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Energy Consumption in a Naturally Ventilated House in Finland

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SYNOPSIS

In this paper, measurement and simulation results are presented that demonstrate the energy performance of a recently built ecological house in Helsinki, Finland. The space heating energy consumption was measured to be 76 kWh/(m^2·a) of which 29% was provided by wood. For comparison, Finnish houses typically consume 120 kWh/(m^2·a) or nearly 60% more energy for space heating. The total energy consumption (121 kWh/(m^2·a)) and electricity consumption (28 kWh/(m^2·a)) were quite low. As a result, the total primary energy consumption was only 162 kWh/(m^2·a), while the primary energy consumption in typical Finnish houses is over 40% higher. The paper also includes simulation results from several cases to illustrate the effect of insulation level, household electricity and domestic hot water consumption, window area, ventilation rate and heat recovery effectiveness on the energy use.

1.0 INTRODUCTION

Currently, there is a rising demand for sustainable low-energy housing that has a limited impact on the environment and provides occupants with excellent indoor air quality (IAQ) and climate. The house studied in this paper (referred to as Tapanila ecological house because it is built in the Tapanila district of Helsinki, Finland) fulfils these criteria, but there are several others in Finland as well (Laine and Saari, 1998 and Leppänen, 1998). The unique aspect of Tapanila ecological house is that it employs several passive systems for controlling the indoor climate and IAQ. The house has no plastic vapour retarder to permit diffusion mass transfer between indoor air and the porous building envelope and a natural ventilation system (Simonson, 2001 and Simonson, 2000). Tapanila ecological house was designed as a low-energy house and the insulation is 250 mm thick in the walls (U = 0.16 W/(m^2·K)) and 425 mm in the roof (U = 0.10 W/(m^2·K)) and has an airtightness of 3 ach at 50 Pa (Simonson, 2001). The house is connected to the Helsinki district heating system, which provides space heating through hot water radiators and pipes embedded in the floor and heat for domestic hot water. A wood-burning fireplace and sauna stove also provide space heating. The two-storey single-family house has a full basement and an unheated porch and has a gross heated floor area of 217 m^2, which will be used to normalise the energy consumption results.

2.0 MEASURED ENERGY AND WATER CONSUMPTION

The energy consumption was monitored from August 1999 to August 2000. During this time, the consumption of district heating energy was recorded weekly. It is assumed that 95% of the delivered district heating energy provides useful heating. The total water consumption was recorded nearly every month and the consumption of hot water was recorded weekly starting in October 1999. The hot water consumption from October 1999 to August 2000 was extrapolated to determine the yearly consumption. The energy required to heat the hot water was calculated assuming constant cold (5°C) and hot (55°C) water temperatures.

The occupants of the house began burning firewood in October 1999 and the mass of consumed firewood was recorded daily. The heating energy from firewood is calculated from the heat value of pine wood, which is 4.15 kWh/kg and 4.2 kWh/kg when the moisture content is 20% and 10% by mass respectively (Työtehoseura, 1997). The moisture content of the firewood was measured to be between 12% and 17%. Since the fireplace in the living room is massive and the two dampers in the chimney are nearly always closed after the burning of the wood, it is assumed that a large portion (70%) of this energy provides space heating (3 kWh/kg). The sauna stove, on the other hand, is much less massive and the damper is nearly always open during use, so only 10% of the wood consumed in the sauna is assumed to provide useful space heating (0.4 kWh/kg). The wood that is burned during the months of June, July and August is assumed to provide no useful space heating.

The consumption of electricity was determined from the electrical meter, which was read by the utility company on May 26, 1999 and May 29, 2000. In addition, the electricity consumption was recorded weekly from May to August 2000. These measurements indicated that the electricity consumption was quite constant throughout the year. Since little electricity was used outside the house, this electricity was not subtracted from the measured values.

The yearly energy and water consumption are given in Figure 1 and, for comparison, the consumption of two other recently-built low-energy houses in Finland known as ESPI 1 and ESPI 2 (Laine and Saari, 1998) and typical Finnish houses (Motiva, 1999) are included. The values for typical Finnish houses are based on a house with 4 occupants and a gross floor area of 140 m^2. Figure 1 shows that the normalised consumption of energy and water is significantly higher in typical Finnish houses than in Tapanila ecological house. A typical Finnish house consumes 50% more total energy, 58% more heating energy, 25% more electricity, 58% more water and 44% more primary energy than Tapanila ecological house. Tapanila ecological house uses comparable amounts of total energy and heating energy, but less electricity and water than ESPI 1 and ESPI 2. When calculating the primary energy consumption, 1 kWh of electricity is assumed to equal 2.5 kWh of primary energy, while 1 kWh of heat energy (wood, oil or district heat) is assumed to equal 1 kWh of primary energy.

