of the heat pump installation.
Repair: change, retrofitting or repair of a part or component after a fault has occurred.

Costs of energy (electricity) for the heat pump were not recorded because of the huge range of electricity prices in Switzerland (the 1200 utilities sell 1kWh electricity for heat pump between 4 and 20 eurocents). This makes any comparison of costs impossible. So we concentrated on costs which are not influenced by local commercial behaviour.

We collected reliable data on 61 plants. The heat sources are: 31 earth probes, 3 earth collectors, 1 energy pile, 22 air, 4 water. 31 heat pumps are for heating and hot water, 30 are for heating only.

The average costs for maintenance are as low as CHF 50 a year (lower than 30 euros). There is no maintenance in the first two years because these are under guarantee.

Repair costs are more variable than expected. Mean value is not accurate in case of heavy damage requiring changes of key components such as compressors. Classic repairs and/or exchanges are much less expensive: heat exchanger, expansion valve, regulation, circulation pump. The average is lower than CHF 120 a year (70 euros) which is quite low. It is clear that a single serious fault can dramatically increase the mean value. But the probability of such a repair depends on the availability of the plants. Since the value is over 99.5%, the risk remains very low.

For an economic calculation, the value of about CHF 170 or EUR 100 a year can be taken into account and added to electricity and capital costs.

5 CONCLUSION

Implementing all the recommendations of the on-site trial, the SPF can be improved by 25% for air/water (3.4 instead of 2.7) and 60% for brine/water (5.5 instead of 3.5). This is confirmed by the average of the 5 best plants measured at 3.1 (air) and 5.0 (brine).

6 GLOSSARY

A/W Air/water plants

B/W Brine/water plants

CI Confidence Interval
It designates the interval in which the true value - that is the mean value of the appropriate characteristic (e.g. SPF) - lies within a particular error probability (here = 5%). The true mean value designates the mean value of the statistical population; in FAWA, therefore, the average over all plants of a particular category (e.g. A/W or B/W) in Switzerland.

$$CI = \hat{M} \pm z\sqrt{Var(\hat{M})}$$

$$Var(\hat{M}) = (1 - \frac{n}{N})\frac{SD^2}{n}$$

$\hat{M}$: Estimated mean value
z : Top $\frac{\alpha}{2}$ Quantile of the Standard Distribution
Var : Variance (Estimate of the true value)
n : Sample size
N : Poulation size
SD : Standard Deviation

COP Coefficient of Performance
Relationship between the heating capacity to the electrical power drawn by compressor, de-icing equipment and pumping equipment (cf. EN 255 and EN14511)

EKZ, Energy Index (for space heating): Heating energy requirements per m^2 energy consumption area.

HW Hot water, with:

- >0%: Hot water partially or wholly supplied using heat pump
- Wi_o_So 100% heat pump: Heat pump heats up the hot water in winter and summer to 100%
- WP Preheat: only pre-heating of hot water by the heat pump
- WP+SoCo: Hot water heated up by heat pump and solar collectors

Mono energetic A second, electrically operated heating element is used to help meet space heating requirements (immersion heater)

monovalent WP aggregate meets the entire space heating requirements

Plant The entire technical heating installation, containing, in particular, the heat source, heat pump aggregate (cf. aggregate), storage tanks, hot water boilers, heat distribution system and auxiliary equipment.

Q Amount of heat

r Pearson coefficient of correlation. This coefficient is a dimensionless index with the range of values $-1.0 \leq r \leq 1.0$ and it is a measure of to what extent a linear relationship exists between two data records.

Value (absolute)	Degree of correlation
0.00	no relation
> 0.00 to 0.40	low relationship
0.40 to 0.70	middle relationship
0.70 to <1.00	high relationship
1.00	complete relation

Rad. Radiators as delivery system

SD Standard deviation
Measure of the spread of a characteristic around its mean value. Calculation of the SD on the basis of a random sample (n < N) are always only estimates of the true value; other values subsequently based on it are, therefore, also only estimates (e.g. the confidence interval).

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{N}(y_i - \bar{y})^2}$$

y_i: Value of a data point i

$\bar{y}$: Mean value of a series of values y

SPF 2 Climate-adjusted SPF 2 Regression value (t = 4°C) of performance coefficients for periods with differing mean ambient temperature

Ta Outside temperature

T_{brine} Temperature of the brine at entry into the heat pump.

Tfl (dim.) Flow temperature at dimensioning conditions (usually Ta = -8°C)

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