Renovation of Swedish single-family houses to passive house standard – sensitivity analysis.

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ABSTRACT

A third of Sweden's two million single-family houses were built in the period 1961-1980, and many of them are in need of renovation. Energy use in these houses is high, and they are fairly homogeneous in technical terms. A previous study of four reference houses showed that final energy use could be reduced in theory by approximately 65-75 % after renovation, by implementing conventional passive house components renovation measures. This paper evaluates the results and uncertainties arising from the previous study by performing a local sensitivity analysis of the most important input parameters, such as number of inhabitants, climate zone, orientation of the houses and alternative renovation measures in a Swedish context. The results presented in this paper show that the previously estimated final energy use reduction can be increased even further, to 75-80 %, by introducing additional renovation measures. The climate zone was shown to have the largest impact, with twice as much space heating required in the coldest evaluated climate compared to the mildest. The impact from inhabitants was less than expected, due to a counterbalancing impact on the final energy use from internal gains and domestic hot water.

KEYWORDS

Deep renovation, Energy retrofit, Detailed energy simulations, Single-family houses.

INTRODUCTION

Single-family houses built between 1961 and 1980 account for one-third of the energy use in Swedish single-family houses, which in turn use about 40 % of all energy in buildings (Swedish Energy Agency 2015). There are roughly 715,000 houses from this period (Statistics Sweden 2015) and they are fairly homogeneous in technical terms, with low levels of thermal insulation, and ventilation with heat recovery is rare (Boverket 2010). Many of these houses need renovation (Boverket 2010), which provides an excellent opportunity to incorporate energy efficiency measures.

In a previous paper (Ekström 2016) theoretical renovation measures were simulated, based on conventional measures from four completed passive house renovations of single-family houses in Sweden, and the energy savings potential was analysed. The

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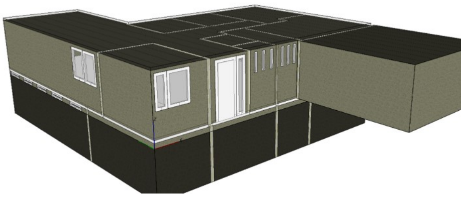
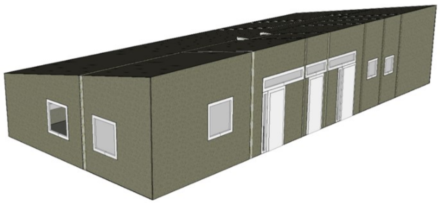
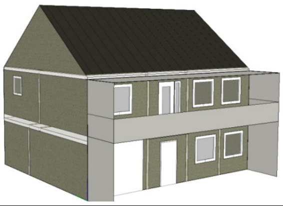
evaluation used four reference houses as case studies (Table 1). The simulations were performed with standardised input data and a specific location for each reference house. The evaluation showed that not all reference houses would reach passive house level with the evaluated renovation measures, however a possible reduction of the final energy use (excluding household electricity) of 65-75 % could be attained if all evaluated measures were implemented.

The purpose of this paper is to: 1) evaluate the uncertainties arising from the used input data in the simulated theoretical renovations of the four reference houses described in the previous paper (Ekström 2016); 2) determine which of the parameters that have the most impact on the result of the energy simulations; 3) evaluate additional renovation measures. This knowledge is important in deciding which parameters are relevant for inclusion in the planned future cost evaluations.

Table 1. Basic data and visualisation for the four reference houses.

	
Location: Malmö, built: 1965, heated floor area: 230 m^2	Location: Göteborg, built: 1961, heated floor area: 140 m^2
	
Location: Stockholm, built: 1965, heated floor area: 163 m^2	Location: Umeå, built: 1977, heated floor area: 142 m^2

METHODOLOGY

A sensitivity analysis was carried out based on different plausible variations of the input data for the inhabitants and locations, as well as different renovation measures. An overview of the method used is shown in Figure 1.

