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Thermo-Economic and Primary-Energy-Factor Assessment Based on the Field Test of an Air-to-Water Heat Pump

Primož Poredoš^a, Tjaša Čož^a, Andrej Kitanovski^a, Alojz Poredoš^a

^aLaboratory for Refrigeration and District Energy, University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia. primoz.poredos@fs.uni-lj.si

Abstract:

This paper presents the results of a thermo-economic and primary-energy-factor assessment based on the field-test results for a residential air-to-water heat pump (AWHP). The AWHP experimental setup consisted of a supervisory control and data-acquisition system, which was connected to a heat meter, an electricity meter, humidity and temperature sensors, a HP control system and a computer. Based on the experimental data, the 4-year-average seasonal performance factor was determined. This information was then applied in a thermo-economic and primary-energy-factor (PEF) analysis. The results served for a comparison of the AWHP with eight different heating systems (HSs). The results reveal that the considered AWHP represents the most thermo-economically efficient system in terms of the average final costs for heat production. The results of the PEF analysis reveal that the HS with the AWHP under investigation can be characterized as the most efficient system.

Keywords:

Heat pump, Field Test, Thermo-economic, Primary energy factor, Energy efficiency

1. Introduction

The heat pump (HP) is undoubtedly one of the most promising heating technologies for energy-efficient buildings. This technology, in combination with renewable energy sources, waste heat and district heat, enables a considerable reduction in the primary energy consumption for heating [1, 2]. In recent years and in many situations, HPs were also proven to be economically beneficial compared to other heating systems (HSs), especially those based on fossil fuels.

One of the greatest uncertainties with a HP relates to its performance under real operating conditions. This is directly related to the seasonal performance factor (SPF) of the HP, which in fact is the average Coefficient of Performance (COP) for the measured or observed period [3]. The performance of, for instance, an air-to-water HP (AWHP) depends on many factors. Two of the most important factors on the air-source side are the external air temperature [4] and the humidity [5], both of which have large fluctuations. Furthermore, in cold and humid climate regions the problem of frost formation on the evaporator is well known. This frost influences the AWHP's operation in two ways: it decreases the overall heat-transfer coefficient from the air to the refrigerant and it causes an increase in the air-pressure drop [6]. On the water-sink side, the demand for space heating is related to the heat losses of the building's envelope, the designed temperature inside the building as well as the demand for sanitary hot water [7]. Since in residential buildings the desired comfort of family members varies with time, the demand for space heating and sanitary hot water is fluctuating as well. All these factors tend to decrease the SPF of the AWHP.

HP manufacturers list the measured COP according to the European standard EN 14511. However, the COP measurements are performed under ideal laboratory conditions, where the temperature and air humidity for an outdoor heat exchanger as well as the outlet temperature of the heated water are carefully kept constant,

according to the prescribed values. As a result, this standard became the subject of many scientific/political debates regarding the real operating performance of the HP. Therefore, this standard is being replaced by stricter rules within the EU, which are in accordance with the Commission Regulation (EU) No. 811/2013 [8] and Commission Regulation (EU) No. 813/2013 [9]. Based on these rules, HPs must achieve the minimum statutory SPF for heating purposes, which follows the specific country legislation [10]. Therefore, the importance of an assessment of the HP based on the real operating performance (based on a field test) is recognized as high [11-21].

The thermo-economic analysis of the AWHP based on a 2-year field test was studied by Popa et al [11]. Based on the measurements, which were acquired for a cold period of time, the medium value of the COP (2.44) was calculated. The thermo-economic analysis showed that the annual total costs for the HP evaluated in the study were the highest, compared to other HSs based on LPG, oil, pellets and HSs based on gasification. Madonna et al. [12] considered the uncertainty of the actual performance of the HPs in a real environment. The field tests of the ASHP were performed in order to provide the necessary data used in the model, which simulated the hourly efficiency of the HP. The authors found that climatic conditions strongly affected the real-data-based SPF of the AWHP.

