COST-EFFECTIVE MEASURES FOR ENERGY IMPROVEMENT OF 1980'S DETACHED HOUSES IN COLD CLIMATE

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ABSTRACT

The paper presents cost-effective energy performance improving measures in a Finnish (cold climate) detached house built in the 1980's. The studied building represents a typical relatively energy efficient Scandinavian detached house with direct electrical heating system. The main objective of the research was to study and compare the cost-effectiveness and energy performance of modern renewable energy production systems and different HVAC systems in addition to the more traditional energy performance improving measures. The research method of the study was simulation-based multi-objective optimization, which was used to minimize the life-cycle cost and the total energy consumption of a case study building. The air-to-water heat pump system with water-based floor heating system in all spaces, combined with additional thermal insulation of roof and new air handling unit with improved heat recovery system (75-80 %) proved to be the global cost-optimum solution. All of the studied heat pump systems and the original direct electrical heating system proved to be more cost-effective main heating systems than the district heating system.

INTRODUCTION

The detached houses were a very popular building type in the Scandinavian countries back in the 1970's and 1980's. Approximately 47 % of the Finnish population and approximately 51 % of the Swedish population was living in detached houses in 2009. According to Üllar et al. 2015, the detached houses are the second largest residential building type in many countries, so they possess a significant national energy saving and greenhouse gas reduction potential. A major share of these detached houses was built during the 1970's and 1980's. The specific energy consumptions of detached houses built during this era are typically high and many of these detached houses are heated by direct electrical or oil heating, which increases the primary energy consumption significantly depending on the national primary energy factors.

The selection of energy performance improving measures should always be based on the real use of the building to deliver cost-efficient solutions for the residents and building owners. The ideal situation is to invest in measures and technologies that decrease the primary energy consumption of buildings and provide cost-effective renovation solutions at the same time.

According to recent studies carried out by Kurnitski et al. 2014 and Üllar et al. 2015, in detached houses where the energy efficiency of the building envelope is at a relatively good level ($U_{external\ walls} < 0.30$ W/(m^{2}K), $U_{roof} < 0.20$ W/(m^{2}K), $U_{windows} < 2.0$ W/(m^{2}K), infiltration $q_{50} \leq 6.0$ m^3/(m^2,h)), the replacement of the original and ineffective heating system to a more effective main heating system, such as a modern heat pump system, is a cost-effective and recommendable measure. Üllar et al. 2015 states that the renovation of detached houses with the aforementioned features should be focused on the technical systems of the house, as the improvements in the energy efficiency of the HVAC and other technical systems are the cost-efficient measures, when the energy performance and cost-effectiveness of existing detached houses with corresponding features are discussed. In Finland, all detached houses built after 1978 correspond to the aforementioned features, as the revised building regulations with tightened requirements in the energy performance of the building envelope came into force in 1978.

The aforementioned studies have focused on the reduction of primary energy consumption of the cold climate detached houses. However, the primary energy consumption is defined by standardized use of a certain building type in the Scandinavian countries and in Estonia and it does not correspond to the real use of a building very accurately. This study focuses on the reduction of delivered energy consumption to determine the cost-optimal renovation measures according to the real use of the detached houses located in cold climate regions. The energy performance and economic viability of modern heat pump systems and solar-based energy production systems were in key role in this study. The studied heat pump systems were a ground source heat pump (GSHP), an air-to-water heat pump (A2WHP) and an air-to-air heat pump (A2AHP) system. In addition, the district heating (DH) system was also studied as a reference system and compared to the cost-effectiveness of the heat pump systems.

The main objective of the study was to determine and provide cost-effective renovation solutions and different alternatives, including modern renewable energy system technologies that are recommendable to carry out in detached houses with similar technical features. The results of this study can be generalized to similar climates and techno-economic environments.

RESEARCH METHODS

Studied detached house and climate conditions

This study focuses on the cost-effectiveness of applicable and potential energy performance measures carried out in typical detached houses built in cold climate regions, e.g. Scandinavian countries and Estonia. A detached house built in the mid-1980's was selected as a case study building. The studied building is located in the suburban environment of a Central Finland city called Ilmajoki and it represents a typical fairly energy efficient Scandinavian-type detached house. According to Statistics Finland 2016, detached houses built in the 1980's form the largest share (~19 %) of the Finnish detached house building stock, when the total floor area of detached houses is discussed (see Figure 1). This is also the main reason why a 1980's detached house was selected as the case study building.

