COMBINING HEAT PUMPS WITH SOLAR ENERGY FOR DOMESTIC HOT WATER PRODUCTION

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Abstract: The knowledge about the reduction of heat demand in dwellings has reached a sophisticated level, especially regarding the building envelope. The next step are net zero energy buildings, where the total amount of yearly energy demand is covered by building integrated generation of energy from renewable sources. The most promising technologies are solar heat panels, photovoltaics and heat pumps. But it is not yet obvious which combination is best.
In a simulation study two combinations of air-to-water heat pumps with either solar thermal collectors or photovoltaics have been scrutinized. All system components applied are field proven and available on the market. The results show that both combinations are nearly equivalent regarding energetic efficiency, economical feasibility and environmental impact. Although the heat pump was sized to cover space heating and domestic hot water demand, the focus lays on the domestic hot water preparation. Both systems cover 50 % of the final energy demand for domestic hot water from solar irradiation, required by local regulations.

Key Words: heat pump, solar heat, photovoltaic, domestic hot water, ecological impact

1 INTRODUCTION AND STUDY CONCEPT

In the two cantons Basel-Stadt and Basel-Land in Northwestern Switzerland the use of at least 50% renewable energy is required for domestic hot water (DHW) production. A master's thesis examined the use of air/water heat pumps combined with solar energy. The following project extended the focus on further systems fulfilling the legal requirements. This paper shows the concluding results concerning ecological and financial aspects.

1.1 Background and objectives

The cantonal by-law on the rational use of energy states that "The domestic hot water in new housing, schools, restaurants, hospitals, sports facilities, swimming pools and other large domestic hot water consumers must be heated by at least 50% renewable energy such as solar energy (solar panels), geothermal energy, wood energy or district heating or otherwise unusable waste heat." (Basel-Land 2010).

Therein brine/water heat pumps (B/W-HP) are allowed without solar energy system, but air/water heat pumps (A/W-HP) are, amongst other reasons because of their lower seasonal performance, only allowed in combination with solar thermal (ST) or photovoltaic systems (PV). Especially for the combinations of A/W-HP with ST or A/W-HP with PV it is not obviously clear which combination is best concerning ecological and economical aspects. The present study examines this question for a single-family house, wherein A/W-HP systems were considered in more detail due to the combination with PV or ST. The influence of non-optimally adjusted and therefore larger solar panels on ecology, cost and hydraulic aspects of the combination of heat pumps and solar heat systems were also examined, but are not shown in this paper. For comparison purposes, further solutions are considered. An overview of the systems is shown in Table 1.

Table 1: examined system combinations for domestic hot water generation

heat generator	solar system
air/water heat pump	photovoltaic
air/water heat pump	solar heat (flat plate)
air/water heat pump	solar heat (vacuum tubes)
brine/water heat pump	-
wood pellet furnace	-
oil furnace	solar heat (flat plate)
gas furnace	solar heat (flat plate)

2 STUDY APPROACH

Background of the study is the legal requirement of 50% renewable coverage for domestic hot water heating. Therefore the results used for the comparison contain only the part for domestic hot water preparation. That means furthermore, that the infrastructure of the heat generators is allocated according to the energy need, which is approximated to 25% for DHW (considered) and 75% for space heating (not considered). The end energy consumption and emissions during operation are calculated only for DHW operation.

The energetic and ecological evaluation for the heat generation systems is based on simulations with the software Polysun (Polysun 2010). As far as possible, ready to use system combinations and product data implemented in the simulation environment were used; and where necessary, completed with more detailed product data. The focus is on market available systems. The heat demand in the simulations consists of a reference building with an energy reference area (EBF) of 200 m^2_{EBF} and the standard domestic hot water demand. The design of the heat generators is in such a way that the solar systems just fulfil the legal 50% requirements and the other heat generators are dimensioned to supply the full domestic hot water as well as the space heating demand.

