DEVELOPMENT AND EXPERIMENTAL VALIDATION OF A TRNSYS MODEL FOR ENERGY DESIGN OF AIR-TO-WATER HEAT PUMP SYSTEM

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The object of this research work is the comparison of the annual primary energy consumption of different types of heating systems, using two different calculation methods. The TRNSYS 18 software makes use of dynamic simulation, while the WinWatt software calculates according to the Hungarian implementation of EPBD (Decree No. 7/2006). There were differences in results which could be caused by the more precise calculation of the TRNSYS software. Differences were shown also in the weather data used by the two computer tools that had one of the most important effects on the results according this investigation. The number of heating degree days used by TRNSYS is 10% less, than that the Hungarian decree provides. Using the yearly measured energy consumption data given by the inhabitant of the investigated family house, the validation of the developed dynamic building energy simulation model by TRNSYS could be also achieved with good agreement.

Key words*: Dynamic Building Thermal Energy Simulation, TRNSYS, Air-to-Water Heat Pump; Condensing Gas Boiler; Energy Consumption*

1. Introduction

Nearly 40% of the energy consumption of Hungary can be attributed to the population and to the energy consumption of the residential buildings. This ratio is similar in the Member States of the European Union. The energy consumption of buildings can be determined in two ways. For existing buildings, actual consumption data can be accurately measured. According to Directive 2002/91/EC on the Energy Performance of Buildings (EPBD), the expected annual energy consumption of the building must be determinable during the design stage as well [1-4]. The relevance of the research topic is shown by the fact that the currently available calculation methods and data in the literature allows only for an approximate estimation of the energy consumption of residential buildings [5-6]. There are no accurate, clear methods. Simulation programs performing energetic calculations provide essential support for building engineering designers to reduce the energy consumption of a building. Nowadays, designers need tools which can answer very specific questions even in the initial phase of design work. Using simulation programs for energetic calculations, designers can decide more easily on scaling issues (e.g. heating, cooling). Designers can investigate the thermal properties of the building before construction and can simulate the energy usage of existing buildings in their current state and provide suggestions for the most energy-efficient renovation [7-10]. Based on the study of the relevant national and international literature, relevant regulations and research findings, it is particularly important to develop simulation models which allow for a significantly more accurate, more realistic energetic examination of buildings compared to the currently used analytical methods. Beside the WinWatt building engineering scaling and design program, the 2018 version of the Transient System Simulation Tool (TRNSYS 18) was used since this is among the most widely used energy software in the world [11-15]. From among the mentioned energetic scaling programs, WinWatt provides a quick, user friendly, well-recognized calculation procedure commonly used in the domestic building engineering practice; the latter (TRNSYS) is becoming more commonly used in societies that are ahead of our country in development. It is less known in Hungary, which is partly due to high investment costs. However, the department procured the TRNSYS program (also suitable for dynamic building energetics simulation tests). The calculation methods provided by the WinWatt program are not detailed in this paper, its usage is already well known to the experienced designer and expert advisor building engineers and building energetics engineers. Since the recent national implementation of EPBD uses simple analytical equations for energy modelling which does not consider dynamic effects of the heat losses and heat gains of buildings, the transient effects of heat storage and thermal inertia of building structures. The national 261/2015. (IX. 14.) regulation declares that one of the solution to consider these significant dynamic effects during the energetic calculations is using a dynamic building energy simulation tool. This reason generated to make exact comparative assessments between the methods, performed in this research, and introduce the results in this paper.

In this paper, the calculation methods are presented provided by TRNSYS and compare it with the WinWatt program through the modelling of a family house heating system with a widely used condensation gas boiler in one case and with an increasingly popular air-to-water heat pump in the other. With TRNSYS 18 computer tool a dynamic simulation energy model was developed, while the WinWatt software calculates by standard analytical heat transfer equations according to the Hungarian implementation of EPBD (Decree No. 7/2006). The results are compared with each other and validated with experimental energy consumption data.