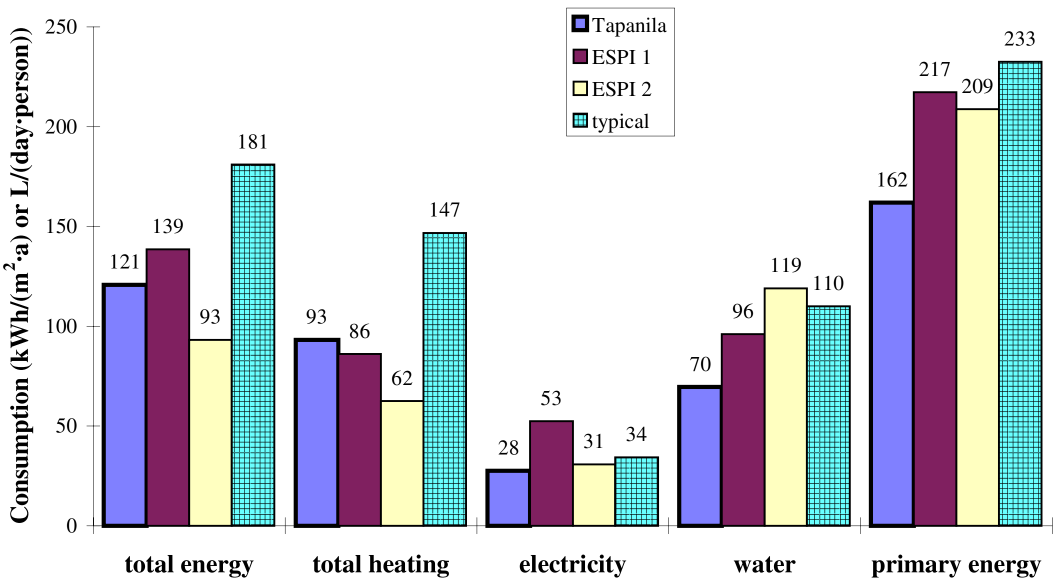

Figure 1. Normalised energy and water consumption in Tapanila ecological house, low-energy houses ESPI 1 and ESPI 2 (Laine and Saari, 1998) and typical Finnish houses (Motiva, 1999).

2.1 Heating Energy Consumption

Since heating energy is a large part (77%) of the total energy, the distribution of the heating energy is presented in Figure 2, where the heating energy is divided into space heating, water heating and heat losses. In Tapanila ecological house, space heating accounts for 82% of the heating energy, water heating accounts for 14% and heat losses account for the remaining 4%. As mentioned previously, the water heating was calculated using the measured hot water consumption and an estimated cold water temperature of 5°C and a hot water supply temperature of 55°C. The space heating was determined by subtracting the water heating from the district heating and adding the wood heating. The heat losses in Tapanila ecological house were assumed to be only 5% of the supplied district heat because the district heat exchanger is located in the basement and most of the heat dissipated will heat the house.

Figure 2 shows that the normalised consumption of total heating energy is higher in Tapanila ecological house than in the ESPI houses. ESPI 1 has an 8% lower consumption and ESPI 2 has a 33% lower consumption than Tapanila ecological house. Similarly, the space heating is 30% lower in ESPI 1 and 44% lower in ESPI 2, but the space heating in typical Finnish houses is 57% higher than in Tapanila ecological house. It is important to note that ESPI 1 and ESPI 2 had significant heat losses because of their heating systems, which were an oil burner and electrically heated water storage tank respectively. The heat losses in ESPI 1 were 27% of space heating energy and in ESPI 2 the heat losses were 16% of the space heating energy, while the heat losses in Tapanila ecological house were only 5% of the space heating energy. Combining the space heating and heat losses gives a total of 80 kWh/(m^2·a) for Tapanila ecological house, 68 kWh/(m^2·a) for ESPI 1 and 49 kWh/(m^2·a) for ESPI 2. The total for the ESPI houses is still the lowest, but only 15% lower in ESPI 1 and 39% lower in ESPI 2 than in Tapanila ecological house (compared to 30% and 44% for space heating alone). The higher space heating in Tapanila ecological house compared to ESPI 1 and 2 is likely due to a combination of the lack of ventilation air heat recovery and the lower electricity consumption in Tapanila ecological house. These effects will be simulated in section 3.