The ecological evaluation is done based on the ecological impact calculated as ecological scarcity (Frischknecht et al. 2009) as well as by global warming potential expressed as CO_2-emission equivalents per year. Therein infrastructure and operation related impacts are calculated and displayed separately. Basic information is taken from ecoinvent-database version 2.01 and 2.2 compiled by ESU-services Ltd. (ecoinvent 2007/1 to ecoinvent 2010). The method of ecological scarcity is applied to the situation and the objectives in Switzerland. The economical evaluation is based on guideline offers for the Basel region and average Swiss energy prices. Detailed information about the assumed parameters is documented in the following.

2.1 Cantonal requirements for air/water heat pumps

An A/W-HP for domestic hot water generation must, for the legal 50% requirement, either have a solar thermal or a photovoltaic system. In the combination of A/W-HP with PV system, the PV system has to generate 50% of the annual heat pump electricity demand, whereat the annual heat pump performance factor is assumed to be 2.3 and the domestic hot water demand to be 50 $MJ/m^2_{EBF}/a$. Hence, the reference building requires PV collector areas between 4.9 m^2 and 8.9 m^2, corresponding to 700 to 1200 W_{peak} depending on the orientation with mono-crystalline modules. In the combination of A/W-HP with solar thermal system, the collectors have to supply 50% of the generated heat supplied to the domestic hot water storage. The resulting aperture areas for flat-plate absorbers are between 2.8 m^2 and 8.3 m^2, for vacuum tube absorbers between 2.4 m^2 and 5.1 m^2.

2.2 Boundary conditions

The boundary conditions were set identical as far as possible. Common boundaries for all systems are:

meteorological station:	Basel-Binningen
shading:	none
cold water temperature:	10 ºC
hot water temperature:	50 ºC
warm buffer storage connections	with siphon
insulation of buffer storage	100 mm PU
pipe length to faucet	10 m

The insulation of the hydraulic pipes is identical in all systems and just fulfilling the cantonal requirements as depicted in Table 2.

Table 2: minimum insulation thickness for SH and DHW distribution lines up to 90 °C

nominal pipe size	nominal pipe size	insulation thickness with $0{,}03 < \lambda < 0{,}05$ W/mK	insulation thickness with $\lambda < 0{,}03$ W/mK
mm	inch	mm	mm
10 - 15	3/8" - 1/2"	40	30
20 - 32	3/4" - 1 1/4"	50	40
40 - 50	1 1/2" - 2"	60	50

2.3 Reference building

Characteristic data of the reference building is summarised in Table 3. The reference building represents a typical building for the canton Basel-Land. The space heat demand and the standard heat load are required for the dimensioning of the heat generators; the energy reference area for the calculation of the domestic hot water heat demand.
Values in Table 3 are yearly average or yearly summed up values. The domestic hot water distribution system is built without a circulation line to keep the temperature in the piping on a high temperature level because a short distance between the storage and the faucets is assumed.

Table 3: Characterisation of the reference building

Energy reference area (gross floor area)	A_{EBF}	196 m^2
standard heat load acc. to SIA 384/201 (SIA 2003)	Φ_{HL}	5.1 kW
heat demand for space heating + domestic hot water	Q_h+Q_{ww}	205 MJ/m^2/a
space heating demand acc. to SIA 380/1 (SIA 2009)	Q_h	155 MJ/m^2/a
domestic hot water heat demand (SIA 2009)	Q_{ww}	50 MJ/m^2/a
domestic hot water heat demand (total)	Q_{ww}	2’722 kWh/a
average daily hot water consumption (50 °C)		160 l/d

2.4 Domestic hot water storage

The domestic hot water storage has a size of 300 litres without and 500 litres with solar thermal system respectively. An internal heat exchanger is used for the heat transfer from the heat generators (including solar heat) to the domestic hot water storage. The storage is made of ordinary steel. The hot water set point is 55 °C.

2.5 Domestic hot water draw off

The domestic hot water heat demand is with 50 $MJ/m^2_{EBF}/a$ assumed to be equivalent to the heat demand according to the Swiss standard calculation of the space heat demand SIA 380/1 (SIA 2009). The draw off profile was taken from the final draft FprEN 16147 (CEN 2010). Therein single draw offs like shower, bath, dish wash and so on are defined with time and drawn energy. The profile has been adapted to the yearly energy demand. During the summer month July and August a 20% reduction of the domestic hot water demand is assumed with a unique demand apart from that. The additional heat generators for domestic hot water generation are only enabled during the night; the wood pellet furnace without solar heat system in the early morning hours. Only a few simulations required additional hot water heating in the afternoon.