Figure 2 presents the main geometry and the floor layout of the studied detached house. The studied house is a single-family house with a heated floor area of 150 m^2. The heated volume of the house is approximately 388 m^3, respectively. There are four occupants living in the house.

The U-values and main features of external structures of the studied house are presented in Table 1. The additional thermal bridges of external structure joints were also taken into account in the energy simulations according to the National Building Code of Finland, part D5 2012 (NBCF D5 2012). The HVAC and other technical systems and their main features are presented in Table 2. All of the structures and technical features presented in Tables 1 and 2 represent the initial state of the simulation-based optimization analysis, before any renovation measures studied in the analysis have been carried out.

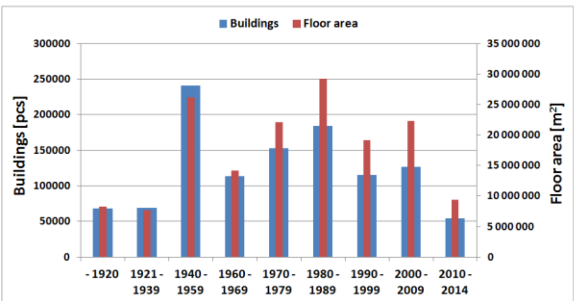

Figure 1 The number and floor area of detached houses (Statistics Finland 2016)

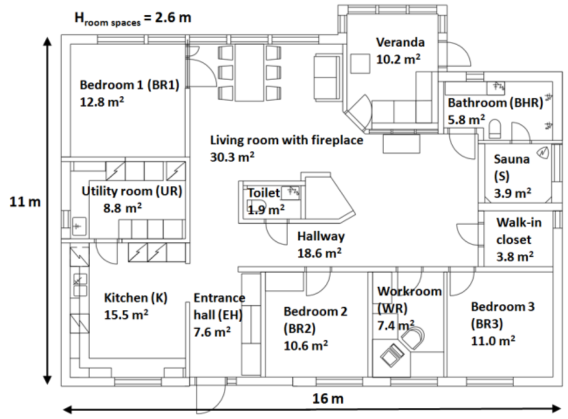

Figure 2 The main geometry (above) and the floor layout (below) of the studied detached house

The internal heat gains from occupants, household appliances and lighting and the occupancy profile of the house were selected according to the detailed room-specific internal heat gains and usage profiles defined by Liljeström et al. 2014 for more detailed calculations of energy performance of Finnish nearly zero-energy buildings. The original heating system of the house is direct electrical heating system for domestic hot water (DHW) system, ventilation system and for room spaces.

Table 1
The U-values of external structures, air-tightness and thermal bridges of the studied detached house

EXTERNAL STRUCTURES AND AIR-TIGHTNESS	
U-value of external walls, W/(m^2K)	0.19
U-value of roof, W/(m^2K)	0.08
U-value of base floor, connected to the ground, W/(m^2K)	0.25
U-value of windows, W/(m^2K) g-value of windows Integrated window shading	0.79 0.52 blinds between outer panes
U-value of external doors, W/(m^2K)	1.0
Air-tightness of the house, q_{50}-value	1.71 m^3/(m^2 h)

Table 2
The HVAC systems and their main features

HVAC SYSTEMS	
Ventilation system	Mechanical supply and exhaust ventilation system with 60 % efficiency heat recovery
Operation schedule of the ventilation system	24h/day, ventilation system is always on
Supply and exhaust design air flow rates	+72 dm^3/s -80 dm^3/s
The specific fan power of the ventilation system	2.5 kW/(m^3/s)
Heat distribution system	Direct electricity heating system with ceiling panels

Room temperature set point for heating in different spaces	21.0 °C in bed and living rooms, 22.0 °C in bathroom, 19.0 °C in entrance hall
Space heating control system	Room temperature control according to room-specific measurement
DHW consumption and circulation system	50 dm^3/(occupant,day), no DHW circulation system

The climate zone III (Jyväskylä) weather data of the revised Finnish test reference year (TRY2012) was used in the simulations. The average annual ambient air temperature is +3.4 °C and the average annual heating degree-day number S_{17}, at indoor air temperature 17 °C, is 4787 Kd.