2. The structure and operation of the multi-zone building component model

One of the most important component models used in my work was the multi-zone building component. Since this type is very complex, it is necessary to configure the component properties using TRNBuild before using it in Simulation Studio. TRNBuild makes it possible, among other things, to design the structures of a building, but if you want to build them with a 3D design software, you should do this before using TRNBuild. This latter option was chosen for my work. The 3D model of the investigated family house was made with SketchUp. The model of the family house can be seen on Figure 1.

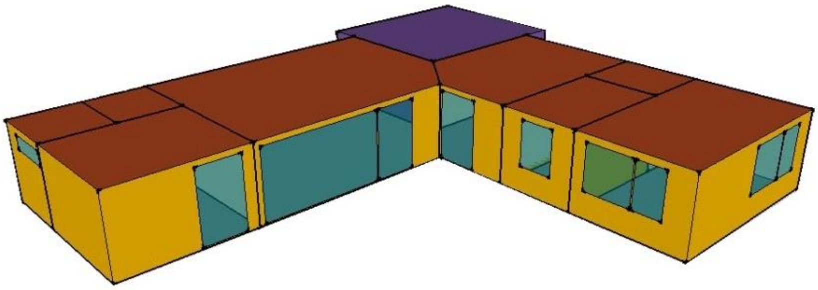

Figure1. Architectural 3D model of the investigated single family house

SketchUp was used because it allows for the quick creation and easy modification of the building structures. SketchUp recognizes if TRNSYS is installed and automatically offers the option of creating so-called TRNSYS thermal zones. Thermal zones play a prominent role in any software running dynamic simulations. The building is divided into these separate units and the software runs the calculations on these. Thermal zones do not necessarily coincide fully with the rooms of the building. The accuracy of the simulation merely requires that each thermal zone includes spaces with similar thermal behavior.

In TRNBuild, I can define a so-called active layer when I specify layer orders. This allows us to provide building structures with underfloor heating (or other surface heating): both the pipe diameter and the laying distance can be set.

The floor heating can also be used to set the heat flow to the thermal zone or the surface temperature of the floor, and these values can also be specified as inputs to be defined later (TRNSYS 18 Tutorial, 2018). The basis of a multi-zone building component model is an energy equilibrium model. The possible heat currents entering a thermal zone are illustrated by Figure 2.

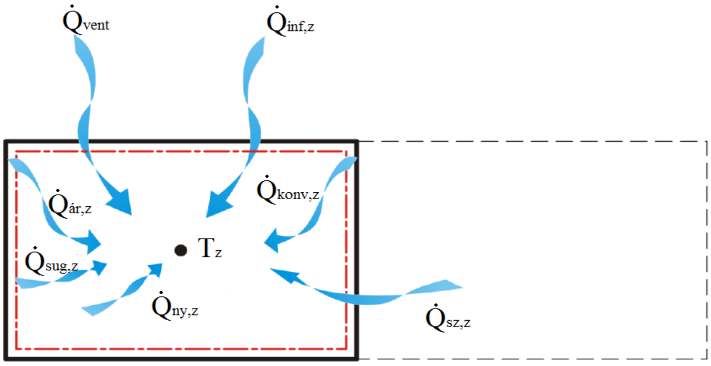

Figure 2. Heat equilibrium of a thermal zone in TRNSYS

2.1. Description of the simulation model for the gas boiler heating systems

The software calculates the outflow temperature and mass flow rate, the power transferred to the heat transfer medium, the heat losses of the boiler to the environment and the power to be fed to the boiler with the fuel from these input data. To determine the latter two metrics, the model uses simple efficiency correlations. In the event no medium enters the boiler, the component adjusts the value of the outflow mass flow rate to zero, sets the temperature of the outflow medium equal to that of the inflow and sets the power transferred to the medium, the value of the losses and the power to be fed to zero as well regardless of the value of the control signal. If the inflow mass flow rate of the boiler is greater than zero, but the control signal is zero (that is, the boiler is turned off), then it sets the values of these properties to zero as well, and the outflow medium temperature similarly equals that of the inflow medium. However, if the inflow mass flow rate of the boiler is not zero, and the control signal is 1, the model first determines the power to be transferred to the medium to reach the required supply temperature using equation 1.