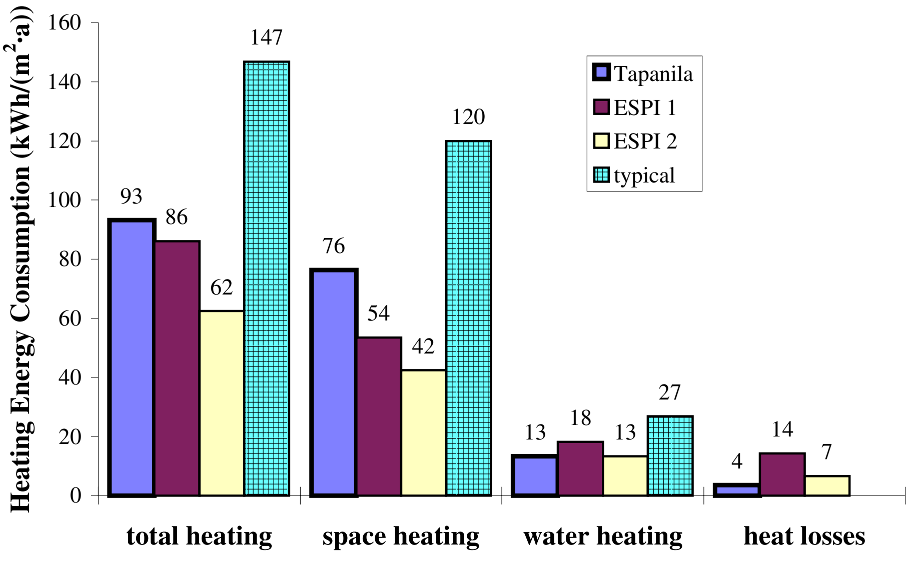

Figure 2. Normalised heating energy consumption in Tapanila, ESPI 1 and 2 (Laine and Saari, 1998) and typical Finnish houses (Motiva, 1999).

2.2 Distribution of Energy Supply

Figure 3 shows that wood provides 19% of the total energy and 29% of the space heating energy (1550 kg and 570 kg of wood were burned in the fireplace and sauna respectively providing 4880 kWh of heat). District heat provides 59% of the total energy and 71% of the space heating energy. Electricity accounts for 23% of the energy supplied.

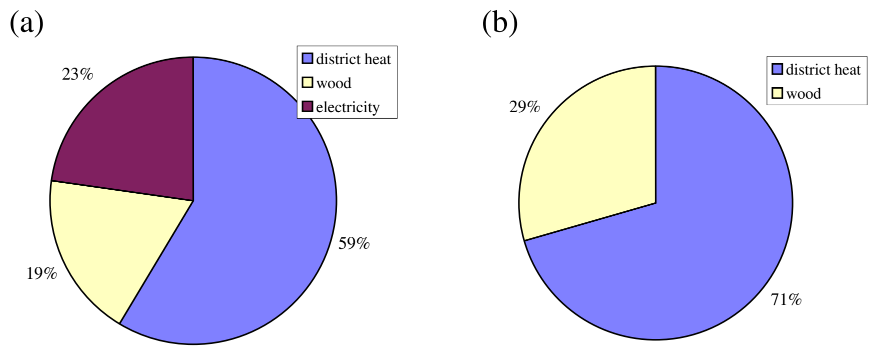

Figure 3. Distribution of total (a) and space heating (b) energy supplied to the house.

