Cost efficiency of ventilation systems for low-energy buildings with earth-to-air heat exchange and heat recovery

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Abstract

Energy demands for heating and auxiliary energy of a typical residential low-energy building are simulated for different ventilation systems with earth-to-air heat exchanger, heat recovery by air-to-air heat exchanger and combinations thereof. Dynamic thermal simulations of a corresponding low-energy house have been performed for a full heating period. They reproduce measurements from a monitored occupied building with regard to energy and zone temperatures under identical weather conditions. This proves the validity of the applied simulation model. From the obtained results, guidelines have been derived for the best advice to yield both primary energy savings and cost efficiency. Results show, that the cost efficiency of heat recovery units depends on local conditions, mainly heating degree days. For earth heat exchangers this dependence is very weak. Considering a broad range of European climates, heat recovery units show a much better cost efficiency for reducing the heating demand of small to medium sized low-energy residential buildings than earth heat exchanger do. The dependence of the cost efficiency on the level of heat recovery efficiency within the range from 65% to 90% is quite small.

Conference topic : design strategies

Keywords : cost efficiency, earth heat exchanger, heat recovery, simulation

1) VENTILATION SYSTEMS

Ventilation systems are widely used in low-energy and passive-solar buildings for a variety of reasons (e.g. energy saving, air quality, control of humidity) [1, 2]. In such houses, the ventilation and infiltration losses are increasingly important because the transmission losses are already kept at very much reduced low values.

The air-tight construction of these buildings necessitates a ventilation system, because the exchange due to infiltration alone does not further assure hygienic conditions. A simple and inexpensive extract air ventilation system with adjustable volume rate is considered as a typical reference case with which more advanced ventilation systems have to be compared. The system is displayed in Fig. 1. This reference case is already energy-efficient, when the air exchange rate is controlled according to the hygienic necessary needs and no excessive air change happens. Then, additional energy savings can be achieved only by tapping ambient energy sources (e.g. an earth-to-air heat exchanger) or by using the energy of waste air (heat recovery).

1.1) Earth-to-air heat exchangers

For residential houses earth heat exchangers (EHX) consist of between 20 and 100 m of (usually) plastic pipes, which are installed in a depth of about 2 m beside, around or under the building (Fig. 2). The overall efficiency is defined as

$$e_{\mathrm{EHX}} = \frac{T_{\mathrm{EHX}} - T_{\mathrm{Fr}}}{T_{\mathrm{Ea}} - T_{\mathrm{Fr}}} \ , \qquad (1)$$

where T_{Fr} is the fresh air temperature and T_{EHX} is the increased air temperature after the EHX. T_{Ea} is the undisturbed earth temperature at the depth of the buried pipes. For small units, which are used for residential houses, the efficiency is usually not much higher than $e_{\mathrm{EHX}} \sim 0.5$.

1.2) Heat recovery units

More advanced in technology are heat recovery (HR) units, indicated by Fig. 3, which consist of a heat exchanger where the energy of the extract air is directly transferred to the fresh air before its distribution inside the building. Necessary is a balanced ventilation system, which consists, in addition to the extract air system, of a centralised supply and distribution system. With T_{Ex} the extract air temperature and T_{Su} the supply air temperature, the efficiency e_{HR} of a HR system is:

$$e_{\mathrm{HR}} = \frac{T_{\mathrm{Su}} - T_{\mathrm{Fr}}}{T_{\mathrm{Ex}} - T_{\mathrm{Fr}}} \ . \qquad (2)$$

With balanced counter-flow channel HR-units, efficiencies e_{HR} up to 0.9 are feasible [3, 4]. Counter-flow sheet HR-units reach efficiencies e_{HR} up to 0.8, and cross-flow sheet HR-units reach about $e_{\mathrm{HR}} \sim 0.65$. For HR-units with highest efficiencies, the outlet temperatures at the heat exchanger would usually drop below zero, causing the moisture of the extract air to freeze in the heat exchange unit. For example, given an extract temperature of T_{Ex} = 20 °C and an efficiency of e_{HR} = 0.9, then for an outdoor temperature of less than -2.2 °C the outlet temperature would drop below 0 °C,

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causing the risk of freezing in the HR-unit. To prevent freezing, often electric heaters are installed at the fresh air inlet, to raise the intake temperature over a critical level at all times. Whereas electric heaters are relatively inexpensive (200 € - 400 €), electricity costs and the corresponding CO_2-emissions can accumulate. Instead, a suitable EHX can also be used to prevent freezing. This option is discussed in the next section.