$$\dot{Q}_{medium} = \dot{m}_{medium} \cdot c_{p,medium} \cdot (T_e - T_{be}) \tag{1}$$

The minimum value of the $\dot{Q}_{medium}$ is zero (i.e. negative power is not calculated if the inflow medium temperature is higher than the supply temperature) and the maximum value is the set nominal value of the boiler. If the value of the $\dot{Q}_{medium}$ is less than or equal to the nominal power of the boiler, the type makes the value of the power transferred to the medium equal the value of the $\dot{Q}_{medium}$ and sets the supply temperature to the set value. However, if the required power is higher than the nominal power of the boiler, the model makes the power transferred to the medium equal to the nominal power, and the temperature of the outflow medium will be determined using correlation 2.

$$T_e = T_{be} + \frac{\dot{Q}_{max}}{\dot{m}_{medium} \cdot c_{p,medium}} \tag{2}$$

Once the power transferred to the medium is determined, the power to be fed to the boiler can be determined using correlation 3.

$$\dot{Q}_{be} = \frac{\dot{Q}_{medium}}{\eta_k} \tag{3}$$

2.2. Description of the simulation model for the air-to-water heating systems

In case the heat pump is in heating mode (i.e. the input signal controlling the fan and the input signal of the heating mode are both 1), the component model first determines the powers for the current external temperature and return temperature (these can also be set as inputs) using interpolation between the data present in the power file. After this, the model can calculate the supply temperature using correlation 4.

$$T_e = T_v + \frac{\dot{Q}_{ft}}{\dot{m}_v \cdot c_{p,v}} \tag{4}$$

In the following step the component model determines the thermal power of the condenser and the evaporator. The software calculates the compressor power by subtracting the electrical power consumed by the fan and the controller from the power values present in the power file: Based on this, the thermal power of the condenser and the evaporator can be determined using equations 5-6.

$$\dot{Q}_{kond} = \dot{Q}_n - \dot{Q}_{ft} \tag{5}$$

$$\dot{Q}_{elp} = \dot{Q}_{kond} + \dot{Q}_{ft} - P_{kompr} \tag{6}$$

If auxiliary heating is used as well, the model uses equation 7 to determine the supply water temperature:

$$T_e = T_v + \frac{\dot{Q}_{ft} + \dot{Q}_{kieg}}{\dot{m}_v \cdot c_{p,v}} \tag{7}$$

The software determines the power factor of the heat pump as follows (eq. 8.)

$$COP_{hsz} = \frac{\dot{Q}_{ft} + \dot{Q}_{kieg}}{P_{kompr} + P_{vent} + P_{vez} + P_{kieg}} \tag{8}$$

2.3. Description of the simulation model for the floor heating systems

In case of the floor heating, the two media between which this energy flow occurs are the water and the concrete encasing the floor heating pipes. Maximum heat exchange would occur if the outflow water cooled down to the temperature of the concrete or if the temperature of the concrete increased to the temperature of the inflow water. The medium which experiences the larger temperature change is the one with the lower thermal capacity. Equation 9 can be used to determine the lower thermal capacity.

$$C_{min} = MIN\left((m_b \cdot c_{p,b}), (\dot{m}_{fk} \cdot c_{p,fk})\right) \tag{9}$$

The thermal capacity of the concrete block is given by the product of the mass and the specific heat of the concrete; which has to be specified ass a parameter of the floor heating component. The mathematical representation of the energy equilibrium between the heating medium and the floor heating element is given by equation 10:

$$m_b c_{p,b} \frac{dT_b}{dt} = -U_f A_f (T_b - T_h) - U_a A_a (T_b - T_a) + \varepsilon C_{min} (T_{be} - T_{ki}) \tag{10}$$

Since the above differential equation (where a and b are constants) can be written as dT/dt=aT+b, TRNSYS can solve it analytically by calling the relevant subroutine. In case of the floor heating model constants *a* and *b* can be determined using equations 11-12.