2.6 Solar heat systems

The solar heat system is characterised as follows:

collector circuit piping:	in total 30 m (2x15 m), thereof 10 m outside
collector circulating pump:	30 W maximum electric power consumption
flat plate collector:	eta_0 = 0.750; b_1 = 3.50 $W/m^2/K$; b_2 = 4.00 $Ws/m^3/K$; A_2 = 0.0200 $W/m^2/K^2$
vacuum tube:	eta_0 = 0.764; b_1 = 0.99 $W/m^2/K$; b_2 = 1.02 $Ws/m^3/K$; A_2 = 0.0053 $W/m^2/K^2$

2.7 Photovoltaic systems

The photovoltaics system is build up from polycrystalline modules and invertors adapted to the collector capacity. The PV modules are characterised as follows:

temperature coefficient	-0.47 %/K	module efficiency STC	0.13
maximum power output STC	180 W	gross module surface	1.4 m^2
soiling	2%	degradation	0.5%
cable losses	4%	mismatching	4%

2.8 Air/Water heat pump

The air/water heat pump reaches a maximum flow temperature of 55 °C (high pressure switch-off at 58 °C). The COP at A2/W35 is 3.4. The set domestic hot water tap temperature of 50 °C was just reached in the simulations. The heat pump switches on at a storage temperature lower than 50 °C and switches off at a heat pump flow temperature above 55 °C. The minimum shutdown period as well as operation time is set to 10 min.

2.9 Ground coupled heat pump

The brine/water heat pump reaches a maximum flow temperature of 60 °C. The COP at B0/W35 is 4.3. The borehole heat exchanger length is 120 m. The heat extraction from the borehole is calculated for DHW and SH operation. The heat pump switches on at a storage temperature lower than 50 °C and switches off at a heat pump flow temperature above 55 °C. The minimum shutdown period as well as the minimum operation time is set to 10 min. The assumed ground has one soil layer with a density of ρ = 2'400 kg/m^3, specific heat capacity cp = 1'300 J/(kg·K) and conductivity of λ = 2.6 W/(m·K).

2.10 Furnace

All furnaces (oil, gas and wood pellets) modulate their capacity between 5 and 15 kW according to the demand. Oil and gas furnace are condensing boilers as required by cantonal law. For the control one temperature sensor in the storage is used.

3 ECOLOGICAL EVALUATION

3.1 Approach

As described all data are taken from the ecoinvent database. The environmental impact is separated basically into the categories “infrastructure” and “operation”. “Infrastructure” means all parts of the equipment for domestic hot water generation on-site. These are for example the solar heat system, the heat pump, the furnace with chimney, the hot water storage and the tap water installation with insulation. The ecological evaluation of the photovoltaic system is discussed separately in chapter 3.2, because it depends mainly on the use of the solar electricity. “Operation” covers the provision of the consumed end energy (fuel, electricity, its transport to the customer), the direct emissions as well as the maintenance expenses (e.g. ash disposal from wood pellets). Provision of the consumed end energy also contains infrastructure elements off-site that are needed for the generation and transport (electric grid, gas distribution system, electric power plant). Therein only the environmental impact for domestic hot water generation is considered. Furthermore, heat pumps are assumed to have no refrigerant losses and the consumed electricity comes from average Swiss electricity grid (apart from combinations with photovoltaics). The generators are dimensioned to supply the full domestic hot water as well as the space heating demand. In all variants about 25% of the generated heat is consumed for domestic hot water. Accordingly, only 25% of the ecological impact of the infrastructure, which is used for domestic hot water and space heating, is considered. Infrastructure only for domestic hot water is considered entirely.