3.0 CALCULATED ENERGY CONSUMPTION

In this section, the energy consumption of Tapanila ecological house will be analysed using the WinEtana simulation program. The WinEtana simulation program has been developed at VTT Building Technology for estimating building energy consumption and is described in publications by Kosonen and Shemeikka (1997) and Shemeikka (1997). The program calculates the energy consumption using a single-zone steady-state thermal analysis, which is based on the National Building Code of Finland – D5 (1985) and the prEN 832 (1998). Kalliomäki and Kohonen (1989) have shown the validity of the steady-state method for estimating energy consumption in Finland. WinEtana calculates the heating, electrical and water consumption and peak demands in the building using monthly average outdoor temperatures and assuming a constant indoor temperature. Despite its simplicity, Kosonen and Shemeikka (1997) have shown that, when simulating the IEA BESTEST validation case (Haapala et al., 1995) with reasonable assumptions, the heating energy consumption calculated by WinEtana is similar to that calculated by several transient simulation models.

3.1 Input Data

The WinEtana program is particularly useful for Finnish buildings because it contains a database of typical input parameters (U-values, window types, water consumption, electricity consumption, internal gains, air change rates, etc.) for Finnish buildings and Finnish regulations (National Building Code of Finland – C3, 1985; D2, 1987 and D5, 1985). These database values will be used together with the size of Tapanila ecological house when describing a "reference" case for Tapanila ecological house as shown in Table 1. The "reference" case uses the actual window (including French doors) and wall areas of Tapanila ecological house. Therefore, the "reference" case represents the case where the envelope of Tapanila ecological house is insulated according to the building code and the electricity and water consumption are as in typical Finnish houses of the same size (665 m^3) and occupancy (5 people). Since the area of windows and doors in Tapanila ecological house is 16.4% of the gross heated floor area, which is slightly greater than the 15% required in the National Building Code of Finland – C3 (1985), a case where the window area is 15% of the gross heated floor area is included (i.e., window (15%)). The input data for the actual and database values are listed in Table 2.

Table 1. Source of input data for the energy simulation cases, where "database" means that the data is from the database in WinEtana and "actual" means that the data reflects the as-built house.

Case	Surface areas	Water consumption	Electricity consumption	U-values	Ventilation system	Σ(UA) (W/K)
reference	actual	database	database	database	database	185
window (15%)	window area 15% of floor area	database	database	database	database	180
code	actual	actual	actual	database	database	185
actual-MV	actual	actual	actual	actual	database	126
actual-NV	actual	actual	actual	actual	actual	126

Table 2. Input data for the simulations obtained from the WinEtana database ("database") and measurements from Tapanila ecological house ("actual").

Water consumption		
	Database:	total: 152 m^3/a, hot water: 53 m^3/a, water heating: 3 070 kWh/a
	Actual:	total: 127 m^3/a, hot water: 50 m^3/a, water heating: 2 880 kWh/a
Electricity consumption		
	Database:	household: 4 880 kWh/a, ventilation: 990 kWh/a, other: 1 070 kWh/a
	Actual:	household: 5 570 kWh/a, ventilation: 0 kWh/a, other: 400 kWh/a
Envelope U-values (W/($m^2\cdot$ K))		
	Database:	walls: 0.28 (0.36 underground), roof: 0.22, floor: 0.36, windows: 1.8
	Actual:	walls: 0.16 (0.21 underground), roof: 0.10, floor: 0.25, windows: 1.2 (Table 3)
Ventilation system (infiltration of 0.15 ach, total outdoor ventilation of 0.5 ach)		
	Database:	mechanical supply and exhaust with 50% heat recovery
	Actual:	natural ventilation system without heat recovery

Table 1 shows that in the code case, the measured water and electricity consumption will be set equal to the measured values, while the thermal performance of the envelope and the ventilation system will be from the database. It is important to note that the measured electricity consumption does not include electricity for the ventilation fans. The WinEtana program will also be used to calculate the actual case where the actual insulation levels (Table 3), which are greater than specified in the building code, are used in the simulation. Actual-MV is the case with a mechanical supply and exhaust ventilation system and actual-NV is the case with natural ventilation. In all cases, a district heating system is used (95% efficiency), the outdoor weather is from Helsinki (1979), the indoor temperature is 22°C, the infiltration rate is assumed to be 0.15 ach (i.e., n_{50}/20 - Sherman, 1987) and the total outdoor ventilation rate is 0.5 ach. In addition to the tests in Table 1, a sensitivity analysis of ventilation rate and heat recovery will be presented. This is important because the database uses a mechanical ventilation system with a 50% effective heat recovery system and a ventilation rate of 0.5 ach, while Tapanila ecological house has a natural ventilation system with no heat recovery and a ventilation rate below 0.5 ach (Simonson, 2001).