$$a = \frac{-\varepsilon C_{min} - U_f A_f - U_a A_a}{m_b c_{p,b}} \tag{11}$$

$$b = \varepsilon C_{min} \frac{T_{be}}{m_b c_{p,b}} + U_f A_f \frac{T_h}{m_b c_{p,b}} + U_a A_a \frac{T_a}{m_b c_{p,b}} \tag{12}$$

The solution of the differential equation gives the temperature of the concrete layer; the component model uses this to determine three heat flows: the heat flow from the heating medium to the concrete layer, the thermal power between the concrete element and the room, the loss heat flow toward the concrete layer and the space below it. The program calculates these using equations 13-15.

$$\dot{Q}_b = c_{p,b} (T_{be} - T_b) \quad W \tag{13}$$

where $\dot{Q}_b$ is the thermal power transferred from the heating medium to the concrete layer.

$$\dot{Q}_h = U_f A_f (T_b - T_h) \quad W \tag{14}$$

where $\dot{Q}_h$ is the thermal power transferred to the room from the concrete element

$$\dot{Q}_{veszt} = U_a A_a (T_b - T_a) \quad W \tag{15}$$

where $\dot{Q}_{veszt}$ is the thermal power transferred from the concrete layer to the space below it [15].

2.4. Modelling the heating technology systems in TRNSYS

Figure 3 shows the interface of Simulation Studio displaying the heating system with a boiler In addition to the components described previously, it shows the component models for exporting the data and for displaying them during the simulation.

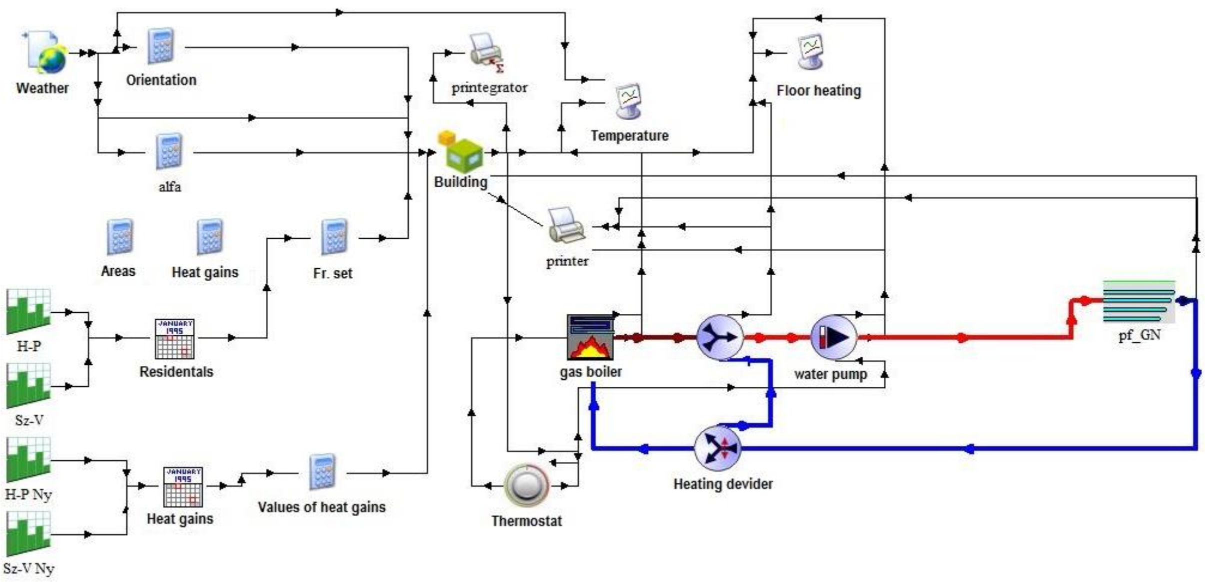

Figure 3. Schematic diagram of the developed model for the gas boiler heating system in Simulation Studio

The structure of the air/water heat pump heating system is very similar to that of the system containing a boiler. The main difference is that this case does not contain return mixing, so the heating system is somewhat simpler. Also, contrary to the boiler, the heat pump component has to be supplied with additional input data as well: connecting the type containing the weather data with the heat pump makes it necessary to also connect the external temperature and the relative and absolute air humidity to the corresponding inputs of the heat pump component. Another difference is that two thermostat component are required to control the heat pump since this is necessary to control the auxiliary heating with a separate signal. As I strived to make the results from WinWatt and TRNSYS as comparable as possible, the heating energy consumption was calculated based on a heat pump with a COP value of 4.3 both in case of WinWatt and TRNSYS. Figure 4 shows the structure of the air/water heat pump heating system in Simulation Studio.