Studied measures and cost data

Table 3 presents the energy performance improving measures studied in this research by using the SBO analysis. The studied measures are the design variables of the optimization problem. The investment cost data related to the studied measures is presented in Table 4. The cost data related to the maintenance and renewal of studied technical systems is presented in Table 5. All of the cost data presented in Tables 4 and 5 was determined by the author, a group of experts and senior consultants and by the owner of the house. Cost estimates for different measures were mainly received by asking proposals from different system manufacturers and also by using the applicable cost data of relevant previous projects with verified cost data.

As it is relatively large investment to renovate the entire original heat distribution system in detached houses, four different alternatives were studied to determine the cost-optimal heat distribution system with each main heating system concept and to avoid over-investing to the systems. The selected renovation alternatives were a complete renovation to a water-based floor heating system (WBFHS), partial renovation to WBFH system for approximately 40 % of spaces, direct electric floor heating system for approximately 40 % of spaces or the original direct electric ceiling panels (DECPs) with some maintenance, but without new investments or installations.

All applicable main heating systems used in detached houses with similar features were studied (5 options). The selected systems included applicable heat pump systems, the original direct electric heating system and also the district heating system. The systems were selected to determine the global optimum main heating system concept in the studied detached house and also to determine what other renovation measures are cost-effective and recommendable to carry out with different main heating systems.

Table 3
The design variables of the SBO analysis

Measure, design variable	Type of the variable	Min. value	Max. value
Additional thermal insulation thickness of roof (mm), λ=0.039 W/mK	Discrete (two options)	0	200
Additional thermal insulation thickness of base floor (mm), λ=0.023 W/mK	Discrete (two options)	0	160
Replacement of the original air handling unit, heat recovery efficiency (%)	Discrete (two options)	60, original	74, new
Installation of PV-panels, area of panels (m^2)	Discrete (six options)	0	48
Installation of solar collectors, area of collectors (m^2)	Discrete (four options)	0	8
Renovation of heat distribution system of spaces	Discrete (four options)	Original ceiling panels	WBFH in all spaces
Installation of an air-to-air heat pump system in living room as auxiliary heating system	Discrete (two options)	No	Yes
Main heating system of the house	Discrete (five options)	Original direct electric heating system	GSHP system, full-power output design
Installation of a waste water heat recovery system, used for preheating of DHW, efficiency ~30 %	Discrete (two options)	No	Yes

Table 4
The investment cost data of studied measures, a Finnish VAT of 24 % is included in all of the prices

Measure	Investment cost estimate
Additional thermal insulation of roof, including installation cost	35 €/ins.-m^3
Additional thermal insulation of base floor, including installation cost	50 €/floor-m^2
Replacement of the original air handling unit, including installation cost	2 600 €
Installation of PV-panels, including installation cost: - 12 m^2, 1.5 kW_p - 18 m^2, 2.25 kW_p - 24 m^2, 3.0 kW_p	 5 030 € 6 620 € 8 000 €

- 36 m^2, 4.5 kW_p - 48 m^2, 6.0 kW_p	11 200 € 14 750 €
Installation of solar thermal collectors, including a 300 dm^3 accumulator tank and installation cost: - 4 m^2 - 6 m^2 - 8 m^2	 4 000 € 4 400 € 4 800 €
Renovation of heat distribution system of spaces, total cost estimates including installation and related construction costs - maintenance of the original electricity ceiling panel system, no new installations - new electric floor heating system in UR, EH, BR 2, BR 3, WR, BHR and S (40 % of total floor area), original ceiling panels in other rooms - new water-based floor heating system in UR, EH, BR 2, BR 3, WR, BHR and S (40 % of total floor area), original ceiling panels in other rooms - new water-based floor heating system in all room spaces	 1 600 € 4 000 € 5 800 € 9 000 €
Installation of the air-to-air heat pump system, including installation cost	1 800 €
Main heating system of the house, total cost estimates including installation cost - original direct electricity heating system - district heating system - air-to-water heat pump system, 8 kW - GSHP system + borehole 180 m, 6 kW - GSHP system + borehole 190 m, 14 kW	 0 € 7 000 € 9 900 € 15 500 € 17 000 €
Installation of the waste water heat recovery system, including installation cost	5 500 €