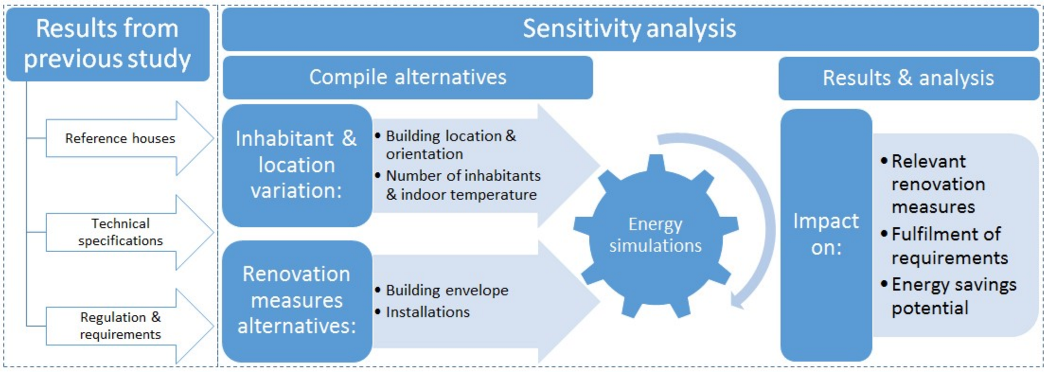


Figure 1. Overview of methodology.

The results from the previous energy simulations were evaluated in a local sensitivity analysis, where one parameter at a time is changed while the others remain constant. The base case used for the reference houses in this study is the total renovation described in the previous study. The first step was to compile additional available renovation measures and installations from suppliers and identify different inhabitant dependent input data for the simulations. The output from the energy simulations (space heating, domestic hot water and property electricity) was then analysed to show what input data is most relevant to use in future work to identify cost-effective renovation measures. The energy use was simulated using a validated dynamic energy simulation tool, IDA Indoor Climate and Energy 4.7 (EQUA 2016). The building models were based on available drawings and descriptions, with one zone for each room.

INPUT DATA FOR SENSITIVITY ANALYSIS

Nine parameters were considered for the sensitivity analysis, where each parameter had different cases as input data. Such a combination formed 22 cases in total, which are described below together with the base case (see Table 2).

Base case – theoretical renovation measures in previous paper

For energy simulations there are standardised input data in Sweden that consider the influence of inhabitants, compiled in Sveby, the sector standard for energy in buildings (Levin 2012). Input regarding the airing and regulating losses for the heating system were taken from the Swedish passive house standard, FEBY 12 (Erlandsson 2012). The thermal bridges were regarded as an increase of the total thermal transmittance by 25 % in the simulations, based on a recommendation from the Swedish certification system, Miljöbyggnad (2014). These standardised input data were used in the previous paper and also in the evaluations in this paper.

The input data for walls, roofs, windows, doors and air tightness used in the previous study were based on renovation measures from completed passive house renovations in Sweden; see base case in Table 2. Due to the original foundations all being concrete slabs, the insulation was placed outside the slab, as illustrated in Figure 2. A demand-controlled and balanced heat recovery ventilation system was installed to reduce the ventilation losses; see base case in Table 2. Indoor electronic room thermostats were installed, reducing regulation losses to 7 % according to FEBY 12.

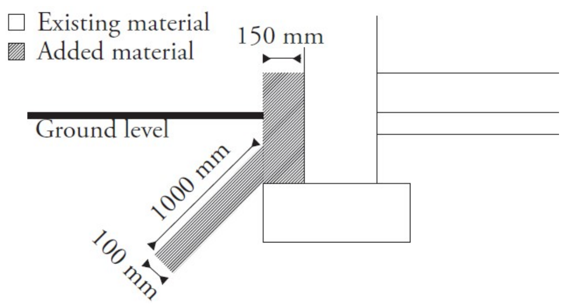


Figure 2. Example of renovation measure used for the foundation.