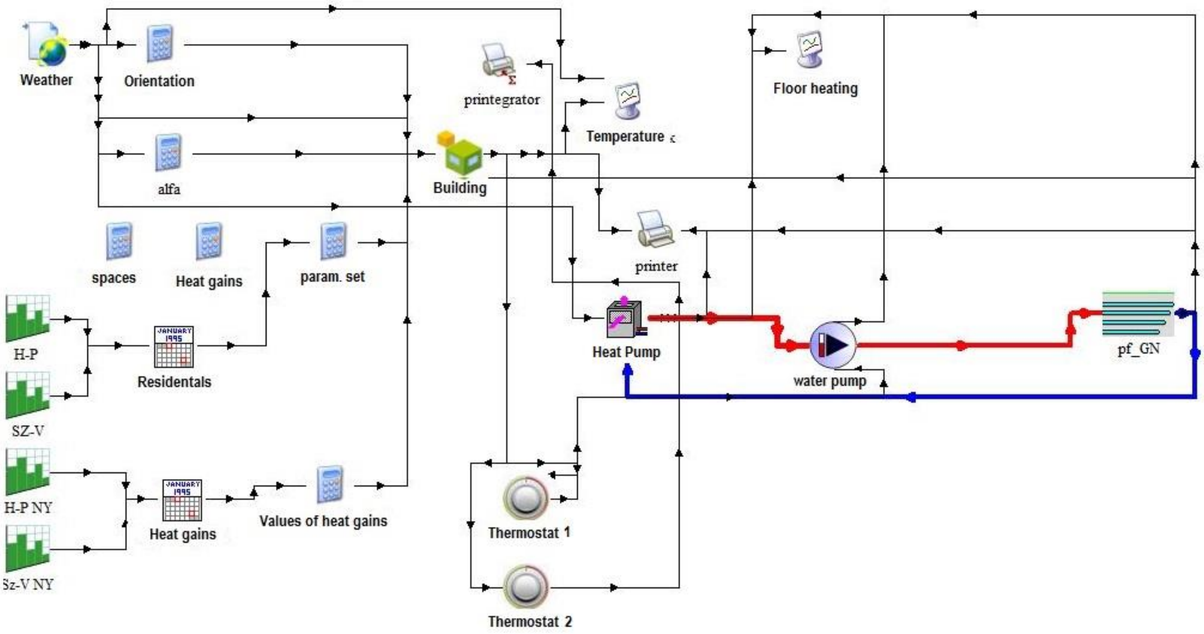

Figure 4. Schematic diagram of the developed model for the air/water heat pump heating system in Simulation Studio

3. Results

3.1. Comparison of the energy consumption of the investigated heating systems

In Decree 7/2006 TNM, heating systems are mainly characterized by their annual primary energy consumption—WinWatt automatically calculated this value after the appropriate heating system was selected. However, in the case of TRNSYS some additional calculation steps were required to determine this value. In case of the examination of the boiler system in TRNSYS, during the simulation run, the software exported the energy consumption data of the boiler in a 15-minute resolution and the annual energy consumption in kJ to a separate file which can be opened with a spreadsheet editor. This was first converted to kWh dimension, and then the resulting annual yearly energy consumption was made specific by dividing it with the heated floor area of the building, which is 156 m^2. These values and the results obtained using WinWatt are presented on Figure 5.