A HP's heating power output as well as the COP reduction in the case of frost formation are some of the greatest concerns during the real operating performance of an AWHP. As a result, the main objective of a large number of field tests for an AWHP are related to the frost phenomena. A field test concerning an AWHP under frosting conditions in nine typical cities in China was performed by Liu et al. [13]. Based on their results, a method to predict the unnecessary defrosting times was developed. Another study, conducted by Wang et al. [14], represents an investigation into an AWHP relating to mal-defrost phenomena. These phenomena are characterized as defrosting operations that occur after a long period with a critical level of frosting, or they occur when not necessary. A field test also showed great potential regarding the validation of numerical models. The real operating performance of a two-stage variable capacity AWHP installed at the Archetype Sustainable House in Canada was studied by Safa et al. [15]. Measurements, performed in both summer and winter seasons for 4–6 weeks, were the source for the model's validation, developed in TRNSYS. A similar study, which used an improved AWHP with a vapor injection economizer in a cold region of China was conducted by Zhang et al. [16]. The upgraded HP could achieve better performance compared to a HP without an EVI. The results of the field test were later used for the monthly and hourly modelling of the thermal performance of four cities in cold and severely cold regions in China.

There are well-known combinations of HPs with other HSs, i.e., bivalent systems. A field test in Germany with a combined solar-assisted AWHP HS has been analyzed by Stark et al. [17]. This trial covered monitoring the system performance for DHW preparation and space heating in single- and multi-family houses.

Besides the field test with the AWHP, the ground-source HP (GSHP) field tests are also of great interest to researchers, since the ground temperature varies with time during the year [18]. One such field test for cooling five residential GSHPs was performed in a hot summer and a cold winter in China [19]. A correlation between the high cooling load and the high COP was also presented. A similar study with a GS HP system in a cooling-dominated area of China was conducted by Zhou et al. [20]. The data, gathered by a field test, was the basis for the TRNSYS model, which also served for the validation. A similar study with five ground-source installations, which served as a validation of a black-box HP model, was investigated by Ruschenburg et al. [21].

A review of the literature shows that a field test of a HP is one of the most important foundations in order to perform a comprehensive, as well as the realistic, thermo-economic or primary-energy-factor assessment. However, based on our search of the existing literature, we found no studies that apply a field-test-based SPF of AWHPs with a sensitivity analyses covering thermo-economic, primary-energy-factor assessments.

In this paper we present an AWHP field test with operating performance results for the case of a one-family residential house during four heating seasons between 2011 and 2015. The experimental data was used to calculate the 4-year-average seasonal performance factor (SPF). Based on this, a thermo-economic assessment of the AWHP was performed. Lastly, a comparison with other systems for domestic heating and sanitary hot water in terms of the primary energy factor was performed. Additionally, all three assessments were subjected to a sensitivity analyses that covered different situations regarding different values of the electricity costs, and different primary energy factors for electricity production.

2. Field-test setup

2.1. Basic characteristics of the one-family residential house

The one-family residential house has a ground plan area of 125 m², where the cellar and the attic are not heated. The attic is isolated with 10 cm of glass mineral wool. Typically, the walls of the house are constructed with 30 cm of bricks, 8 cm of insulation, 6 cm of bricks and 2 cm of the final façade. The windows have a U-value of 1.4 W/(m²K). The calculated overall heat-transfer coefficient of the walls is 0.27 W/(m²K). The calculated heat losses are estimated to be 10.5 kW. The HS, shown schematically in the Fig. 1, consists of a floor heating circuit and a radiator heating circuit.

Fig. 1: Schematic of HS for the one-family residential house.

The characteristics of each heating circuit are presented in Table 1. Both circuits are connected to hot-water storage (WPPS 300, Austria Email AG), which has a volumetric capacity of 300 l. The sanitary hot water is stored in a boiler (WP SOL 350, Austria Email AG,) with a volumetric capacity of 350 l.

Table 1: Characteristics of the HS for the one-family residential house.

	Floor heating	Radiator heating
Heated area	90 m ²	35 m ²
Design temperature regime	35/32 °C	45/40 °C
Installation	800 m installed pipes	3 radiators

2.2. Experimental setup

The AWHP (TČZ ZV 12/13 E1, Kronoterm) under investigation operates in the range of external air temperature from -20 °C to +35 °C. Defrosting using a reverse cycle allows the HP to operate at higher values of air humidity. The AWHP was put into operation in 2011. All the basic technical data from the manufacturer of the AWHP under investigation is shown in Table 2.