3.2 Photovoltaics and ecological benefit

A correct ecological evaluation of a commodity allocates the environmental impact to its consumer. In fact, the consumer is also the originator. Building a solar system does not generate an ecological value for the owner compared to conventional heat or electricity. The decisive point is on the one hand who consumes the generated solar energy and on the other hand whether conventional energy could be replaced. For a solar heat system the owner is also consumer. Hence he has to bear the ecological burden of the infrastructure but also benefits from the reduced end energy demand and finally receives an ecological added value. The ecological added value of a PV system on the other hand could possibly be sold with the sold PV generated electricity and the PV owner and operator could buy average Swiss grid electricity (55% nuclear, 40% hydro and 5% fossil) for his own needs. For the ecological evaluation of this study, the following PV scenario is assumed. Because of the temporal difference between PV production and electricity consumption all the PV generated electricity is fed to the grid and the user draws the same amount of solar generated electricity from the grid when he needs it; the grid is used as virtual storage. This construct reflects the actual situation where all the expenditure for electricity storage is assumed to be covered by the solar generated electricity cost. The ecological impact of the PV system covers all components that are installed on the building site. The electricity storage in the grid is for this study assumed to be without ecological impact.

3.3 System comparison

Figure 1 shows the ecological impact for the air/water heat pump combinations with PV, flat plate and vacuum tube solar heat systems. For comparison further cantonal permitted systems are shown. These are:

- brine/water heat pump
- wood pellet furnace
- oil furnace with solar heat system (flat plate absorber)
- gas furnace with solar heat system (flat plate absorber)

The figure shows the higher greenhouse gas emissions (GWP) of the fossil fuel systems. Also in combination with solar heat systems oil and gas furnace are in this category significantly worse than the other systems. But the gas furnace system has a slight advantage considering the ecological impact. For wood pellets the direct CO_2 emissions are not considered since it is assumed that the growth of plants reabsorbs these CO_2 emissions. The wood pellet greenhouse gas emissions only originate from their processing and provision. Therefore the wood pellet system can compete with the heat pump systems. Solar heat systems come with the highest infrastructure impacts because of the included bigger hot water storage. Vacuum tube systems are slightly better than flat plate systems. The brine/water heat pump is comparable with the air/water heat pump variants with a slightly higher ecological impact and equal greenhouse gas emissions. The air/water heat pumps with additional solar system are best in the greenhouse gas emissions. The matchmaking point for heat pumps is the ecological impact of the consumed electricity.