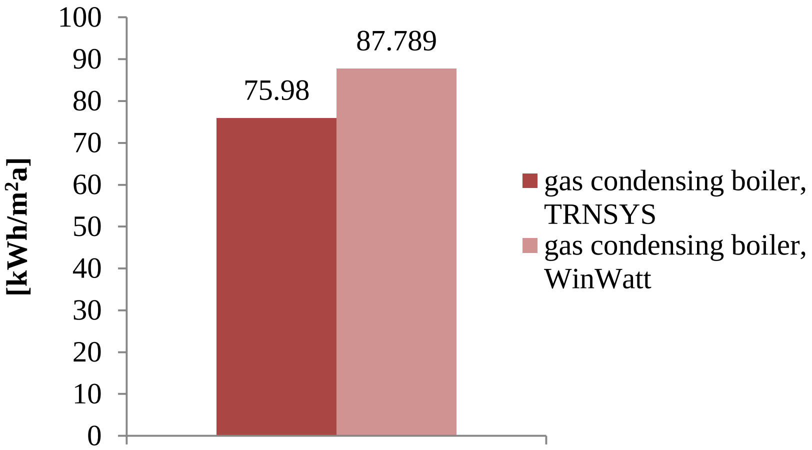

Figure 5. The annual specific primary energy consumption of the gas boiler heating system in case of different calculation methods

The energy consumption of the TRNSYS models containing the air/water heat pump heating system was determined similarly; the only difference was the consideration of the effect of the primary energy conversion factor as the heat pump uses electricity for its operation and not natural gas. Similarly to the calculation of the boiler system, the software exports the electrical energy consumption of the heat pump and the annual energy consumption to a separate file (in kJ). After the conversion to kWh, this value was multiplied by the primary energy conversion factor, which was assumed to be 1.8 like in the case of WinWatt. After that, the annual primary energy consumption was made specific by dividing it with the floor area. Figure 6 shows the results that were calculated using the two software.

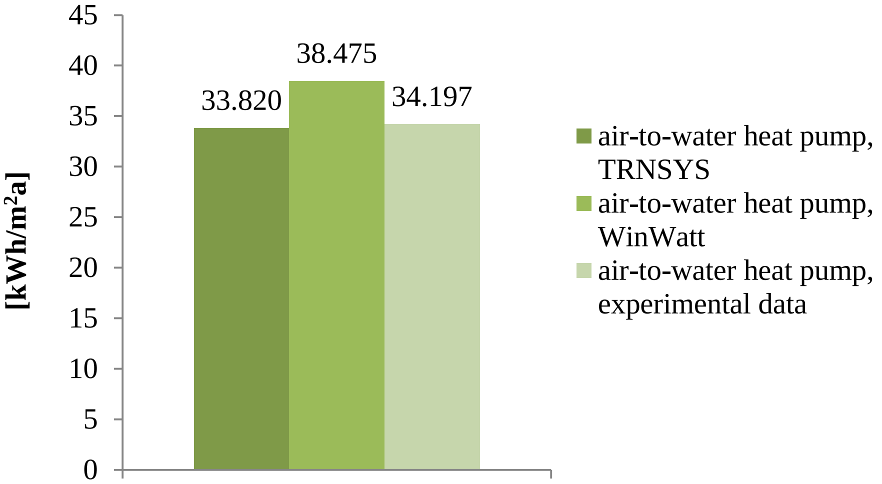

Figure 6. The annual specific primary energy consumption of the heat pump heating system in case of different calculation methods

Using the 3 years measured consumption data (in 2015: 33,971; in 2016: 34,356 and in 2017: 33,653 kWh/m^{2}a) given by the investor, figure 6 shows that the difference between the measured consumption data and simulated date by TRNSYS is only 1,11% and by WinWatt is 12,51%. By this way the difference between the real consumption data and calculated data based on Hungarian building energy decree (Ministerial Decree TNM 7/2006) is quite high.

WinWatt calculated a greater value for the annual specific energy consumption in case of both heating systems: for the gas boiler heating system, the calculation result of WinWatt was 87.789 kWh/m^2/a and the calculation result of TRNSYS was 75.98 kWh/m^2/a. In the case of the heat pump system, the difference between the two values is smaller: the calculation result for the annual specific heating energy consumption was 38.475 kWh/m^2/a with the software using the calculation method provisioned by the Hungarian Decree and 33.82 kWh/m^2/a with the software performing the dynamic simulation. In the case of heat pump systems, the difference is smaller, but Figure 6 clearly shows that the energy consumption values themselves are smaller as well.