Table 5
The cost data related to the maintenance and renewal of studied technical systems, a Finnish VAT of 24 % is included in all of the prices

System	Maintenance and renewal cost estimate
Ventilation system	100 €/a
Solar-based electricity production system, PV-panels	Annual maintenance cost of 2 % from the total investment cost of the system
Solar-based thermal production system, solar collectors	Annual maintenance cost of 3 % from the total investment cost of the system
A2WHP system	100 €/a, renewal cost of 1 280 € after 15 years
GSHP system	100 €/a, renewal cost of 1 550 € after 15 years

The renewal cost of both the A2WHP and the GSHP systems includes a scenario, where it is assumed that the compressors, circulation pumps, exchange valves and a few temperature sensors of the heat pump systems are renewed after 15 years of operation. Other technical systems included in the analysis are assumed to be used without any major renewal or maintenance costs for the selected 20-year discount period of the economic calculations.

The energy prices of different energy carriers were determined according to the location of the studied detached house (Ilmajoki, Finland). Economic calculations of the SBO analysis were conducted using the following energy prices (all prices include the 24 % Finnish VAT):

- 66 €/MWh for district heating energy, according to delivered energy consumption
- a fixed basic fee of 421 €/a for district heating system, fixed cost for detached houses located in Ilmajoki
- 107 €/MWh for electrical energy, including energy fee, transfer fees and all taxes.

Simulation-based optimization

Dynamic energy simulations of the SBO analysis were conducted by using IDA Indoor Climate and Energy (IDA ICE, version 4.6.2) simulation software. The performance and reliability of IDA ICE has been validated in several research projects before, carried out by Sahlin 1996 and Travesi et al. 2001 for example. IDA ICE software has also been tested against measurements e.g. by Travesi et al. 2001.

The Early Stage Building Optimization (ESBO) Plant model of IDA ICE was used to simulate the studied heat pump systems and solar-based energy production systems. The ESBO Plant model shows promising capabilities in simulating the renewable energy production systems as a part of dynamic energy simulation of buildings. The operation and performance of the ESBO Plant model has been discussed in more detail in a study carried out by Niemelä 2015.

The optimization software used in the study was MOBO (Multi-Objective Building Performance Optimization, version 0.3b). MOBO has been developed by VTT Technical Research Centre of Finland and Aalto University during 2010-2016. MOBO can be used as the optimization engine with many different simulation programs and it can be used to carry out one- and multi-objective optimization tasks. User can freely choose a suitable optimization algorithm according to the optimization problem and objectives from a numerous different algorithms included in MOBO. Variables, functions and operation of MOBO are controlled by using a graphical user interface (GUI). Furthermore, it is possible to use parallel simulations with MOBO to improve the performance of the building optimization analyzes by using MOBO with modern multi-core microprocessors. MOBO is still a relatively new software and in beta phase at the moment, but according to recent study carried out by Nguyen et al. 2014, it has the potential to become the major optimization engine in coming years in the building performance optimization analyzes.

Furthermore, MOBO can also be used for multi-objective optimization analyzes, where different thermal comfort and indoor climate condition metrics of a building are optimized in addition to the energy performance and economic viability. The more detailed features of MOBO in optimization of thermal comfort metrics have been extensively studied by Hamdy 2012. In addition, Hamdy 2012 has also compared the performance, features and reliability of MOBO to some of the more established optimization tools, such as GenOpt and Matlab. The full features and a more detailed description of MOBO has been presented in a study carried out by Palonen et al. 2013.

The basic principle of combining the simulation and optimization programs and the main operation of the simulation-based optimization analysis used in this study is presented in Figure 3 to demonstrate the main components and their relationships. The optimized objective functions in the multi-objective optimization analysis were the net present value of 20-year life-cycle cost and the delivered energy consumption of the studied house. Both of the selected objective functions were minimized in the SBO analysis.