The different cases are arranged in such a way that each subsequent case uses increasing actual data from Tapanila ecological house. In this way, the impact of various parameters can be assessed. The difference between the code and reference cases shows the impact of the actual electricity and water consumption on the energy consumption of Tapanila ecological house, while the difference between the window (15%) and reference cases shows the impact of the window area. However, the differences between the hot water consumption, electricity consumption and window areas between these cases are very small as can be seen in Table 1 and Table 2. The difference between the actual-MV case and the code case indicates the impact of the improved building envelope on the energy consumption. Finally, the difference between the actual-NV and actual-MV shows the impact of the natural ventilation system on energy consumption.

Table 3. U-value, surface area, description and external boundary conditions for the envelope.

part of building envelope	U-value (W/(m^2·K))	surface area (m^2)	description	external bounday condition
normal walls	0.16	185	250 mm insulation	ventilated cavity
roof	0.1	72	425 mm insulation	ventilated cavity
basement floor	0.25	62	expanded clay	ground
basement wall	0.27	42	expanded clay	outdoor air
basement wall	0.21	42	expanded clay + insulation	ground
windows	1.2	6.64	triple, low e, argon	North
windows	1.2	2.28	triple, low e, argon	East
windows	1.2	13.98	triple, low e, argon	South
windows	1.2	2.75	triple, low e, argon	West
entry roof	0.3	4.1	125 mm insulation	outdoor air
entry wall	0.18	6.7	160 mm insulation	outdoor air
entry floor	0.25	4.2	~125 mm insulation	crawl space
entry windows	1.8	0.91	triple, clear	South
doors	1.8	5.25	double door, 1 glass	outdoor air
balcony doors	2.2	3.78	double door, 1 glass	outdoor air

3.2 Results

The simulated energy consumption for the five different cases compared to the actual consumption measured in Tapanila ecological house are presented in Figure 4. These results shown that the reference case has a total, space heating and electrical energy consumption of 154 kWh/(m^2· a), 102 kWh/(m^2· a) and 32 kWh/(m^2· a) respectively. This means that if the envelope and equipment in Tapanila ecological house were according to typical Finnish standards, the total, space heating and electrical energy consumption would be greater than that measured in Tapanila ecological house by 28%, 33% and 16% respectively. The reference case has the highest total and space heating energy consumption.

The actual-MV case (actual house, but with mechanical ventilation) has the lowest total and space heating energy consumption (118 kWh/(m^2· a) and 69 kWh/(m^2· a) respectively), but the actual-NV case (actual house with natural ventilation) has the lowest electricity consumption (28 kWh/(m^2· a)). The total, space heating and electrical energy consumption in the actual-MV case are 2% lower, 10% lower and 17% higher than the measured values respectively. The calculated total and space heating energy consumption for the actual-NV case are about 10% higher than the measured consumption because the actual ventilation rate is below the assumed value of 0.5 ach in the simulation. Assuming that 1 kWh of electrical energy requires 2.5 kWh of primary energy, the primary energy consumption of a natural and mechanical ventilation system are quite comparable as shown in Figure 4. This emphasises the importance including total energy consumption (and possible primary energy consumption) when assessing the performance of ecological houses. Space heating energy consumption alone is not an adequate measure of performance.