1.3) Earth heat exchanger combined with heat recovery

The amount of ventilation losses of a building depends for a given air change rate on the difference between indoor temperature T_{Ex} and supply air temperature T_{Su}. Whereas a HR is generally the most efficient unit to decrease this temperature difference, an *additional* EHX can be used to raise the inlet temperature T_{Su}, and, therefore, decrease ventilation losses further, as well as prevent freezing of the exhaust air. This concept is illustrated in Fig. 4. The corresponding efficiency is:

$$e_{HR+EHX} = \frac{T'_{Su} - T_{Fr}}{T_{Ex} - T_{Fr}}, \qquad (3)$$

where T'_{Su} is the further increased supply temperature due to the EHX (compared to the case with mere HR). The efficiency of the HR-unit is, of course, unchanged, and can now be written as:

$$e_{HR} = \frac{T'_{Su} - T_{EHX}}{T_{Ex} - T_{EHX}}, \qquad (4)$$

with T_{EHX} the inlet temperature of the HR, and, at the same time, the outlet temperature of the EHX (see Eq. 1). Using Eqs. (1) and (4), the combined efficiency (Eq. 3) becomes:

$$\begin{aligned} e_{HR+EHX} &= e_{HR} + e_{EHX}(1 - e_{HR})\frac{T_{Ea} - T_{Fr}}{T_{Ex} - T_{Fr}} \\ &= e_{HR} + (1 - e_{HR})\frac{T_{EHX} - T_{Fr}}{T_{Ex} - T_{Fr}} \end{aligned} \qquad (5)$$

The efficiency of the combined system is always increased compared to a stand alone HR. However, especially for a very effective HR with $e_{HR} \sim 0.9$ the second term is strongly reduced, i.e. the additional effect of an EHX is rather small, because e_{HR+EHX} must be always less than 100%. For T_{Ex} = 20 ºC, T_{Ea} = 10 ºC, T_{Fr} = 0 ºC, an EHX with an efficiency of e_{EHX} = 0.6 would increase the efficiency of the overall system from e_{HR} = 0.9 to e_{HR+EHX} = 0.93. Even for lower outdoor temperatures, the combined efficiency would be always between $0.9 < e_{HR+EHX} < 0.95$. The effective HR system provides a thermal separation of the building against the fresh air, which the EHX increases in temperature. However, as mentioned in Sect. 1.2, without an EHX, the effective HR system needs to be kept ice free (usually) with an electric heater for temperatures lower than about -2 ºC, which can occur rather often, depending on the climate region. From the point of view of the primary energy, which is roughly a factor of three higher for electrical energy, the combined efficiency can be different. This is because a properly designed EHX can compensate for an electric heating system and corresponding electrical energy. This topic is discussed further in Sect. 3.3.

2) DYNAMIC SIMUMATION METHOD

For an assessment of the long-term efficiency of technical equipment, which is used to reduce ventilation losses, the complete time series of outdoor temperatures and global radiation during a heating period is relevant. For a low-energy or passive-solar house this period is shorter than for buildings with higher energy demand, because internal and solar gains suffice longer to maintain the desired indoor air temperatures, even at low outdoor temperatures. With regard to this fact, heating days have been defined for low-energy houses on the basis of 12 ºC / 20 ºC (12 ºC outdoor and 20 ºC indoor). Beyond that, temperature variations influence for example the performance of EHX. In longer cold spells the efficiency of the EHX is reduced through the decreased earth temperature around the unit, depending on the actual running conditions. All these time dependent effects are taken into account with the use of dynamic simulation programs.