Table 2: Basic technical data from the manufacturer of the AWHP under investigation.

Heating power* [kW]	Electric power* [kW]	COP*	Refrigerant (type [/], charge [g])
12.8–11.9	3.5–4.5	3.7–2.6	R407C, 4200g

*at A2/W35-55

The AWHP data acquisition, data storage and management were performed with a supervisory control and data-acquisition (SCADA) system (SCADA Eltec Petrol), which connects:

- the heat meter (CF Echo II, Enerkon)
- the electricity meter (ElNet LT, Feniks pro)
- the temperature and humidity sensors (QFA3171D, Siemens)
- the HP control system (Termotronic 3000, Kronoterm)
- the measurement computer (AMD Athlon II X3 460, 4.00 GB RAM, Windows 7 Pro 64-bit)

The SCADA system with all the connected subsystems is shown in Fig. 1. All the measured data is transferred from each meter/sensor as well as the HP control system to the SCADA system through the Modbus and M-Bus protocols, while the SCADA system is connected to the measurement computer with Ethernet.

One example of the HP data provided by the SCADA system during the operation of the AWHP on 4 Jan 2016 between 12:15 and 16:16 is shown in Fig. 2. The data in the graph includes: compressor electric power, HP heating power, external air temperature and humidity, supply temperature, return temperature, hot-water storage temperature and the Boolean value (0, 1) of the fan.

Fig. 2: Data visualization of the AWHP's operation on 4 Jan 2016 between 12:15 and 16:16.

3. Operation performance of the HP

The operating performance of the considered AWHP is presented in Table 3 for four heating seasons from 2011/2012 to 2014/2015. Cumulative values of the generated heat, denoted as $Q_{cv,g}$, and the consumed electrical energy, denoted as $W_{cv,c}$, were read each month of a particular heating season from the heat meter and the electric meter, respectively. The monthly average external air temperature, denoted by T_{ea} , was calculated from the temperature- and humidity-sensor measurements. Based on the cumulative values of $Q_{cv,g}$ and $W_{cv,c}$ the monthly, seasonal and 4-year-average SPF_n were calculated using the well-known equation:

$$SPF_n = \frac{\sum_{i=1}^n Q_{cv,g}}{\sum_{i=1}^n W_{cv,c}} \quad (1)$$

where i denotes a particular month. The cumulative values of the generated heat, the consumed electric energy, the measured average external air temperature and the calculated SPF_n for seasons 2011/2012 to 2014/2015 are shown in Table 3. The 4-year-average SPF was calculated using the data given in Table 3 and its calculated value is $SPF_{32} = 2.76$. This value was applied in all the subsequent calculations regarding the thermo-economic assessment and the primary-energy-factor analysis.

Based on the field-test results, shown in Table 3, we can see that the 4-year-average SPF (2.76 at A8/W45-50) is relatively high compared to the nominal COP, provided by the manufacturer (3.7–2.6 at A2/W35-55). It must be noted that in the months with a high relative humidity the defrosting occurred quite often (check Fig. 2). It must also be noted that the considered AWHP was also used for the heating of sanitary hot water, and the temperature in the supply pipes increased to 50 °C, which lowered the SPF.

Table 3: AWHP operating characteristics during four heating seasons from 2011/2012 to 2014/2015.

Heating season	T_{ea}^* [°C]	$Q_{cv,g}$ [kWh]	$W_{cv,c}$ [kWh]	SPF [/]
2011/2012	6.9	21849	7661	2.85
2012/2013	7.2	16635	6285	2.65
2013/2014	9.2	15381	5634	2.73
2014/2015	8.5	17729	6374	2.78
Sum		71594	25954	
Average	8.0			2.76