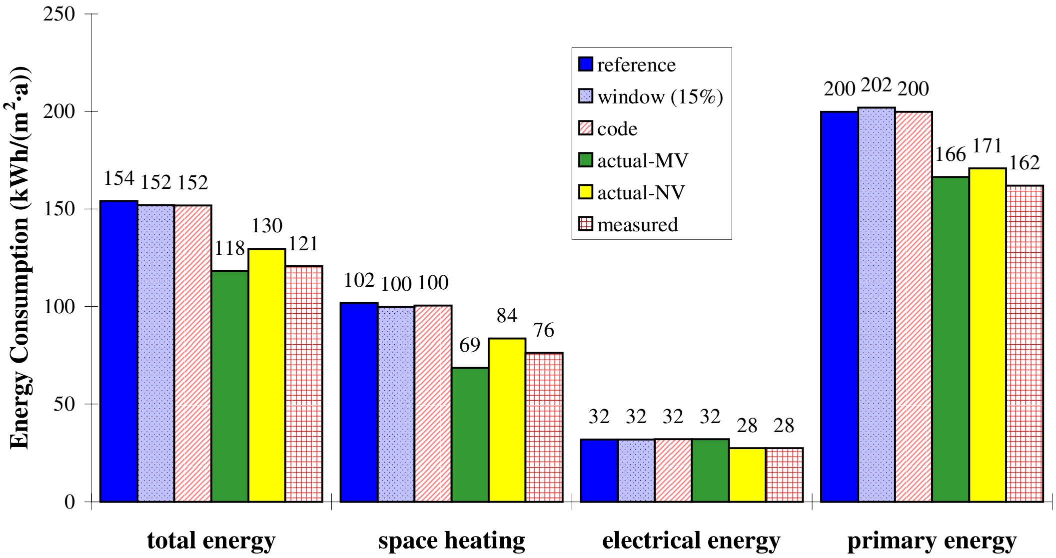

Figure 4. Calculated energy consumption of Tapanila ecological house for the cases in Table 1.

Figure 5 shows the impact of various parameters on the calculated energy consumption. Reducing the window area from 16.4% to 15% of the gross heated floor area, decreases the energy consumption very little. Similarly, changing the water and electricity consumption from the database to the actual values has a small effect on the energy consumption because the consumption of water and electricity are very similar in both cases. However, if the changes in window area, electricity consumption and water consumption were greater between the database and actual values, the differences would be greater. For example, simulation results show that if the household electricity consumption increased by 10 kWh/($m^2\cdot$ a), the space heating would decrease by 4.4 kWh/($m^2\cdot$ a). This is important and shows that increasing the consumption of household electricity can decrease the consumption of space heating energy. Naturally, the actual heating required by a house is independent of the electricity consumption, but the typically reported space heating consumption depends on the electricity consumption because the waste heat from electrical appliances is not included in the reported space heating. This is particularly important because electricity is a higher valued energy source than district heat (IEA ECBCS Annex 37) and the production of electrical energy is about 2.5 times more resource intensive than the production of heat energy.

Changing the U-value of the envelope from the database value (i.e., building code value) to the actual value (i.e., greater thermal insulation) decreases the total and space heating energy by 34 and 32 kWh/(m^2· a) respectively. Changing the ventilation system from the database system (i.e., mechanical ventilation with heat recovery) to the actual system (i.e., natural ventilation) increases the total and space heating energy by 11 and 15 kWh/(m^2· a) respectively, but decreases the electricity consumption by 5 kWh/(m^2· a).

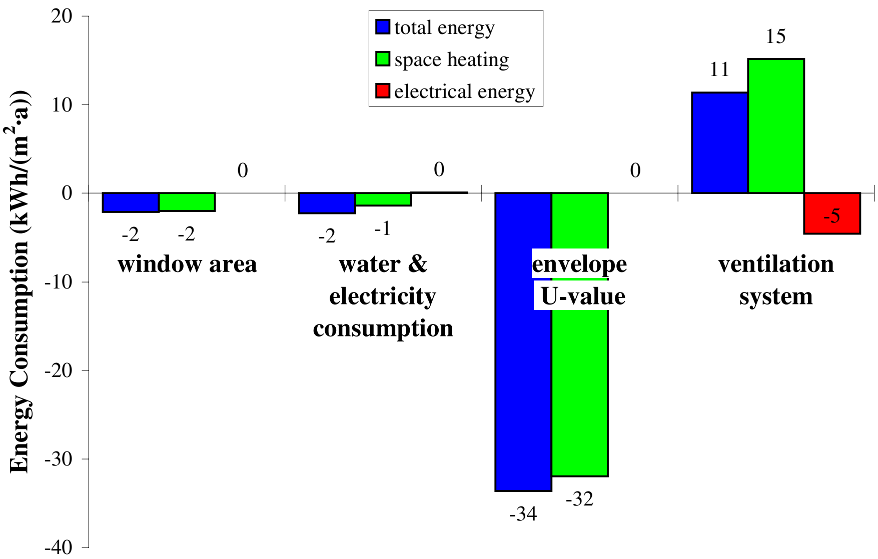

Figure 5. The change in calculated energy consumption when changing various parameters from the database value to the actual value.