2.1) Sample building

As the sample building for this paper, a low-energy building in Wenden-Hillmicke (Germany) is used. See [5] for details of the building and corresponding measurements. The two-family low-energy house was built in 1998. The house is a massive construction with heated basement and two upper floors. The net heated area is 204 m². Pre-built concrete elements with integrated insulation for walls and roof are

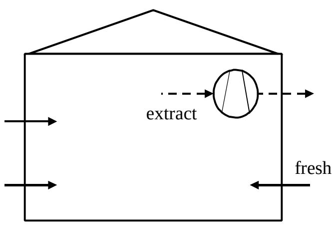

Fig. 1. *Layout of the reference case to which the different extended systems are compared.*

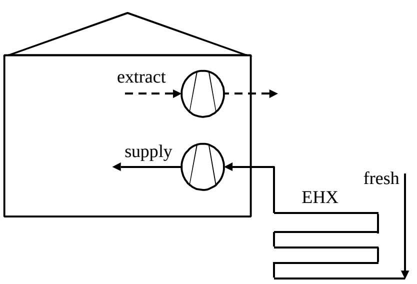

Fig. 2. *Layout of the ventilation system with earth heat exchanger (Case 1).*

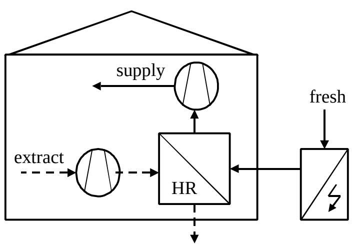

Fig. 3. *Layout of a balanced ventilation system with heat recovery. A defroster is used to prevent freezing in the heat exchanger (Case 2).*

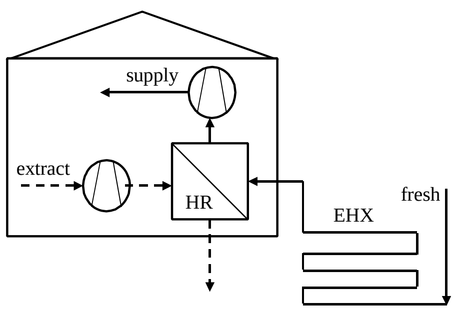

Fig. 4. *Layout of a system combining both, heat recovery unit and earth heat exchanger (Case 3).*

used. Triple pane highly insulating windows are installed. The heat is provided by a condensing gas burner with maximum power of 11 kW, and by flat-plate solar collectors. The heat distribution is by a balanced ventilation system with HR by a counter-flow channel heat-exchanger and by additional radiators. The airflow rate is 255 m^3/h. An additional EHX prevents freezing.

Room temperatures and energy flows into the building, as well as weather conditions, have been measured for one year in 1998/1999. The measured energy demand for heating, normalised to 3500 Kd/a, is 25.3 kWh/(m^2a).

2.2) Dynamic simulation

The simulation software *TRNSYS* [6] is used to model the sample building. The model consists mainly of a *Type 56* unit which is divided into 8 zones. The mean U-value of the opaque envelope is 0.12 W/(m^2K), and the windows have an U-value of 0.8 W/(m^2K). Natural infiltration is assumed as 0.2/h and the airflow rate of 255 m^3/h corresponds for the total volume of 619 m^3 to an additional exchange rate due to ventilation of 0.41/h. Zone temperatures are set to 20 ºC, with an allowed operation range for the heating control of ±0.2 ºC. Internal gains of two households with together 7 persons are considered. Maximum power of the heating system is 16 kW to account for the higher heating demand in the different cases for the ventilation system and climate considered here.