*Monthly average external air temperature

4. Thermo-economic comparison of HP and other HS

When choosing the right HS, one of the most important aspects for end-users and large-scale investors is the economic assessment. However, in the case of the legislation related to national, EU or international policy, the energy efficiency and environmental aspects represent the most important issue that relates to the evaluation of different technologies, systems or devices. The optimal choice is obtained not only by evaluating the annual costs of the consumed heat or investment costs. The optimal decision is found by taking into account the investment costs, the annual operating costs (the annual heat-source costs with the annual electricity costs) and the annual recurring costs (annual cleaning costs with annual maintenance costs). To make such decisions easier, a thermo-economic assessment for eight HSs was performed. The following systems were considered in the analysis:

- Condensing (CB) – oil boiler
- Condensing – natural-gas boiler
- Biomass – wood-logs boiler
- Biomass – wood-pellets boiler
- Biomass – wood-chips boiler
- Condensing – LPG propane boiler
- Air-to-water HP presented in this paper
- Electrical resistance heater

This assessment was performed for the one-family residential house under investigation. Based on the data provided in Table 3 the average annual energy consumption ($\bar{Q}_{ec,a}$) is 17.899 MWh/a. All the costs of all the

heat/energy sources were calculated for the date range between the second half of 2011 and the first half of 2015 from various Slovenian sources [22-25]. The procedure for the calculation of the thermo-economic analysis is given in the Appendix. All the calculated values regarding the thermo-economic assessment of the HP under consideration and the other HSs are found in Table 4. Based on the presented results, the HP under consideration is the most thermo-economically efficient in terms of the average final costs for heat production (88 €/MWh). The most expensive HS is the HS based on the LPG propane heat source (157 €/MWh), which is followed by the HS based on oil (147 €/MWh). The biomass HS, based on wood logs, takes the third place (98 €/MWh). The HS based on natural gas can be found in 4th place (109 €/MWh), which is followed by the HS based on an electrical resistance heater (128 €/MWh). Between the latter HS and oil there are two biomass systems, based on wood chips and wood pellets (133 €/MWh and 140€/MWh, respectively).

Fig. 3: Relative share of final costs (average annual final costs or average final costs for heat production) of an individual HS compared to a HS based on the HP under consideration. The analysis considered an additional four possible costs of electricity ($0.50 \times C_{el}$, $0.75 \times C_{el}$, $1.25 \times C_{el}$, $1.5 \times C_{el}$) besides the 4-year-average cost of electricity denoted as C_{el} . Note: CB: condensing boiler, NG: natural gas, AW: air-to-water, El. res.: electrical resistance

If we consider the relative share of the final costs, shown in Fig. 3, being the average annual final costs or the average final costs for heat production, we can see that the graph is made up of five columns. The middle column with the green color denotes the relative share of the final costs for the 4-year-average cost of electricity, denoted as C_{el} . In the scenarios with the falling costs of electricity, if the cost of electricity is 75% or 50% of the C_{el} , all the other HSs become less attractive compared to the HP, with the exception of the electrical resistance heater. This system has the lowest investment costs. On the other hand, in scenarios with higher costs of electricity, i.e., 125% or 150% of C_{el} , the HS based on the wood logs is thermo-economically more efficient than the HP. The HS based on natural gas is comparable with the HP in the case that the electricity costs are equal to or higher than 150% of C_{el} .

Table 4: Thermo-economic assessment for eight different HSs under consideration.

Heating system	Oil	Natural gas	Biomass			LPG propane	AW HP	Electric resistance heater
	/	/	Wood logs	Wood pellets	Wood chips	/	/	/
Cost of heat/energy source [€/unit]	0.99 €/l	0.77 €/sm ³	0.035 €/kWh	0.057 €/kWh	0.024 €/kWh	0.9 €/l	0.1125 /2.76* €/kWh	0.1125 €/kWh
Calorific value [kWh/unit]	10 kWh/l	9.5 kWh/sm ³	/	/	/	7.23 kWh/l	/	/
Cost of final product heat [€/kWh]	0.0990	0.0811	0.0350	0.0570	0.0240	0.1245	0.0408	0.1125
Boiler efficiency [%]	90	95	75	85	80	95	/	/
Cost of useful heat [€/kWh]	0.1100	0.0854	0.0467	0.0671	0.0300	0.1311	0.0408	0.1125
Annual costs for heat production [€/a]	1969	1528	835	1200	537	2346	769	2014
Investment costs (VAT included) [€]	7050	3500	6510	12600	16300	4000	9500	2500
Annual interest rate [%]	5	5	5	5	5	5	5	5
Duration of the investment [year]	20	20	20	20	20	20	15	20
Monthly payment amount for 1 st period [€/m]	47	23	43	83	108	26	75	16
Annual electricity cost [€/a]	30	30	50	100	200	30	30	30
Annual cleaning costs [€/a]	60	60	130	130	130	60	0	0
Annual maintenance costs [€/a]	95	95	300	200	400	95	95	95
Monthly payment amount for 2 nd period [€/m]	28	14	26	50	65	16	45	10
Average annual final costs [€/a]	2638	1953	1762	2495	2386	2805	1576	2297
Average final costs for heat production [€/MWh]	147	109	98	140	133	157	88	128
Relative share of final costs [/]	1,67	1,24	1,12	1,58	1,51	1,78	1,00	1,46