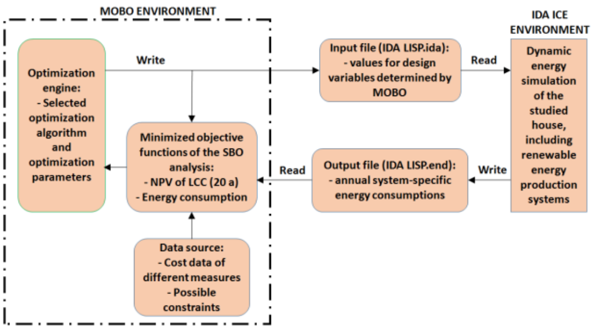

Figure 3 The basic principle and the operation of the simulation-based optimization

Economic calculations

The cost-effectiveness of the studied renovation measures was assessed by minimum net present value (NPV) of life-cycle cost (LCC) during a 20-year discount period. The life-cycle cost used in the economic calculations was calculated by using Equation (1):

$$NPV_{LCC,20a} = \sum I_{tot} + \sum M_{tot} + \sum R_{tot} + \sum E_{tot} \quad (1)$$

The total investment cost of the renovation measures is presented in Table 4. The total maintenance, renewal and energy costs during the 20-year discount period were calculated by using Equations (2-4):

$$\sum M_{tot} = \frac{1-(1+r)^{-n}}{r} \times M_a \quad (2)$$

$$\sum R_{tot} = \frac{1}{(1+r)^{k_i}} \times R_M \quad (3)$$

$$\sum E_{tot} = \frac{1-(1+r_e)^{-n}}{r_e} \times E_a \quad (4)$$

The potential residual value of different measures after the 20-year discount period was not taken into account in this study. The real interest rate used in the basic economic calculations was 3.0 %. The estimated average escalation increase rate of energy prices was assumed to be 2.0 %/a for both electrical and district heating energy. In addition, additional sensitivity analyzes were conducted with the economic calculations by using a higher interest rate and by using different energy price escalation scenarios.

RESULTS AND DISCUSSION

Cost optimum renovation solutions

A total of ten individual optimization analyzes were carried out in the study based on different main heating system solutions. The main reason for this is the fact that MOBO can only handle numeric information and parameters, not discrete information, e.g. automatically change main heating systems or heat distribution systems. This can be solved by adjusting the simulation models manually to correspond to the desired main heating and heat distribution systems and by carrying out the SBO analyzes individually.

Figure 4 presents the optimization results of an individual optimization analysis with the district heating system in a situation, where the original direct electrical ceiling panel heating system is renovated to the water-based floor heating system in all room spaces. The cost-optimum solution of the individual analysis is highlighted and a reference solution, where only the minimum measures are conducted, is also presented in Figure 4. The presented reference solution includes the maintenance of the original electric ceiling radiation panel system, but no other measures or new installations.

Figure 5 presents the cost-optimum solutions of all the individual SBO analyzes with the global-optimum solutions being highlighted. The cost-effectiveness of the A2WHP system was studied with a regular and a more detailed calibration of the ESBO Plant A2WHP model, which are both presented in Figure 5. An important aspect regarding the solar energy systems is also to take the matching of solar-based electricity production capacity with PV-panels and the electricity consumption of the detached house into account, when the PV-panel system is dimensioned, as the peak electricity production is typically higher in detached houses during summer time than the electricity consumption.

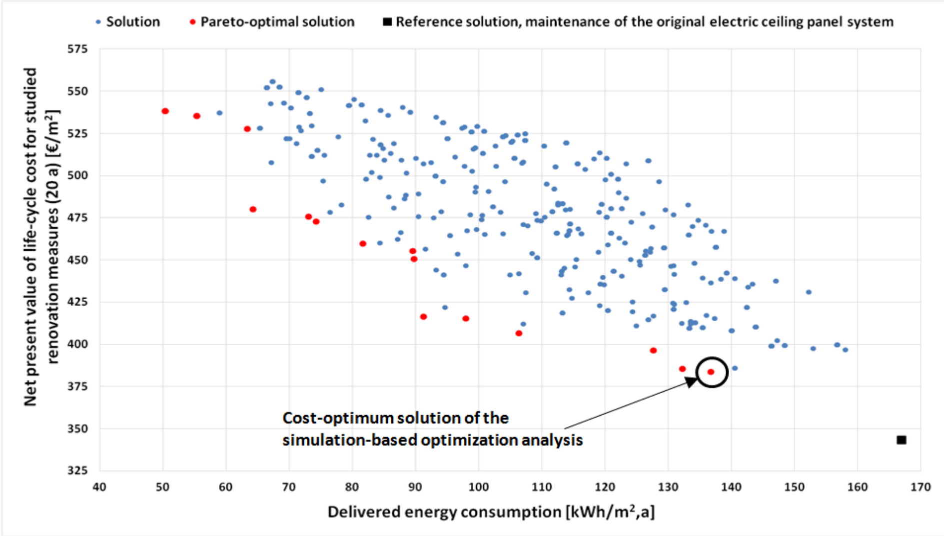

Figure 4 The main results of an individual simulation-based optimization analysis with the district heating system and renovation of the heat distribution system to water-based floor heating system in all room spaces