For the EHX a hypocaust model is used (*Type 61)* [7]. The length of the pipes is 10 m, of which 4, 6 or 9 are used in parallel with a distance of 1.5 m. The pipes have a diameter of 15 cm and are buried at depth 2 m in soil with heat conductivity of *?* = 1.5 W/(mK) and heat capacity of c = 2412 kJ/(Km^3). In a depth of 4.2 m the soil has the mean temperature of the corresponding location: Mannheim (D) 11.2 ºC, Trier (D) 9.1 ºC, Klagenfurt (A) 7.8 ºC, Stockholm (S) 6.1 ºC. The resistance between soil surface and ambient air is R = 0.054 (m^2K)/W. The EHX is operated only when the fresh air temperature is lower than the undisturbed earth temperature at the depth of the buried pipes, and bypassed at other times.

For the HR-unit *Type 5* is used, with constant efficiencies of e_{HR} = 0.65, 0.80 and 0.90, respectively.

The weather data for the four locations considered here were generated on a hourly basis with the program *METEONORM* [8]. The heating degree days (see Tables 2-4) are defined by the difference of 20 ºC and the mean daily outdoor temperature, when the latter is below 12 ºC.

In the period from 17.12.1998 to 31.3.1999 the simulation results for the mean air temperatures have been compared with the measured ones on the basis of 15 minute values. For this comparison the measured outdoor temperature and solar radiation were used as input for the simulation. The difference between measured and simulated house temperature forms a Gaussian distribution with mean value of μ = -0.1 K and standard deviation of s = 0.2 K. The heating energy demand for this period was measured as 2587 kWh, whereas the simulation gives 2607 kWh. The comparisons of temperature and energy show, that the simulation model does reproduce the real building quite exactly.

3) RESULTS AND DISCUSSIONS

The *TRNSYS* model for the sample building is used to calculate the energy demand for heating for the different cases of the ventilation system and climate conditions. For the reference case (Fig. 1) the energy balance for a heating period is shown in Fig. 5. From the heating demand and the auxiliary energy, necessary to operate the extended ventilation system, the cost efficiency is calculated. The performance of the different ventilation systems can be compared best on the basis of the primary energy demand. For the conversion of heating demand to primary energy $E_{\text{primary}} = 1.1 \cdot E_{\text{heating}}$ is used, which accounts for production and distribution losses. Assuming that for heating a highly efficient condensing gas or oil burner with efficiency of about 100% is used, the conversion losses into heat are minimised. For electric energy a conversion relation of $E_{\text{primary}} = 3 \cdot E_{\text{electric}}$ is used. The factor of 1.1 for the relation between primary energy and heating demand might be too optimistic. A 10% higher value for this factor would lead to about 10% more primary energy saving. This would result in about 10% better cost efficiency for the cases presented here.

The second part of the cost efficiency are the system costs, which are somewhat indefinite or varying in practice. For all three cases, the additional system costs compared to the reference case are calculated according to the total element prices listed in Table 1. The prices are valid for one or two family homes with air flow rates of up to 300 m^3/h, which is represented by the sample building used.

From the additional investment costs needed to realise the cases 1-3 on the basis of the reference case and the corresponding saved primary energy, a cost efficiency can be calculated. First, the total investment is compared to the yearly saved primary energy:

$$C_{\text{tot}} = \frac{\text{total investment costs}}{\text{saved yearly primary energy}}, \quad [C_{\text{tot}}] = \frac{€}{\text{kWh} \cdot \text{a}^{-1}} . \quad (6)$$

The efficiency C_{tot} is suitable for a ranking of cost efficiency. To calculate an absolute efficiency, i.e. to answer the question if the energy savings can make up for the investment costs for technical equipment during the lifetime of the equipment, one additional step is necessary. The relevant annuity factor A_{inv} depends on the yearly interest rate p for a loan or an alternative investment, respectively. With n the lifetime of the equipment in years, which is equal to the total loan period, the annuity factor is:

$$A_{\text{inv}} = \frac{p \cdot (1+p)^n}{(1+p)^n - 1}, \quad [A_{\text{inv}}] = \frac{1}{\text{a}} . \quad (7)$$