Note: CB: condensing boiler, AW: air-to-water.

*Four-seasonal COP of HP under consideration

5. Comparison of the primary energy factor of HP and other HS

The analysis of the primary energy factor allows us to determine the quantity of primary energy used to produce the final energy product, being electricity, gas, gasoline or heat. The primary energy factor includes the primary energy required for extraction, transport, conversion, distribution, transmission and control losses, etc. of the heat/energy source [26]. Here we present the results of the analysis of the primary energy factor (PEF) for the considered HP and its comparison with other HSs. The PEF for heat production was calculated using:

$$PEF_{hp} = \frac{PEF_{hs}}{\eta_b} \quad (2)$$

where PEF_{hs} denotes the primary energy factor of the heat source and η_b denotes the efficiency of the boiler. The annual consumed primary energy was calculated from:

$$PE_a = PEF_{hp} \cdot \bar{Q}_{ec,a} \quad (3)$$

where $\bar{Q}_{ec,a}$ denotes the average annual energy consumption of the one-family residential house, which is 17.899 MWh.

PEF_{hs} values for the HSs based on oil, natural gas, biomass and LPG propane were found in [27, 28]. The average PEF value of the electricity generation mix in the EU-28 between 2010 and 2013 was found with the GEMIS model database version 4.93 [29]. This database was also the source of all the PEF values for the electricity generation mix for each country in the EU for 2010 (including the UK).

Based on the results provided in Table 5 we can see that the lowest and highest calculated PEFs for heat production are provided by the HS based on the electrical resistance heater (2.49) and the HP under consideration (0.90).

Table 5: Primary energy factor analysis for the eight different HSs under consideration.

Heating system		PEF of heat source [/]	Boiler efficiency [%]	PEF for heat production [/]	Annual consumed PE [MWh/a]	Relative share of consumed PE [/]
Oil	CB	1.10	90	1.22	21.876	1.35
Natural gas	CB	1.22	95	1.28	22.985	1.42
Biomass	Wood logs	1.26	75	1.68	30.069	1.86
	Wood pellets	1.26	85	1.48	26.532	1.64
	Wood chips	1.12	80	1.40	25.058	1.55
LPG propane	CB	1.09	95	1.15	20.536	1.27
AW HP	/	2.49* / 2.76**	/	0.90	16.148	1.00
Electric resistance heater	/	2.49	/	2.49	44.567	2.76

Note: CB: condensing boiler, AW: air-to-water.

*PEF of the electricity generation mix in the EU-28, 2010–2013

**Four-year-average SPF of HP under consideration

The second highest relative share of the PE is found for the HS based on LPG (1.15). HSs based on oil and natural gas were in third and fourth places with PEF_{hp} values of 1.22 and 1.28, respectively, while biomass HSs based on wood chips, pellets and logs follow with PEF_{hp} values of 1.40, 1.48 and 1.68, respectively. In terms of the annual consumed primary energy for the one-family residential house, the HS based on the

electrical resistance heater would consume 44.567 MWh of PE, while the HSs based on the HP under consideration would consume 16.148 MWh of PE.