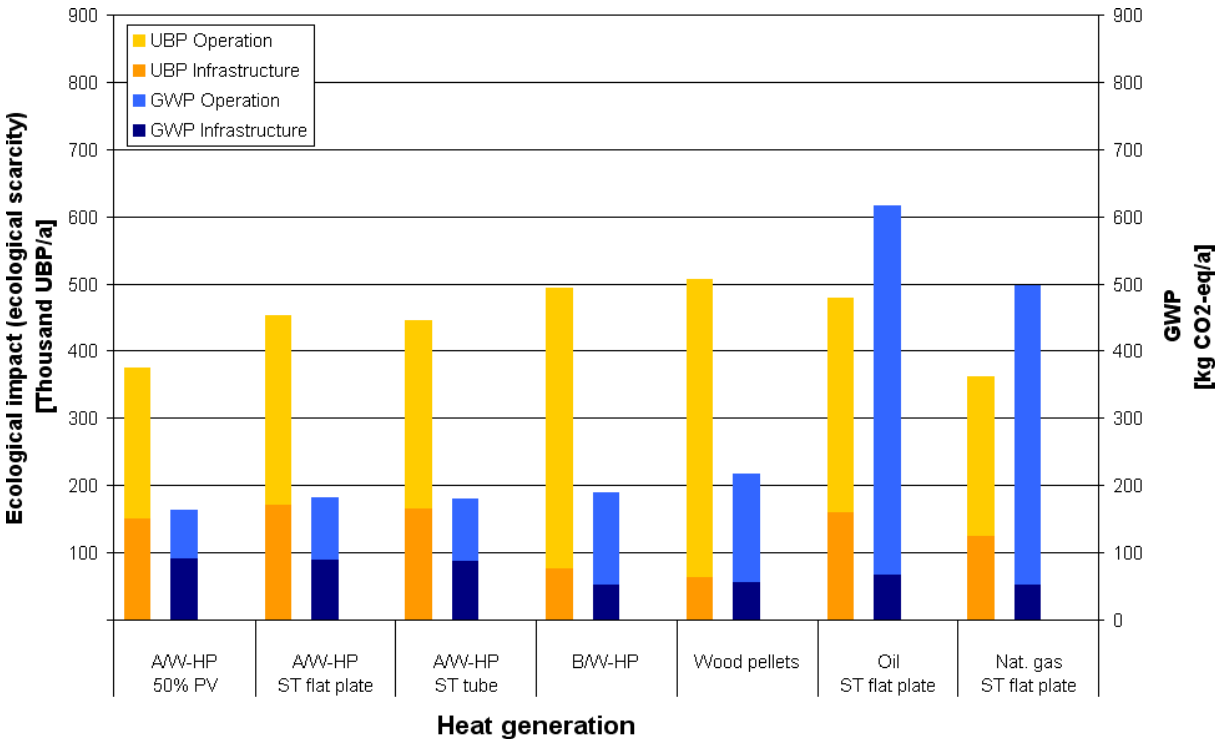

Figure 1: ecological system comparison

3.4 Photovoltaic variants

In this subchapter the influence of the PV panel orientation on the ecological impacts is compared. Domestic hot water is heated by an air/water heat pump. Half of this consumed electricity is produced by photovoltaics. A PV system with polycrystalline modules is assumed.

The ecological evaluation shows the results for the following variants:

1. The user consumes 100% average Swiss grid electricity. This variant is for comparison reasons only. It does not fulfil the legal requirements.
2. The user consumes his own PV generated electricity and covers 50% of the heat pump demand and covers the other 50% with average Swiss grid electricity. Since he himself uses his PV current, he also has to bear the ecological infrastructure burden. In this variant the PV panels have an optimal orientation (south, 45° slope).
3. Same as variant 3, but with a different orientation (west, 45° slope, east would be equivalent). Therefore the collector area increases to 5.2 m^2.
4. Same as variant 3, but again with a different orientation (west, 90° slope, east would be equivalent). Therefore the collector area increases again to 8 m^2 in this case.