Assuming that a complete refurbishment or exchange of the ventilation system and the EHX is necessary after about 20 years, and with an interest rate of p = 8%, the annuity factor becomes A_{inv} = 0.10/a. The cost efficiency C_{inv} of the investment is the product of total efficiency and annuity factor according to

$$C_{\text{inv}} = C_{\text{tot}} \cdot A_{\text{inv}}, \quad [C_{\text{inv}}] = \frac{€}{\text{kWh}} . \quad (8)$$

Earth heat exchanger	40 €/m
Extract air ventilation system	2500 €
Upgrade from extract system to balanced supply air ventilation system	1500 €
Heat recovery unit with 65% efficiency	2000 €
Heat recovery unit with 80% efficiency	2500 €
Heat recovery unit with 90% efficiency	3000 €
Defroster unit for heat recovery	300 €

Table 1. *Mean prices for elements, which are used in the different cases considered, including installation and tax.*

Cost efficiency C_{inv} can be compared directly with the energy costs. If C_{inv} is smaller than primary energy costs C_{PE}, the investment pays back. Today the primary energy costs, including the base price, and for amounts which are needed in small to medium size residential buildings, which are considered here, are at about $C_{PE} \tilde{}$ 0.05 €/kWh. The energy prices are subject to almost unpredictable fluctuations. In general, one can assume raising energy costs in the long run. Therefore, if the investment is financially rewarding at today's energy costs ($C_{inv} < C_{PE}$), this is very likely to be true over the whole period, too.

3.1) Efficiency of earth heat exchanger (case 1)

For a given airflow rate, the efficiency of an EHX depends on the overall length of the pipes in the earth. In view of case 3, the lengths for all EHX are chosen such, that they are sufficient to prevent freezing of the most effective HR-units, even if there is no such unit installed. This allows a better comparison of all three cases. Table 2 shows the results of the dynamic simulations using the *TRNSYS* model of the sample building. The table gives the values of the heating energy demand and the electric energy for fans. In the reference case, the energy for the fan is 0.2 Wh/m^3, whereas with an EHX and corresponding filters an energy of 0.22 Wh/m^3 is necessary.

The saved primary energy is calculated using $E_{primary} = 1.1 \cdot E_{heating} + 3.0 \cdot E_{electric}$ in the cases with and without EHX. If EHX of equal lengths (90 m) are considered, the heating demand is 35.5 kWh/(m^2·a) in Mannheim and 43.8 kWh/(m^2·a) in Trier.

The total investment costs of EHX are 40 €/m including modifications to the extract air system, installation and tax. Dividing the total investment costs by the saved primary energy, the total investment efficiency C_{tot} is conceived, which is also listed in Table 2. Assuming an annuity factor of A_{inv} = 0.1/a, the cost efficiencies of the EHX are about C_{inv} = 0.2

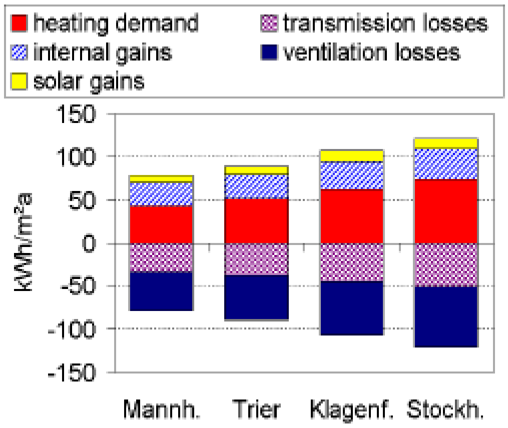

Fig. 5. *Energy balance of the sample building for the reference case (see Fig. 1) for four different locations***.**

€/kWh. This value is well above today's primary energy costs of $C_{PE} \tilde{}$ 0.05 €/kWh. From the point of view of the cost efficiency for heating in small to medium low-energy residential houses in Europe, EHX have a quite poor performance. See Sect. 4 for a further discussion.

3.2) Efficiency of heat recovery units (case 2)

For using HR, the building must be equipped with a balanced ventilation system for extract and supply air. In addition to air pipes, fans and the HR-unit (i.e. a heat exchanger), a defroster must be installed to prevent freezing of the extract air in the recovery unit at cold days. The defroster is usually an electric heater, which is installed at the fresh air inlet, and heats the fresh air so that the exhaust air temperature does not drop below 0 ºC.