More efficient circulation pumps were installed (Swedish Energy Agency 2014). Indoor temperature variation was used, reducing the indoor temperature from the standard 21 °C to 18 °C when no one is home and when the inhabitants are asleep. This was assumed to be between 08:00 and 16:00 on weekdays and, at night, 23:00-06:00 on weekdays and 00:00-08:00 at weekends.

Climate and inhabitant variation

The first parameter was climate, which was evaluated by placing all four reference house building models both in the mildest climate (Malmö) and coldest (Umeå) of the four locations. The next parameter was orientation, which affects the solar radiation striking window glazing, evaluated by rotating the houses 0°, 90°, 180° and 270°. The indoor temperature was also evaluated. While the average indoor temperature in Sweden for single-family houses is 21 °C (Levin 2012), the following indoor temperatures were also evaluated: 20 °C, 22 °C and 23 °C.

The number of inhabitants was varied and their corresponding impact on the internal gains, household electricity and domestic hot water was evaluated. The number of inhabitants was assumed to be from two to five, which accounts for over 90 % of the 200 evaluated households in terms of household electricity in a report by the Swedish Energy Agency (Zimmermann 2009). The Sveby standard includes two different ways of estimating household electricity and domestic hot water. The first, used in the base case, is a normalised annual energy usage for a single-family household of 30 kWh/m² for household electricity, and 20 kWh/m² for domestic hot water. The other alternative is based on the number of inhabitants, cases 9 and 10. The annual household electricity need is calculated to be 2500 kWh plus 800 kWh per inhabitant living in the household, and for domestic hot water, annual energy usage per inhabitant is 781 kWh. Of the household electricity, 70 % was assumed to be utilised as internal gains, based on the Sveby recommendation (Levin 2012).

Alternative renovation measures

The parameters external walls and roofs were evaluated with different insulation thicknesses, based on gathered construction alternatives from suppliers and on the original construction of the houses, to determine the impact from achievable *U*-values. The parameter windows and doors were varied on the basis of existing window alternatives from suppliers and their *U*-value. The parameter air tightness was compared to the best achieved in the completed passive house renovations, Finnängen (Molin 2012), as well as the impact from an estimated level of a failed air sealing. For the demand-controlled heat recovery ventilation system, three alternative air handling units (AHU) were chosen from different suppliers included in an evaluation performed by the Swedish Energy Agency (2016), each with specific performance in terms of temperature efficiency, air flows and specific fan power (SFP).

Evaluated cases

Table 2 shows an example of one of the reference houses, Malmö, with all the evaluated input data in cases 1-22. All cases were evaluated for each of the reference houses. Cases 9 and 10 use input data that are a combination of number of inhabitants, household electricity and domestic hot water, where case 9 is based on the fewest number of inhabitants (2) and case 10 on the highest (5). Cases 11 onwards involve the input regarding alternative renovation measures that were evaluated.

Table 2. Compilation of all cases, with examples from reference house Malmö.

Parameter		*Base case*	*Cases*			*Units*
Location		Original	***1:*** Malmö	***2:*** Umeå	-	Climate
Orientation		0	***3:*** 90	***4:*** 180	***5:*** 270	°
Indoor temperature		21	***6:*** 20	***7:*** 22	***8:*** 23	°C
Inhabitants		3	***9:*** 2	***10:*** 5	-	Number
Household electricity		30	17.8	28.3		kWh/m²/a
Domestic hot water		20	6.8	17		kWh/m²/a
U-value	External wall	0.10	***11:*** 0.09	***12:*** 0.08	***13:*** 0.07	W/(m²·K)
	Roof	0.08	***14:*** 0.07	***15:*** 0.06	-	W/(m²·K)
	Window & door	0.80	***16:*** 0.90	***17:*** 0.70	-	W/(m²·K)
Air tightness (based on envelope area)		0.30	***18:*** 0.50	***19:*** 0.10	-	l/(s·m²)
HRV	Air flow – max.	0.35	***20:*** 0.35	***21:*** 0.35	***22:*** 0.35	l/(s·m²)
	Air flow – min.	0.10	0.15	0.10	0.10	l/(s·m²)
	SFP	1.50	1.26	1.30	1.25	kW/(m³/s)
	Temperature eff.	80.0	85.0	87.0	89.9	%