The difference between the data obtained with the calculation method provisioned by the Hungarian decree and the data obtained using TRNSYS can also be attributed to several factors. The difference in the annual specific primary energy consumption can mostly be attributed to the fact that the weather data used by the two calculation methods are different. During the model developing the by TRNSYS, the weather data file published by Meteonorm was used, which was prepared using the measurements of the Budapest-Pestszentlőrinc meteorological station. Meteonorm's TMY (typical meteorological year dataset) is based on the results of decades of measurements using the data of

GEBA (Global Energy Balance Archive) from between 1991 and 2018 as starting points, while the Decree is based on meteorological data measured between 1901 and 1930 from the last century.

3.2. Economic comparison of the investigated heating systems

The calculated investment and operational costs are summarized in Table 2.

Table 2. The investment and annual operational costs of the gas boiler heating system and the heat pump heating system

	Investment cost [EUR]	Annual operational cost [EUR]
Condensing gas boiler	6.279	666
Air/water heat pump	14.989	443

The above values were used to investigate the progression of the investment and operational costs of the two systems in a period of 20 years; this is shown on Figure 7.

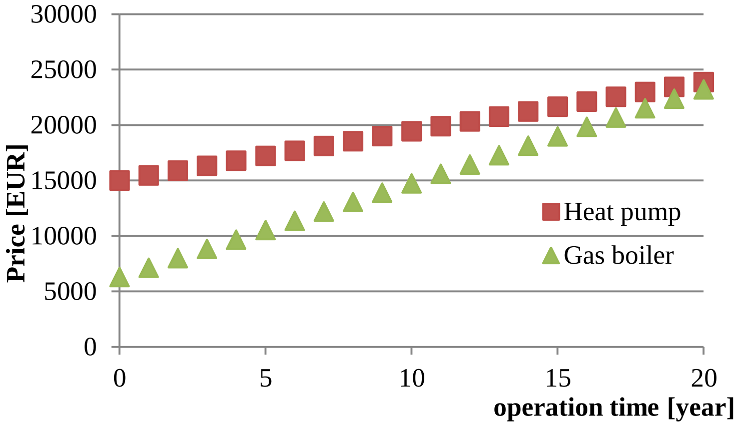

Figure 7. Comparison of the investment and annual operational costs of the gas boiler heating system and the heat pump heating system

The above figure shows the significant difference between the investment costs of the heat pump and gas boiler systems. Due to the high installation costs, the heat pump—in spite of the lower operational costs—is not more cost efficient in the investigated period. Using the initial data I considered, the heat pump would only become more cost efficient by the end of the 46th year–this interval, however, exceeds the life span of the heating systems. In my calculations, the ratio of the unit price of the electricity and that of the gas is 2.445. Decreasing this value improves the cost efficiency of the heat pump: The investigated heat pump system becomes more cost efficient in 20 years.

According to my calculations, if I choose an equipment 20% cheaper than the original Daikin heat pump, the heat pump system would become more cost efficient than the boiler system augmented with air conditioning by the end of the 20th year. The higher level of cooling comfort ensured by the heat pump can also be an important decision-influencing factor: this system eliminates the uncomfortable effects of blown cold air and the draft effect. Another argument on the side of the heat pump system is that in case of a gas boiler, in addition to the connection of the gas the fume exhaust (the cost of the former can really high: if the pipe of the gas distribution network is far away from the building, it will be necessary to dig a trench and lay connecting pipes) the cost of the gas plan and the chimney plan since these are necessary for the authorization.

4. Conclusion

In the first part of my work, we described the heat generators and heat emitters of the heating systems widely used in family houses especially the most common types: the condensing gas boiler, the air/water heat pump, the radiators and the various floor heating solutions.