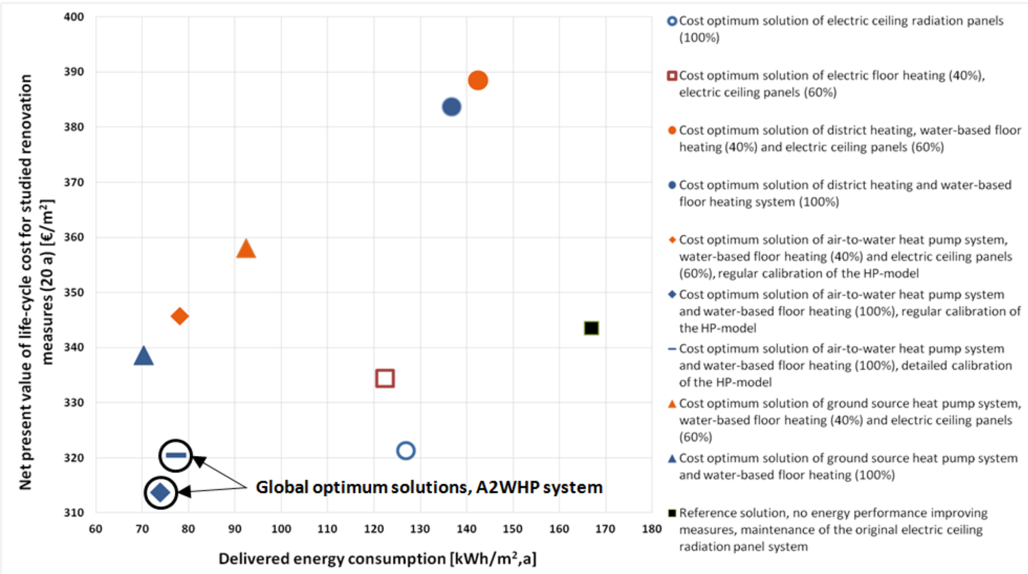

Figure 5 The cost optimum solutions of the individual simulation-based optimization analyzes with the global optimum solutions being highlighted

Cost-effective renovation measures

The cost-effective and recommendable energy performance renovation measures according to the SBO analysis are presented in Tables 6 and 7. Table 6 presents the recommendable measures for the A2WHP system, which was the cost optimum system concept. Table 7 presents the recommendable measures for the original direct electric ceiling panel heating system concept, which proved to be extremely close to the A2WHP system concept, when cost-optimality in a 20-year discount period is discussed.

Table 6

Recommendable renovation measures with the A2WHP system to reach different energy performance criteria

Delivered energy consumption (kWh/m²,a)	Heat distribution system	Additional thermal insulation thickness of roof (mm)	Additional thermal insulation thickness of base floor (mm)	Heat recovery system of waste water	Replacement of the original air handling unit	Installation of air-to-air heat pump system	Dimensioning power output of the heat pump system (kW)	Area of PV-panels (m²)	Investment cost of the measures (€/m²)	NPV of LCC (20 a) (€/m²)
74ª / 78ª	WBFHS in all room spaces	200	0	no	yes	no	8.0	0	146	314 / 320
70	WBFHS in all room spaces	0	0	no	yes	no	8.0	12	172	324
60	WBFHS in all room spaces	0	0	no	yes	no	8.0	18	190	333
40	WBFHS in all room spaces	200	0	no	yes	no	8.0	36	235	348
30	WBFHS in all room spaces	200	160	no	yes	yes	8.0	36	296	401
20	WBFHS in all room spaces	0	160	no	yes	yes	8.0	48	322	412

a = cost optimum solution for both the regular and the detailed calibration of the simulated heat pump model

Table 7

Recommendable renovation measures with the original direct electric ceiling panel system to reach different energy performance criteria