Table 3 shows the results of the dynamic simulations using the *TRNSYS* model of the sample building for the heating demand and the electric energy for fans and defroster. In the reference case, the energy for the fan is 0.2 Wh/m^3, whereas for balanced ventilation systems with HR and corresponding filters an energy of 0.4 Wh/m^3 is assumed. With the defroster, the fresh air inlet temperature T_{Fr} is kept above -10.8 ºC for HR-units with efficiency of 65%, -5.0 ºC for 80% and -2.2 ºC for 90%. These temperatures are controlled, and depend on the actual extract air temperature, which varies slightly around 20 ºC. The defroster provides exhaust air outlet temperatures of above 0 ºC, and, therefore, keeps the HR-unit ice free at all times. The investment costs include costs for: 1) upgrade of the ventilation system; 2) HR-unit; and 3) defroster (see Table 1 for the amounts).

	Mannheim (D)		Trier (D)		Klagenfurt (A)		Stockholm (S)	
Heating degree days	2740 Kd/a		3254 Kd/a		4031 Kd/a		4508 Kd/a	
Length of earth heat exchanger	zero	4×10 m	zero	6×10 m	zero	9×10 m	zero	9×10 m
Heating demand in kWh/(m^2·a)	42.2	38.1	50.4	45.2	62.6	55.0	74.4	66.7
Electric energy for fan(s) in kWh/(m^2·a)	1.30	1.38	1.33	1.42	1.45	1.55	1.60	1.70
Saved primary energy by earth heat exchanger in kWh/a		871		1112		1644		1667
Investment costs per saved primary energy C_{tot} in €/(kWh·a^{-1})		1.84		2.16		2.19		2.16

Table 2. *Simulation results of heating demand and electric energy for fans for systems without (reference) and with an earth heat exchanger (case 1). Corresponding savings due to the EHX are shown, as well as total cost efficiencies* C_{tot}.

	Mannheim (D)			Trier (D)			Klagenfurt (A)			Stockholm (S)		
Heating degree days	2740 Kd/a			3254 Kd/a			4031 Kd/a			4508 Kd/a		
Heat recovery efficiency e_{HR} in %	65	80	90	65	80	90	65	80	90	65	80	90
Heating demand in kWh/(m²·a)	22.7	18.4	15.7	27.7	22.6	19.4	35.1	28.8	25.0	43.4	36.3	32.2
Electric energy for fan(s) in kWh/(m²·a)	2.59	2.59	2.59	2.66	2.66	2.66	2.90	2.90	2.90	3.19	3.19	3.19
Electric energy for defroster in kWh/(m²·a)	0.00	0.23	0.80	0.02	0.70	1.59	0.47	2.28	3.75	0.36	2.54	4.56
Saved primary energy by heat recovery in kWh/a	3586	4410	4668	4268	4996	5169	4996	5302	5255	5763	6022	5706
Investment costs per saved primary energy: C_{tot} in €/(kWh·a^{-1})	1.06	0.98	1.03	0.89	0.86	0.93	0.76	0.81	0.91	0.66	0.71	0.84

Table 3. *Simulation results of heating demand and electric energy for fans and defroster for systems with heat recovery (case 2). Corresponding savings due to the heat recovery are shown, as well as total cost efficiencies* C_{tot}.

In Fig. 6 the total primary energy demand for heating, ventilation and defroster is shown for the cases without HR (reference) and with three different HR efficiencies for Stockholm. Because the heating demand increases with heating degree days, the total savings due to heat recovery are higher in Stockholm (up to 6.0 MWh/a for the sample building) than in Mannheim (up to 4.7 MWh/a). However, due to the use of electrical energy for the defroster, the dependence of the total saved primary energy on the HR efficiency is rather small. This is true in warmer climates (i.e. Mannheim), because the heating demand itself is small in the first place. However, this is also true in colder climates (i.e. Stockholm), because the increasing demand of electrical energy for the defroster of highly efficient HR-units makes up for the higher savings of thermal energy.