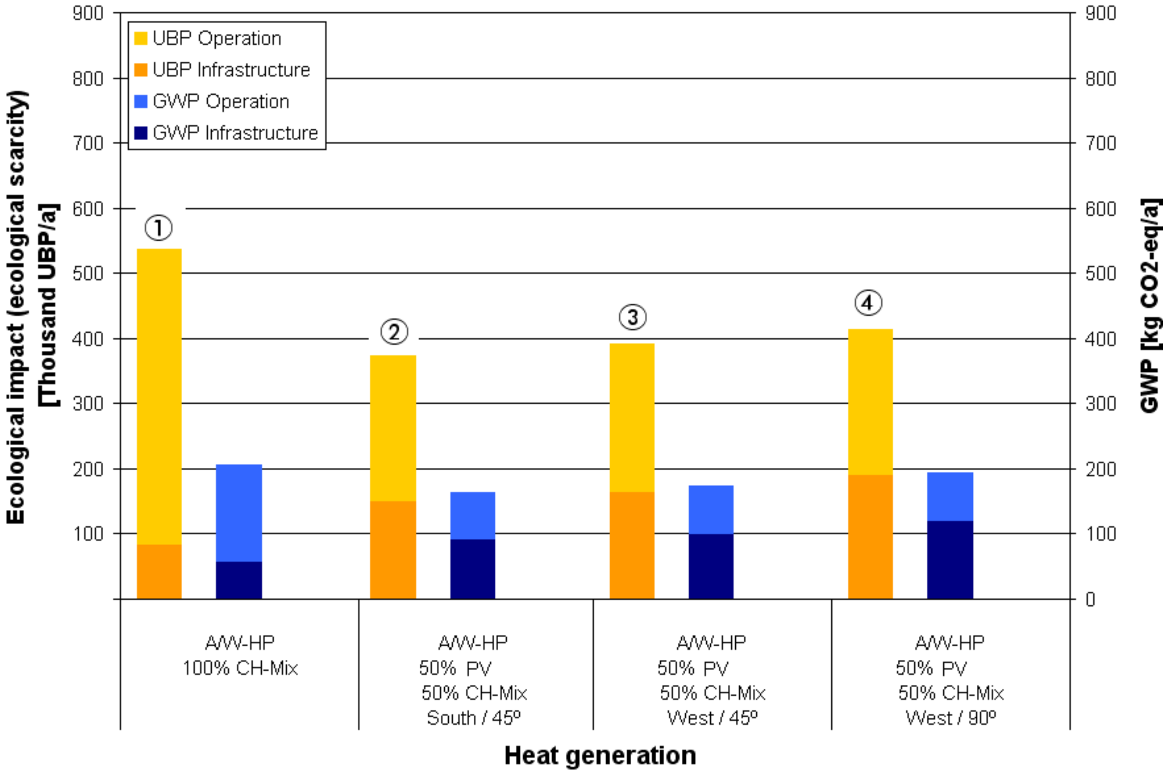

Figure 2: Ecological comparison of PV variants

The ecological impact for the variants is shown is Figure 2. The increasing PV panel surface with an unfavourable orientation leads to decreasing advantages considering the global warming potential, but the variations of the orientation are of minor importance considering the ecological impact. The most important fact is that solar generated electricity is used in the end.

4 FINANCIAL EVALUATION

4.1 Basics and System comparison

The economical evaluation is based on guideline offers for the Basel region and representative Swiss energy prices. The investment costs were calculated for the smallest possible systems satisfying the legal 50% requirement. The investment costs cover the heat generator, solar systems where present and the domestic hot water storage with installation cost, but without tap water and space heating distribution and emission system since they are equal in all variants. Not considered are costs for anything provided by the customer (e.g. fuel storage or chimney).

Table 4: payout time of the system components

component	economic lifetime
photovoltaic plant (without inverter)	30 years
inverter	15 years
heat pump	20 years
borehole heat exchanger	40 years
domestic hot water storage	20 years
solar heat system	25 years
furnace (incl. flue gas losses)	20 years
gas connection	40 years

For the evaluation yearly costs are calculated for the compared system variants, including a real interest rate (inflation-adjusted nominal interest rate) of 3% and payout times as shown in Table 4. The assumed energy costs are shown in Table 5 and reflect the current costs at the time of the study (2010).

Table 5: energy costs

energy source	reference unit	cost in CHF
wood pellets	ton	400
light fuel oil	Litre	0.85
domestic gas (excl. connection charges)	kWh	0.08
domestic gas, connection charge	-	3’000
average grid electricity	kWh	0.14
solar generated electricity	kWh	0.75
feed in tariff solar generated electricity	kWh	0.16
KEV (cost covering feed in tariff)	kWh	0.62
100 CHF ≈ 106 USD ≈ 78 EUR ≈ 8700 YEN		

Incentives are not considered in the calculations. In this chapter furthermore all the consumed electricity is calculated as average grid electricity. This is the worst economical situation. For illustrating the possible income from a cost covering feed in tariff (KEV), the annual income without electricity meter rent is indicated with KEV. The assumptions for maintenance costs are shown in Table 6.

Table 6: assumed maintenance costs

component	annual cost in CHF
solar system	1% of investment
gas furnace	90
oil furnace	220
wood pellets furnace	200
heat pump	100

Assuming an optimally oriented solar system (south, 45° slope) leads to the annual costs shown in Figure 3. The compared variants are the same as in Figure 1. Again all variants fulfil the legal 50% renewable energy requirement. Between the air/water heat pump variants with solar system, the differences are rather small. Under the taken assumptions the PV combination would be slightly cheaper, with a cost covering feed in tariff the PV variant would be the cheapest. For the PV systems it has to be mentioned that the system considered here with a peak power of 1 kW_{peak} is comparatively expensive. The guideline offers show investment costs of about 13’000 CHF/kW_{peak} for such a small PV system, whereas with PV systems bigger than 5 kW_{peak} the cost could be halved. Comparing the other systems, again the brine/water heat pump and the gas furnace solar system are the most attractive systems. The solar-oil system and the wood pellet system are the most expensive ones.