Delivered energy consumption (kWh/m²,a)	Heat distribution system	Additional thermal insulation thickness of roof (mm)	Additional thermal insulation thickness of base floor (mm)	Heat recovery system of waste water	Replacement of the original air handling unit	Installation of air-to-air heat pump system	Area of solar thermal collectors (m²)	Area of PV-panels (m²)	Investment cost of the measures (€/m²)	NPV of LCC (20 a) (€/m²)
127[a]	original DECPs	200	0	no	yes	no	0	12	59	322
120	original DECPs	200	0	no	yes	no	0	18	72	326
90	original DECPs	200	0	no	yes	no	0	48	142	353
80	original DECPs	200	160	no	yes	yes	0	48	209	394
70	original DECPs	0	160	no	yes	no	8	48	235	426
60	original DECPs	200	160	yes	yes	yes	8	48	287	461

a = cost optimum solution

According to the SBO analysis, the air-to-water heat pump system combined with renovation of the heat distribution system to water-based floor heating system in all room spaces proved to be the cost optimum main heating system concept. Other recommendable measures were the additional thermal insulation of roof (+200 mm) and the replacement of the original air handling unit to a more energy efficient model (74% heat recovery efficiency). Additional sensitivity analyzes indicated that the expected return on investment has a relatively significant impact on the recommendable renovation measures. When higher than 3.0 % real interest rate is used in the economic calculations, the original direct electrical main heating system was the global optimum system concept. Same conclusion can be determined by using a shorter discount period than 20 years. However, the 3 % real interest rate is more than enough to cover the loan expenses of the house owner at current loan interest rate levels.

According to additional analyzes, if the price of electricity increased more than 2 %/a, the A2WHP system would be the recommendable main heating system along with other measures presented in Table 6. However, if the electricity price increased significantly more than 2 %/a, e.g. 6 %/a, the GSHP system combined with water-based floor heating system in all room spaces would also become a recommendable and cost-effective main heating system concept compared to other systems. The main reasons why the GSHP system is not as cost-effective system in the original SBO analysis, even though it provides the lowest delivered energy consumption, are the high investment cost of the system and the relatively low delivered energy consumption of the studied house. If lower than 2 %/a energy price escalation rate was used, the original direct electricity heating system would be the global optimum solution in this case, respectively.

The results indicate that it is recommendable to install a moderate area of PV-panels with the direct electrical heating system, but not with the studied heat pump systems. The PV-panels would mainly be used to heat domestic hot water accumulator tank by using additional electrical resistors installed in the tank during summer time, as the use of electricity to lighting and household appliances is relatively low in detached houses in summer time. It is also important to notice that in Finland the price of electrical energy is relatively low at the moment compared to some other countries located in cold climate, which also makes the direct electric heating system a relatively cost-efficient heating option.

According to the study, all of the studied heat pump systems and the original direct electricity heating system delivered better energy performance and cost-effectiveness than the district heating system. Furthermore, the high performance HVAC systems proved to be the recommendable renovation measures over the studied renovation measures regarding the building envelope, when cost-optimality and energy efficiency are discussed.

The recommended overall solutions represent typical modern energy performance measures, which can be applied to the case study house and to other Finnish detached houses with similar features. The costs of different renovation measures are typical average costs and are therefore usable, when renovation of other electrically heated detached houses with similar features are planned. Typically the modern heat pump systems (especially the GSHP and A2WHP) are cost-efficient and recommendable investments in existing Finnish detached houses. The A2WHP system is often a cost-effective alternative to the GSHP system in smaller (<180 m^2) houses due to its lower initial investment cost. Furthermore, there are several Finnish case houses with the A2WHP system installed that are delivering excellent measured energy performance in real conditions as well, in addition to the high performance of the energy simulations.

According to Statistics Finland 2016, there are approximately 500 000 electrically heated detached houses with a total floor area of over 70 000 000 m^2 in Finland. Largest share (~18 %) of these houses have been built in the 1980's so the energy saving potential of the studied building stock is significant. By applying the results and conclusions of this study, up to 380 million euros could potentially be saved, with a decrease of up to 1.2 TWh of electrical energy at the same time, over the next 20 years in the Finnish 1980's detached houses alone. Furthermore, the results of this study can also be generalized to Finnish detached houses built in the late 1970's, 1990's and early 2000's, which already covers approximately 50 % of the entire Finnish detached house building stock.