Considering the relative share of the consumed PE in Fig. 4, the middle column in the green color indicates the average PEF value of the electricity generation mix in the EU-28 between 2010 and 2013, which is denoted as avg(EU PEFs). It is evident that the electrical resistance heater is the worst solution in terms of consumed PE, since it would consume 2.76 times the PE compared to the HS based on the HP. This ratio is in fact the SPF of the HP under consideration. The other two columns in Fig. 4 indicate the minimum and maximum values of the PEF for the electricity generation mix of all the EU countries separately. These two values are denoted as min(EU PEFs) and max(EU PEFs). Based on the data, the minimum PEF value for electricity generation comes from Latvia (PEF = 1.54), while the maximum PEF value comes from Lithuania (PEF = 3.61). In the first case, with the minimum value of PEF for electricity generation, all the HSs have a relative share of consumed PE that is at least 2 times higher compared to the HP under consideration. When considering the maximum PEF of the electricity generation, all the HSs based on fossil fuels (oil, natural gas and LPG) have a relative share of consumed PE lower than the AWHP (0.93, 0.98, and 0.88 compared to 1.00, respectively). The HS based on the biomass wood chips has a relative share of consumed PE comparable to the HP (1.07 compared to 1.00).

Fig. 4: Relative share of consumed primary energy of the individual HSs compared to the HS based on the HP under consideration. The analysis considered the average, minimum and maximum PEF of the electricity generation mix of all the EU countries. Note: CB: condensing boiler, NG: natural gas, AW: air-to-water.

6. Conclusions

In this paper we present thermo-economic and primary-energy-factor assessments based on field-test results for an air-to-water heat pump (AWHP). The nominal characteristics were determined from the manufacturer's laboratory test for A2/W35-55. The AWHP, which started operations in 2011, was installed in a one-family residential house with two heating circuits, i.e., floor heating and radiator heating, with a designed temperature regime of 35/32 °C and 45/40 °C, respectively. The calculated heat losses for the house were estimated to be 10.5 kW. Based on the experimental data, provided by the SCADA system, the four-seasonal COP between the 2011/2012 and 2014/2015 heating seasons of the AWHP under consideration was determined to be 2.76.

Based on the experimentally determined SPF the thermo-economic assessment for the 8 heating systems (HSs) including the AWHP under consideration was made. The results reveal that the considered AWHP represents the most efficient system in terms of the average final costs for heat production (88 €/MWh). The most expensive HS is based on the LPG propane heat source (157 €/MWh). The sensitivity analysis showed that if the cost of electricity is 75% or 50% of the base electricity cost, all the presented HSs are less attractive compared to the AWHP. With the scenario of 125% or 150% for the base cost of electricity, the HS based on

wood logs would be more thermo-economic compared to the AWHP. The HS based on natural gas is comparable with the AWHP only in the case of 150% of the electricity cost.

The primary energy factor (PEF) analysis reveals that the HS based on the considered AWHP is the most efficient in terms of PEF for heat production (0.90). The least efficient HS in terms of the PEF for heat production was determined to be the HS based on the electrical resistance heater (2.49). Other HSs between the mentioned systems have the following PEF for heat production: LPG (1.15), oil (1.22), natural gas (1.28), wood chips (1.40), pellets (1.48) and logs (1.68). If we consider the maximum PEF of the electricity generation for all the EU countries, all the HSs based on the fossil fuels (oil, natural gas and LPG) have a relative share of consumed PE that is lower than the AWHP (0.93, 0.98, 0.88 compared to 1.00, respectively). The HS based on the biomass wood chips has a relative share of consumed PE comparable to the AWHP (1.07 compared to 1.00).

The final highlights of the presented paper are:

- The main advantage of the field test is that the AWHP operates in real conditions. It was proven that the COP measurements performed under ideal laboratory conditions are not comparable to the field-test-based SPF factor.
- The AWHP under consideration is the most efficient HS in terms of thermo-economics and the PEF for heat production when considering the average cost of electricity and the average PEF of the electricity generation mix in the EU-28.
- Electricity should not be directly converted to heat by using the electrical resistance heaters. In the case of lower electricity costs, the electrical resistance heater poses a great threat to efforts to lower the greenhouse-gas emissions and primary energy use. This HS has the highest PEF factor for heat production, with the average PEF of the electricity generation mix for electricity generation in the EU-28.
- When considering the heat source for individual buildings or a larger area, besides the thermo-economic assessment, the primary energy factor analysis should be considered. Furthermore, when considering the heat source we should take into account the various analyses that cover different domains, such as CO₂ eq emissions, LCA, exergetic, particle emissions analyses, etc. in order to achieve carbon neutral and sustainable technology for heat production.