The most important part of my research was the examination of the annual specific primary energy consumption of the air/water heat pump and condensing gas boiler heating systems with different calculation methods. Comparing the energy consumption values obtained using TRNSYS 18 working with dynamic simulation and the ones obtained using WinWatt working as provisioned Decree 7/2006 TNM, it can be stated these values are lower in case of TRNSYS. Using the dynamic simulation, 87.9% lower annual specific primary energy consumption was obtained in case of the heat pump heating system and a 86.55% lower value in case of the boiler system. The more accurate calculations of the dynamic simulation may have contributed to the difference, but in my opinion, the most important reason for the lower energy consumption is that the two calculation methods used different weather data. TRNSYS calculated with a 10% lower degree day based on the temperature data of the recent decades.

Based on my calculations considering the current electricity and natural gas prices, the air/water heat pump heating system is not as cost efficient as the boiler heating system; however, the former provides higher levels of comfort, because with the usage of heat pump not only heating, but also cooling in summer season can be provided.

Further research in the topic could aim to build more accurate heating system models (particularly in terms of their control) and to extend the investigation to cooling and air conditioning systems as well.

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Nomenclature

$\dot{Q}_{z}$	the heat flow entering the zone [W],
$\dot{Q}_{konv,z}$	convectional heat flows coming from the boarder surfaces of the heat zone [W]
$\dot{Q}_{inf,z}$	infiltration heat flows entering the zone from the environment [W],
$\dot{Q}_{szell,z}$	heat flows entering the zone from the ventilation system [W],
$\dot{Q}_{ny,z}$	convective heat flows from the sources present in the zone [W],
$\dot{Q}_{sz,z}$	heat flows arriving through air from the adjacent zone [W],
$\dot{Q}_{sug,z}$	solar radiation entering the zone from the external windows, which becomes a convective gain for the internal air upon entering the zone [W],
$\dot{Q}_{ar,z}$	solar radiation absorbed by the internal blinds, which becomes a convective gain for the internal air upon entering the zone [W],

T_e	supply water temperature [°C],
T_v	return water temperature [°C],
$\dot{Q}_{ft}$	power transferred to the heating water [W],
$\dot{m}_v$	mass flow rate of the circulated heating water [kgs-1]
$c_{p,v}$	specific heat of the heating water [J/kg·K)
$\dot{Q}_{medium}$	the power to be transferred to the medium, W]
$\dot{m}_{medium}$	the mass flow rate of the medium [kg/s]
$c_{p,\ medium}$	specific heat of the heating medium [J/kg·K]
T_e	the set supply temperature [°C]
T_{be}	the temperature of the medium when entering the boiler [°C]
$\dot{Q}_{max}$	the nominal power of the boiler [W]
$\dot{Q}_{be}$	power to be fed to the boiler using the fuel [W]
η_k	boiler efficiency [-]
$\dot{Q}_{kond}$	thermal power of the condenser [W]
$\dot{Q}_n$	heating power of the heat pump [W]
$\dot{Q}_{elp}$	thermal power of the evaporator [W]
P_{kompr}	power of the compressor [W]
$\dot{Q}_{kieg}$	is the thermal power of the auxiliary heating [W]
COP_{hsz}	the power factor of the heat pump [-]
P_{vent}	power of the fan [W]
P_{vez}	power of the controller fW]
P_{kieg}	electrical power consumption of the auxiliary heating [W]
m_b	mass of the heating concrete element [kg]
$c_{p,b}$	specific heat of the concrete [Jkg-1K-1]
$\dot{m}_{fk}$	mass flow rate of the heating medium [kgs-1]
$c_{p,fk}$	specific heat of the heating medium [Jkg-1K-1]
T_b	temperature of the heating concrete assumed to be isotherm [°C]
U_f	thermal conductivity factor of the layers between the concrete element and the room, which incorporates the heat transfer coefficient [Wm2-1-K-1]
U_a	the thermal conductivity factor between the concrete layer and the space below it, [Wm2-1-K-1]
A_f,A_a	size of the upper and lower surface of the concrete element [m2]
T_h,T_a	temperature of the space above (room) and below the concrete layer [°C]
ε	efficiency of the heat exchange between the heating medium and the concrete [-]
T_{be}, T_{ki}	inflow and outflow temperature of the heating medium [°C]

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