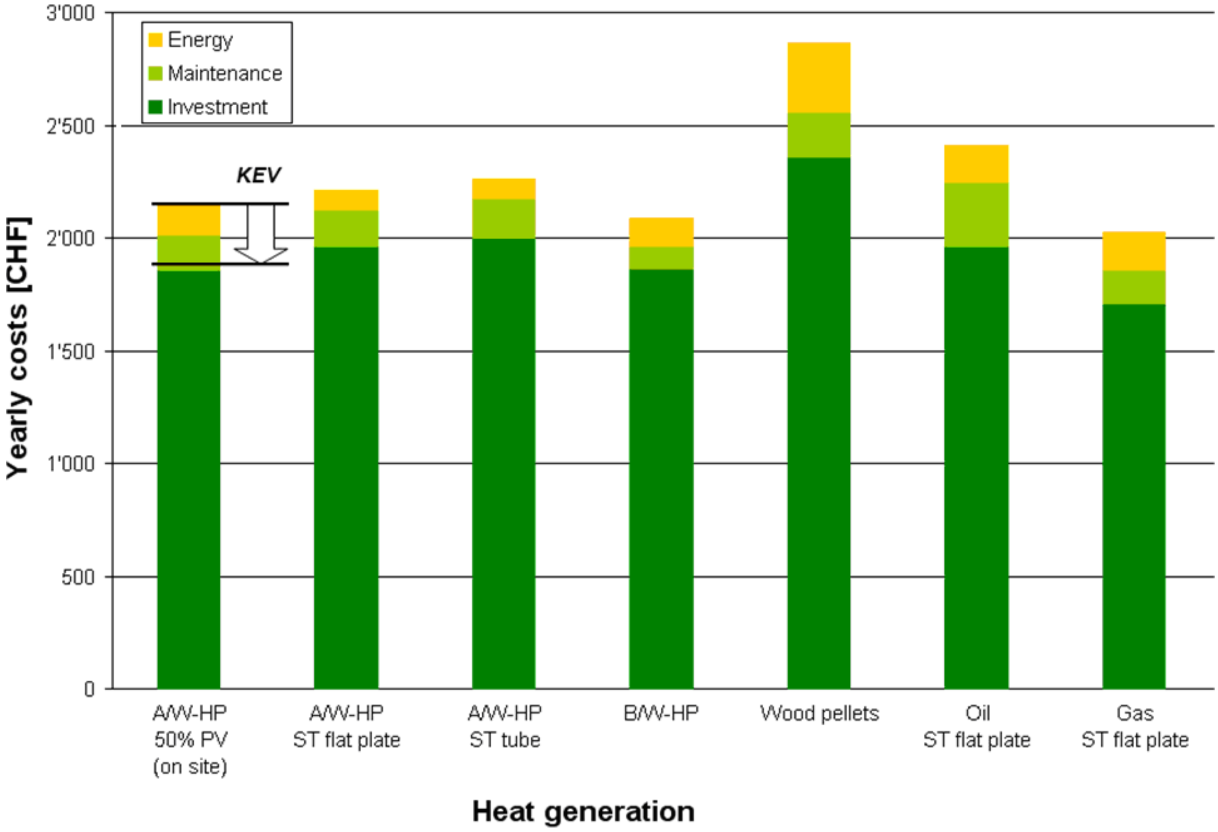

Figure 3: annual cost comparison

5 CONCLUSIONS

This study shows for the assumption of a 50% renewable coverage of the domestic hot water generation, that there is no decisive difference between heat pump systems combined with solar heat or combined with photovoltaic systems considering as well as for ecological aspects as for economical aspects. Therein the solar heat storage is realised and financed in the building, whereas the solar electricity storage is assumed to be covered by the grid and to be included in the solar generated electricity tariff. But on the other hand bigger PV systems are considerably cheaper than small systems in the range of 1 kW_{peak} like applied here. Solar heat systems with vacuum tubes have a slight advantage compared to flat plate systems because of a smaller required collector area. Important for the ecological evaluation of solar generated electricity is to consume it and not to sell it to get a cost covering feed in tariff.

6 ACKNOWLEDGEMENTS

The authors are grateful for the project advising and funding by the government of the cantons Basel-Stadt and Basel-Land. The project contributes to the IEA SHC Task 44 / HPP Annex 38 “Solar and heat pumps” (IEA 2010).

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