Appendix

The time period for which the thermo-economic assessment was performed was taken to be 30 years. The duration of the investment for all HSs except the HP was 20 years, which is the 1st period. In the case of the HP the duration of the investment was 15 years, which is also the 1st period. The 2nd period in the case of the HP is 15 years, for all other systems it is 10 years. The average annual final costs ($\bar{C}_{f,a}$) were calculated using the following equation:

$$\bar{C}_{f,a} = \frac{1^{st}}{1^{st} + 2^{nd}} \cdot (A_{1^{st}} \cdot 12 + C_{hp,a} + C_{el,a} + C_{cl,a} + C_{m,a}) + \frac{2^{nd}}{1^{st} + 2^{nd}} \cdot (A_{2^{nd}} \cdot 12 + C_{hp,a} + C_{el,a} + C_{cl,a} + C_{m,a}) \quad (A.1)$$

where $A_{1^{st}}$ and $A_{2^{nd}}$ denote the monthly sum of the periodic payment amounts for the 1st and 2nd periods, respectively, $C_{hp,a}$ denotes the annual costs for heat production, $C_{el,a}$ denotes the annual electricity costs, $C_{cl,a}$ denotes the annual cleaning costs and $C_{m,a}$ denotes the annual maintenance costs. The monthly payment amount for both periods was calculated from [30]:

$$A_{1^{st}/2^{nd}} = p_{inv} \cdot C_{inv} \cdot \left(\frac{j}{100} / 12 + \frac{\frac{j}{100} / 12}{\left(1 + \frac{j}{100} / 12\right)^n - 1} \right) \quad (A.2)$$

where C_{inv} denotes the investment costs, j denotes the annual interest rate, n denotes the total number of payments and p_{inv} denotes the investment factor, which is different for both periods. In the case of the 1st period the value of this factor is 1, while in the case of the 2nd period the value of this factor is 0.6. This decision

is based on the assumption that the investment at the beginning of the 2nd period would not be as high as at the beginning of the 1st period. The annual costs for heat production were calculated using:

$$C_{hp,a} = Q_u \cdot \bar{Q}_{ec,a} \quad (A.3)$$

where Q_u denotes the useful heat and $\bar{Q}_{ec,a}$ denotes the average annual energy consumption of the one-family residential house. The useful heat was calculated using the following equation:

$$Q_u = \frac{Q_{fp}}{\eta_b} \quad (A.4)$$

where Q_{fp} denotes the final product heat and η_b denotes the efficiency of the boiler. The efficiencies of the condensing and biomass boilers were found in the standard DIN V 18599-5 [31]. In the cases where Q_{fp} was not known, it was calculated using:

$$Q_{fp} = \frac{C_{hs}}{CV} \quad (A.5)$$

where C_{hs} denotes the costs of the heat source and HV denotes the calorific value of the fuel. The average final costs for heat production were calculated from:

$$\bar{C}_{f,hp} = \frac{\bar{C}_{f,a}}{\bar{Q}_{ec,a}} \quad (A.6)$$

Nomenclature

A	monthly sum of periodic payment amount [€]
C	costs [€]
CV	calorific value of the fuel [kWh/unit]
j	annual interest rate [%]
n	total number of payments
p	factor
PE	primary energy [kWh]
PEF	primary energy factor
Q	heat [kWh]
SPF	seasonal performance factor
T	temperature [°C]
W	energy [kWh]

Greek symbols

η	efficiency
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Subscripts and superscripts

a	annual
b	boiler
c	consumed
cl	cleaning
cv	cumulative value
ea	external air
ec	energy consumption
el	electricity
f	final

fp	final product heat
g	generated
hp	heat production
hs	heat source, heating system
i	particular month
inv	investment
main	maintenance
n	number of months
u	useful heat

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