RESULTS

The results from the 22 simulated cases (Table 2) in the local sensitivity analysis for the four reference houses are shown in Table 3 and presented per heated floor area. The space heating for the reference houses before renovation is presented for comparison. The specific energy use for the base case is divided into its components. For each case, the impact on energy use relative to the base case is shown.

The results in Table 3 show that climate had the largest impact on the space heating demand; this was doubled when all reference houses were located in the coldest climate (Umeå) instead of the mildest (Malmö). Still, the renovation measures reduced the space heating by 75-80 % for all houses and in all climates compared to before renovation. The second largest increase in space heating demand was caused by the indoor temperature setting, where a change of ±1 °C from the original 21 °C corresponds to a change in the annual space heating demand of 4 to 7 kWh/m². Rotating the houses had a great impact on the houses with the largest and most uneven distribution of windows between the facades, increasing the annual space heating demand of up to +7 kWh/m² for reference house Göteborg. The annual space heating of reference houses with a more even distribution of windows was in the range of +1-3 kWh/m².

Table 3. Results from energy simulations for base case (total energy use) and the 22 cases (deviation from base case, kWh/m²/a) for all four reference houses.

Reference houses			*Malmö*	*Göteborg*	*Stockholm*	*Umeå*
Unit		*Type*	kWh/m²/a			
Before renovation		Space heating	135	201	184	154
Base case (after renovation)		Space heating	26.0	37.6	42.3	39.8
		Domestic hot water	20.0	20.0	20.0	20.0
		Property electricity	3.2	3.5	3.4	3.5
		Specific energy use	49.2	61.1	65.7	63.3
Parameter	***Case***		Relative energy use compared to base case			
Location	***1:***	Space heating	0.0	-3.4	-10.2	-20.6
	2:	Space heating	27.7	30.7	21.4	0.0
Rotation	***3:***	Space heating	2.1	3.5	0.5	0.5
	4:	Space heating	3.1	6.6	-1.1	1.2
	5:	Space heating	1.6	4.3	1.2	0.4
Indoor temp.	***6:***	Space heating	-4.3	-5.5	-5.7	-4.1
	7:	Space heating	5.3	6.2	6.2	4.6
	8:	Space heating	11.4	13.5	13.2	9.9
Inhabitant + household electricity + domestic hot water	***9:***	Space heating	7.9	2.9	5.8	3.3
		Domestic hot water	-13.2	-9.0	-10.4	-9.0
		Specific energy use	-5.3	-6.1	-4.6	-5.7
	10:	Space heating	-1.4	-11.8	-9.6	-13.0
		Domestic hot water	-3.0	7.9	4.0	7.5
		Specific energy use	-4.4	-3.9	-5.6	-5.5
External wall	***11:***	Space heating	-0.9	-0.9	-1.2	-1.1
	12:	Space heating	-1.9	-1.8	-2.4	-2.3
	13:	Space heating	-2.9	-2.5	-3.7	-3.4
Roof	***14:***	Space heating	-0.4	-0.9	-0.5	-0.6
	15:	Space heating	-1.0	-2.0	-1.1	-1.3
Windows & doors	***16:***	Space heating	1.3	3.6	2.7	3.3
	17:	Space heating	-1.3	-3.5	-2.7	-3.2
Air tightness	***18:***	Space heating	2.1	3.3	2.2	2.6
	19:	Space heating	-2.1	-3.3	-2.2	-2.6
HRV	***20:***	Specific energy use	-0.9	-0.9	-1.1	-1.4
	21:	Specific energy use	-0.4	1.1	0.9	1.1
	22:	Specific energy use	-1.8	-2.9	-3.4	-3.7