The large amount of electric energy for defrosting of highly efficient HR-units in cold climates can lead to inverse relation between cost efficiency C_{inv} and HR efficiency e_{HR}. For the assumed price difference of 1000 € between e_{HR} = 0.65 and e_{HR} = 0.9, the lower HR efficiency would have the best cost efficiency in Stockholm. For an annuity factor of A_{inv} = 0.1/a, the cost efficiency for this unit is C_{inv} = 0.066 €/kWh, which is indeed comparable with today's energy prices. Therefore, if a electric defroster is used, a HR unit with e_{HR} = 0.65 can have a good cost efficiency at a location with a high value of heating degree days and yearly temperature profile like Stockholm.

3.3) Efficiency of earth heat exchangers combined with heat recovery units (case 3)

Presented results of investigations have shown, that the energy efficiency of high performance HR-units is limited by the necessary energy for defrosting. An appropriate EHX can substitute the defroster and the corresponding electric energy. The auxiliary energy for ventilation does thereby increase from 0.40 Wh/m³ to 0.42 Wh/m³ due to the increased pressure drop in the buried pipes of the EHX. Table 4 reveals, that the saved primary energy is increased compared to case 2 mainly by the amount for the defroster energy. Reductions of heating demand are quite small, especially for the cases with e_{HR} = 0.9, because of the thermal separation from of the building to the EHX, which is provided by the very effective HR (see Eq. 5).

Compared to case 2, the defroster (300 €) is supplemented by the EHX (1600 € to 3600 €). The cost efficiency C_{tot} and, therefore, also C_{inv} is growing (i.e. becoming worse) in case 3 compared to case 2. This is especially true for small HR efficiency (e_{HR} = 0.65), because the amount of electric energy for defrosting which can be saved by the EHX is very small. Fig. 7 shows the effect of the EHX in combination with HR for Stockholm. In cold climates (Stockholm) and high HR-efficiency (e_{HR} = 0.90), the savings of an EHX in combination with HR are substantial.

	Mannheim (D)			Trier (D)			Klagenfurt (A)			Stockholm (S)		
Heating degree days	2740 Kd/a			3254 Kd/a			4031 Kd/a			4508 Kd/a		
Heat recovery efficiency e_{HR} in %	65	80	90	65	80	90	65	80	90	65	80	90
Length of earth heat exchanger	4×10 m			6×10 m			9×10 m			9×10 m		
Heating demand in kWh/(m²·a)	21.3	17.7	15.4	26.0	21.8	19.0	32.7	27.8	24.7	40.9	35.4	32.0
Electric energy for fan(s) in kWh/(m²·a)	2.67	2.67	2.67	2.75	2.75	2.75	3.00	3.00	3.00	3.29	3.29	3.29
Saved primary energy by combined system in kWh/a	3852	4659	5175	4606	5549	6177	5761	6861	7556	6483	7717	8480
Investment costs per saved primary energy: C_{tot} in €/(kWh·a^{-1})	1.32	1.20	1.18	1.28	1.15	1.12	1.23	1.11	1.07	1.10	0.98	0.96

Table 4. *Simulation results of heating demand and electric energy for fans for systems with heat recovery and earth heat exchanger (case 3). The savings of the yearly primary energy demand compared to the reference case and* C_{tot} *are shown.*

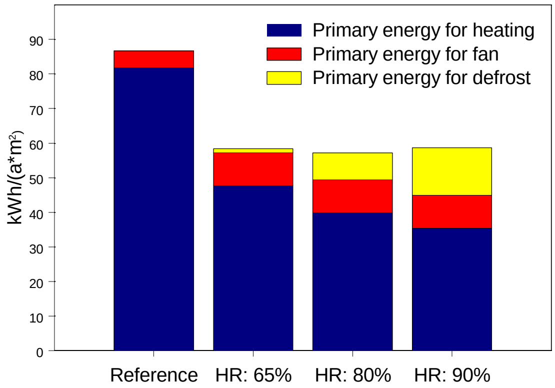

Fig. 6. *Simulation results of primary energy demand for the reference case compared to systems with different heat recovery efficiencies (case 2) in Stockholm (S).*