CONCLUSIONS

The study focused on determining cost-effective energy performance renovation measures in typical Finnish (cold climate) detached houses built in the 1980's and heated by direct electrical heating system for both spaces and DHW. According to the study, the A2WHP system is the recommendable main heating system concept along with the energy efficient ventilation system with high heat recovery efficiency and good thermal insulation of roof. The original direct electrical heating system, combined with new and improved air handling unit, additional thermal insulation of roof and a moderate area of PV-panels, proved to be a cost-effective and relatively energy efficient main heating system concept as well, when delivered energy consumption is discussed instead of primary energy consumption. According to the study, the renovation measures should be focused on improving the energy performance of the main HVAC systems in detached houses. Furthermore, the measures to be conducted should be carefully selected and dimensioned according to real use of the house to provide cost-effective renovation solutions to the house owners. The results of this study can be generalized to similar climates and techno-economic environments.

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NOMENCLATURE

$\mathrm{NPV}_{LCC,20a}$,	total net present value of the 20-year life-cycle cost in the studied house, €;
$\sum I_{tot}$,	total investment cost of the studied renovation measures, €;
$\sum M_{tot}$,	total maintenance and repair cost of the studied renovation measures, €;
$\sum R_{tot}$,	total renewal cost related to the studied renovation measures, €;
$\sum E_{tot}$,	total energy cost of the studied house during the 20-year period, €;
M_a,	annual maintenance and repair cost of the studied measures, €/a;
R_M,	renewal cost related to a single renovation measure, €;
E_a,	annual energy cost, €/a;
k_i,	year from the beginning, when the renewal measure is carried out;
n,	discount period, 20 years;
r,	real interest rate;
r_e,	real interest rate including the escalation rate of energy price.

REFERENCES

Hamdy, M. 2012. Combining Simulation and Optimisation for Dimensioning Optimal Building Envelopes and HVAC Systems. Doctoral Dissertation, Department of Energy Technology, School of Engineering, Aalto University 2012, Espoo, Finland. ISSN 1799-4942.

Kurnitsti, J., Kuusk, K., Tark, T., Uutar, A., Kalamees, T., Pikas, E. 2014. Energy and investment intensity of integrated renovation and 2030 cost optimal savings, Energy and Buildings 75 (2014), pp. 51–59.

Liljeström, K., Hurme, M., Raiko, M. 2014. Suggestion for initial energy calculation data of the nearly zero energy buildings, Sisäilmastoseminaari 13.3.2014, SIY Report 32, pp. 251–256. SIY Sisäilmatieto Oy 2014, Bookwell Oy, Juva. ISBN 978-952-5236-42-2.

Nguyen, A-T., Reiter, S., Rigo, P. 2014. A review on simulation-based optimization methods applied to building performance analysis, Applied Energy 113 (2014), pp. 1043–1058.

Niemelä, T. 2015. Cost Optimal Renovation Solutions in the 1960s Apartment Buildings, Master's Thesis, Aalto University, School of Engineering, Department of Energy Technology, HVAC 2015, Espoo, Finland.

Palonen, M., Hamdy, M., Hasan, A. 2013. MOBO a new software for multi-objective building performance optimization, Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26–28, 2013.

Sahlin, P. 1996. Modelling and Simulation Methods for Modular Continuous Systems in Buildings. Doctoral Dissertation, Department of Building Sciences, Division of Building Services Engineering, Royal Institute of Technology 1996, Stockholm, Sweden. ISSN 0284-141X.

Statistics Finland. Official Statistics of Finland (OSF): Buildings and free-time residences [e-publication], 2016. ISSN=1798-6796. Helsinki: Statistics Finland, accessed on 20th January 2016, http://www.stat.fi/til/rakke/tau_en.html.

Travesi, J., Maxwell, G., Klaassen, C., Holtz, M. 2001. Empirical validation of Iowa energy resource station building energy analysis simulation models, IEA Task 22, Subtask A, 2001.

Üllar, A., Allikmaa, A., Kalamees, T. 2015. Potential for finance and energy savings of detached houses in Estonia, 6th International Building Physics Conference, IBPC 2015, Energy Procedia 78 (2015), pp. 907–912.