DISCUSSION

Input data regarding inhabitants, household electricity and domestic hot water varies greatly, but the impact on the specific energy use is relatively small. This is because the input data items counterbalance each other; more inhabitants increase internal gains and household electricity, which decreases the need for space heating, but at the same time more inhabitants also increase domestic hot water use. The results show a variation of up to 10 %, depending on chosen input. Using the Sveby normalised input data resulted in the highest specific energy use, indicating that taking into consideration the actual number of inhabitants in a household will only decrease the simulated specific energy use. An evaluation of inhabitant behavior was not performed. The influence of inhabitants was assessed by using a normalized usage of a house commonly used in energy simulations in Sweden, Sveby (Levin 2012) and by varying the number of inhabitants and desired indoor temperature. This normalized usage simplifies the presence of the inhabitants with a uniform usage profile. Taking into account real fluctuations of the presence and usage profile could result in even larger variations of the energy demand, as shown in measurement studies like THUVA II (Bagge 2015).

The exact level of air tightness that can be attained in each of the reference houses are not known, this depends both on the original construction and the focus that is put into making the houses air tight. The needed products to improve the air tightness to the three evaluated levels are likely the same. Instead the difference in performance likely depend on the workmanship when performing the renovation measure to reach the higher level of air tightness and improved energy efficiency.

The results from the different types of AHU show that, since the specifications for the alternatives are very different, determining the specific energy use without simulation would be difficult. This is because all alternatives have their strengths in different areas, such as temperature efficiency, SFP or possible variations of air flows, but the overall performance is very similar. Case 22 is the most energy efficient, with an improvement of roughly 5 kWh/m²/a depending on the AHU chosen. This shows the importance of simulating and comparing many alternatives before a decision is made.

CONCLUSIONS AND IMPLICATIONS

As shown in the sensitivity analysis, more can be done to reduce the space heating to reach the passive house level for specific energy use of 63 kWh/m² for Umeå's climate zone and 55 kWh/m² for the other reference houses. The inhabitant-dependent parameters all have a greater individual impact on energy use than individual fine-tuning of the renovation measures. However, by combining the evaluated renovation measures, the energy demand in the reference houses base case can be further reduced from 65-75 % to 75-80 %, leading to a total reduction of the space heating between 80-90 %. The combination of the best cases of the renovation measures, cases 11-22, save roughly 9-15 kWh/m²/a, which is the same magnitude as increasing the indoor temperature by 2 °C. This shows the importance of reducing the indoor temperature when possible.

In the previous paper only reference house Malmö and Umeå fulfilled the passive house requirements in their original location. A comparison of the same reference house located in the mildest climate (Malmö) to the coldest (Umeå) showed that the coldest climate required twice as much energy for space heating. Therefore, attaining the passive house level will depend greatly on location, since the additional specific energy use allowed in the FEBY requirements (Martin Erlandsson 2012) of 8 kWh/m²/a, is significantly smaller than the increased energy demand of 20-34 kWh/m²/a. Comparing the reference houses in the mildest climate (Malmö) and the coldest (Umeå) also showed that the reference house in Stockholm fulfils the passive house requirements when located in the mildest climate with the base case renovation measures. While when located in the coldest climate only the reference house in Umeå fulfilled the passive house requirements. Incorporating all the most energy efficient renovation measures from the sensitivity analysis leads to all reference houses fulfilling the requirements in their respective original location and the mildest climate, but still only the reference house in Malmö and in Umeå fulfilled the passive house requirements when located in the coldest climate.

Nevertheless, energy savings from the renovation measures are great and roughly in the same relative proportions, regardless of climate. The varying results for the parameters in the sensitivity analysis shows that extensive energy renovations require detailed energy simulations of different alternatives to ensure a satisfactory result.

ACKNOWLEDGEMENTS

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