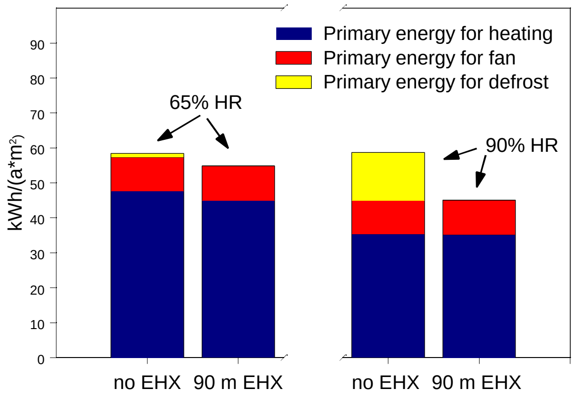

Fig. 7. *Simulation results of primary energy demand for two different heat recovery efficiencies with (case 3) and without (case 2) an earth heat exchanger in Stockholm (S).*

4) CONCLUSIONS

Simulations results have been presented for the primary energy demand of a low-energy building with different realisations of the ventilation system. Results are applicable to small and medium size residential buildings. Cost efficiencies are calculated including the system costs. For the three considered cases of a ventilation system beyond the reference case, following conclusions can be drawn:

Earth heat exchanger: The extension of a mere ventilation system with an earth heat exchanger to reduce the heating demand is not cost efficient for residential low-energy buildings in Europe. The investment costs exceed the savings of energy costs by a factor of 4 for all climates considered. The correlation between outdoor temperature and earth temperature results in a very weak dependence of cost efficiency on climate. On the one hand, low outdoor temperatures lead to a high heating demand, and therefore, high potential of energy saving. On the other hand, the earth temperature is accordingly lower, which decreases the performance of an earth heat exchanger, in contrast to heat recovery. Cost efficiency may be different for office buildings, because there air flow rates are significantly higher, and a substantial cooling demand may exist in summer. For cooling usually electric energy is used, which needs a factor of three higher primary energy demand. Nonetheless, the investment costs do not change, if the earth heat exchanger is used in summer. Therefore, it might be possible, that in the case of substantial cooling demand in summer, an earth heat exchanger has a very good cost efficiency.

Heat recovery: The use of heat recovery units can reduce the primary energy demand for heating significantly (by more than 30%). Because of the electrical energy used to prevent freezing, the saving of primary energy demand depends only weakly on heat recovery efficiency in the range from e_{HR} = 65% to e_{HR} = 90%. In cold climates, the investment costs can indeed be balanced by energy savings, because the savings potential is higher for higher heating demand. For mild climates the cost efficiency of a heat recovery can become unfavourable. However, cost efficiency of heat recovery is always by about a factor of 2 better than that for an earth heat exchanger, as far as heating demand in low-energy residential buildings is concerned.

Combination of heat recovery and earth heat exchanger: An additional earth heat exchanger does not enhance the cost efficiency of a heat recovery unit. The smallest impact of an earth heat exchanger on cost efficiency is for heat recovery units with the highest efficiencies. In these cases, (especially in cold climates) substantial amounts of primary energy for defrosting can be saved by the usage of earth heat exchangers.

Summary

From the point of view of mere cost efficiency, the best system to reduce the heating demand in low-energy residential houses is an inexpensive heat recovery unit, even if the efficiency is as low as about 65%.

From the point of view of energy saving in the first place, and cost efficiency coming second, for reducing the heating demand in residential low-energy buildings the highest priority should be given to highly efficient heat recovery units (e_{HR} = 0.9), which should be complemented by earth heat exchangers as compensation for an electric defroster in cold climates (= 4000 Kd/a).

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