The previous results show that the calculated energy consumption for Tapanila ecological house is slightly greater than the measured consumption. This may be a result of slightly warmer outdoor temperatures during the measurements than during the reference year of 1979 because simulation results show that if the average temperature increases by 2°C, the space heating will decrease by 13% (11 kWh/(m^2·a)). Nevertheless, the main reason for the difference between measured and calculated energy consumption is that the ventilation rate in Tapanila ecological house is typically less than 0.5 ach. Figure 6 contains the calculated total energy consumption and space heating energy consumption for the different cases as a function of the ventilation rate. Comparing the actual-NV case to the measured values indicates that the actual ventilation rate is likely about 0.4 ach, which is comparable to that expected during the heating season (Simonson 2001).

The effect of ventilation rate on energy consumption is also evident in Figure 6. As expected, the energy consumption in the actual-NV case is the most sensitive to the ventilation rate because this case has no heat recovery. The increase in total energy consumption for every 0.1 ach increase in ventilation rate is 6.0 kWh/(m^2·a) for the actual-MV case and 9.7 kWh/(m^2·a) for the actual-NV case. The increase in space heating energy consumption for every 0.1 ach increase in ventilation rate is 4.5 kWh/(m^2·a) and 9.2 kWh/(m^2·a) for the actual-MV and actual-NV cases respectively, which means that the sensitivity to ventilation rate is double for the case without heat recovery. This means that a house with a 50% effective heat recovery system and a ventilation rate of 0.5 ach will have the same space heating energy consumption as a house with no heat recovery and a ventilation rate of 0.25 ach. Furthermore, a higher ventilation rate is possible with the same total energy consumption when a mechanically ventilated house includes heat recovery. If the heat recovery effectiveness is 50%, the ventilation rate can be 1.8 times higher and if the effectiveness is 70%, the ventilation rate can be 2.7 times higher. It is important to note that these results are based on the WinEtana simulation program, which neglects the fact that the fan energy consumption increases as the heat recovery effectiveness increases. The heat recovery effectiveness has a significant impact on the calculated energy consumption as shown in Figure 7. Here a 10% change in heat recovery effectiveness changes the space heating energy consumption by 3.3 kWh/(m²·a) when the ventilation rate is 0.5 ach.

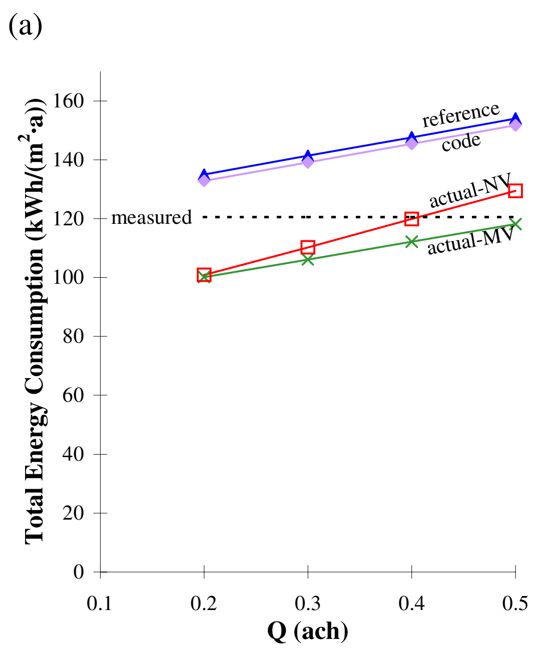

Figure 6. Total (a) and space heating (b) energy consumption as a function of the total outdoor ventilation rate.

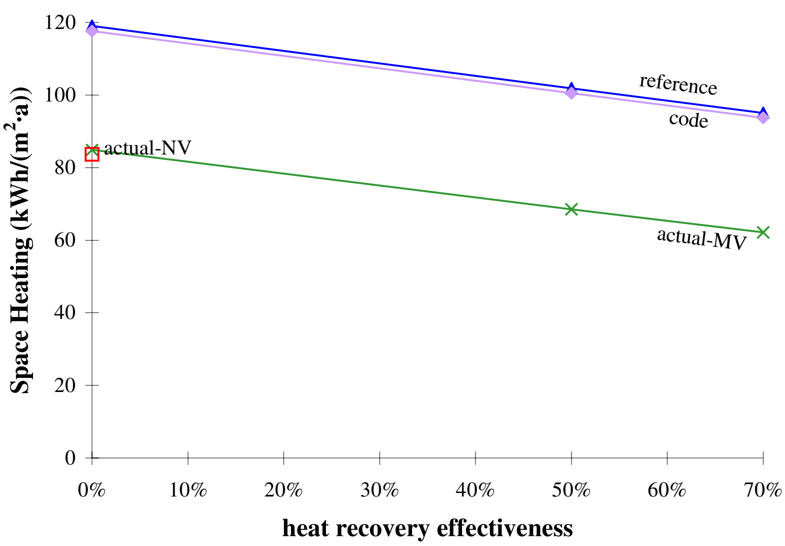

Figure 7. Space heating energy consumption as a function of heat recovery effectiveness for a ventilation rate of 0.5 ach.

4.0 SUMMARY

The results presented in this paper show that Tapanila ecological house uses significantly less energy than typical Finnish houses. The normalised total energy consumption is 50% higher in typical Finnish houses (181 kWh/(m^2·a)) than in Tapanila ecological house (121 kWh/(m^2·a)). The natural ventilation system saves electrical energy for fans, but increases the space heating because there is no possibility for heat recovery. As a result, the measured space heating energy consumption (76 kWh/(m^2·a)) is greater than in other single-family low-energy houses in Finland (e.g., ESPI 1 - 54 kWh/(m^2·a) and ESPI 2 - (42 kWh/(m^2·a)). Nevertheless, typical Finnish houses use nearly 60% more energy for space heating (i.e., 120 kWh/(m^2·a)) than Tapanila ecological house. The normalised consumption of electricity in Tapanila ecological house is 28 kWh/(m^2·a) (5970 kWh), which is much lower than in ESPI 1 house (53 kWh/(m^2·a)) and ESPI 2 house (31 kWh/(m^2·a)), while a typical Finnish house consumes 34 kWh/(m^2·a). The total energy consumption in Tapanila ecological house is comparable to other low-energy houses. The total normalised energy consumption is 15% higher in ESPI (139 kWh/(m^2·a)) and 23% lower in ESPI 2 (93 kWh/(m^2·a)) than in Tapanila ecological house. The normalised primary energy consumption is the lowest in Tapanila ecological house, with ESPI 1, ESPI 2 and a typical Finnish house having 34%, 29% and 44% higher primary energy consumption respectively.

The calculated energy consumption using the WinEtana simulation program shows good agreement with the measured data when the ventilation rate is assumed to be 0.4 ach. The results presented in this paper show that Tapanila ecological house would have consumed 34 kWh/(m^2·a) more energy (28%) if the building envelope was built according to the current building code. Similarly, the space heating would increase by 32 kWh/(m^2·a) (42%) without the highly insulated envelope. In other words, the space heating is expected to be about 40% higher (~108 kWh/(m^2·a)) if the envelope was insulated according to the building code. Since the well-insulated envelope decreases the heating energy consumption, but has no effect on the electricity consumption, the primary energy consumption is significantly lower with a well-insulated envelope.

Unlike a well-insulated envelope, the natural ventilation system increases the space heating because there is no possibility for heat recovery from the ventilation air, but saves electrical energy because there are no ventilation fans. The natural ventilation system increases the space heating by 15 kWh/(m^2·a) (22%), but decreases the electricity consumption by 5 kWh/(m^2·a) (14%) compared to a mechanical ventilation system with 50% effective heat recovery. Therefore, if Tapanila ecological house had a mechanical ventilation system with heat recovery (50% effective) that provided the same ventilation rate as the natural ventilation system, the space heating consumption is expected to be about 60 kWh/(m^2·a). Even though a house with a mechanical supply and exhaust ventilation system has a lower total energy consumption than a similar house with a natural ventilation system, the primary energy consumption is nearly the same for both systems.

Increasing the ventilation rate and decreasing the heat recovery effectiveness increases the energy consumption. The increase in space heating energy consumption for every 0.1 ach increase in ventilation rate is 2.7, 4.5 and 9.2 kWh/(m^2·a) when the heat recovery effectiveness is 70%, 50% and 0% respectively. At 0.5 ach, a 10% change in heat recovery effectiveness changes the space heating energy consumption by 3.3 kWh/(m^2·a).

ACKNOWLEDGEMENTS

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