HEAT PUMP SYSTEMS FOR SINGLE FAMILY AND MULTI FAMILY nZEB

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Abstract: In near zero energy buildings (nZEB) the space heating demand will decrease and the domestic hot water (DHW) demand will account for a larger share of the total energy use. This requires a new generation heat pump systems with lower capacity, lower price and performance to cope with these conditions. The challenge is to develop a system concept that could provide a competitive Life Cycle Cost (LCC) to the end consumer. This paper aims at describing two system concepts including a single family and a multifamily nZEB where heat pump prototypes have been developed for. The developed system concepts and prototypes have been assessed from an energy savings point of view as well as from an LCC point of view. The results shows that heat pumps can be cost effective solutions for single family as well as multifamily nZEB but that future prices for: electricity, district heating and pellet will be important for the competitiveness of the heat pump systems assessed here.

Key Words: nZEB, single family house, multifamily house, LCC, specific energy use

1 INTRODUCTION

The Energy performance of buildings directive (EPBD 2010/31/EC) requires very low energy use in all new and refurbished buildings as of 2021. This means that the space heating demand will decrease and the domestic hot water (DHW) will account for a larger share of the total energy use. Heat pump manufacturers currently lack complete heat pump system solutions that meet future requirements for near zero energy buildings (nZEB) .The final requirement levels for nZEB are to be determined nationally regarding energy and cost efficiency which means that there will be as many definitions as there are member states in the EU. Nevertheless this requires a new generation heat pump systems with lower capacity, lower price and performance to cope with the requirements of the RES Directive. The challenge is to develop a system concept that could provide a competitive Life Cycle Cost (LCC) to the end consumer.

1.2 Background

Sweden has been early in the development and implementation of heat pump technology. However in terms of ground source heat pumps, the main focus has been relatively large heat pumps for replacement of oil boilers or electric boilers in older existing houses. In connection with a procurement of technology in the mid -1990s smaller ground source heat pumps were developed, however these have now disappeared from the market. In Sweden for existing single family houses with direct electrical heating, without a hydronic heating system, air to air heat pumps have dominated the market whereas on the market for new single family houses exhaust air heat pumps have dominated (SVEP 2013). Calculations carried out within a former research project Economic heating and cooling systems for low energy houses - Calculations, comparisons, and evaluation of various systems (Ruud 2010) by applying the software TMF Energy (TMF 2014) shows that grounds source heat pumps are the best solution from an energy efficiency point of view in nZEB but the investment cost is too high for them to be competitive to other heating solutions. TMF Energy is an Excel based software developed by SP and TMF to calculate the energy performance of buildings according to the Swedish Board of Housings rules that comes as a result of the (EPBD, 2010/31/EC). The results from the calculations also show that energy use for fans and circulating pumps is too high and that the standby losses need to be reduced. The work carried out within the IEA HPP Annex 32 (Ruud 2010) also shows that today's ground source heat pumps on the Swedish market are too large for single family nZEBs. Results from earlier projects performed within the Swedish Research Program for heat pumping systems, effSys+, “Operating Optimization of Heat Pump systems” (Karlsson 2004) and Conversion of Electrically heated single-family homes (Fahlén 2004) show the potential for energy savings by changing to ground source heat pumps. Results from calculations performed in earlier studies also show that if a new generation heat pump system are developed and 'green' electricity used, heat pumps are very favorable settlement from and environmental point of view. In combination with solar electricity, there is prerequisite to achieve a zero or plus energy goal although household electricity included (Axell et al. 2010). The purpose of this project is to look at the building as a system in the process of developing concepts for new heat pump systems for new constructions and reconstructions, and to perform dynamic models energy calculations as well as LCC calculations.

1.3 Objective

The overall objective is to collaborate with project partners to develop competitive heat pump system solutions and build prototypes that meet nZEB requirements and have the potential to plus energy levels with the possibility to use different heat sources based on local conditions where intelligent system integration of the exhaust air is a key. Basically, there are more physical similarities than differences between small and multifamily houses, however they differ in design requirements. Here the heat pump system is defined as the whole system including the heat pump and distribution system that is the entire system space heating and production of domestic hot water.

2 METHOD

In this project a system concept is applied, which is a necessity to meet the new, more stringent energy requirements.

Step 1: Literature review

A state of the art analysis was done regarding small energy-efficient heat pump system, ground heat sources, domestic hot water systems and distribution systems for single family houses. Regarding multifamily houses the main focus was on describing state of the art systems and current dimension criteria’s used when designing heat pump systems for multifamily houses. Also a state of the art analysis regarding the building envelope, the possibilities for heat recovery and the effect of various behaviors among people and how it will affect future needs for heating, cooling and domestic hot water in nZEB was performed.

Step 2: Development of requirements specifications for the prototypes together with the industry group

This was done using the overall knowledge in the project group. In addition, an interpretation of the EU directives affecting the requirements specifications was done, including EPBD (EPBD 2010/31/EC), Renewable Energy Directive (RES 2009/28/EC), F-gas regulation (F-gas 2006/842/EC) and the Eco Design Directive (Eco Design Directive 2009/125/EC). Beyond this, it was important to collect relevant information in the construction industry to take into account for market demand from future customers that may affect the specifications, such as building types, economy and environment. This step included the selection of refrigerant based on the F-Gas Directive. For exporting companies, it was also important to adjust the specifications so that the requirements for the export markets of interest were expected to be met by the country-specific requirements on an nZEB for Sweden.

Step 3: Development of calculation models for both energy use and LCC calculations
Developments of computational models for nZEB that take into account both energy consumption and LCC. System losses and quality of input data becomes very important factors to consider, as well as economic boundary conditions such as internal interest rates, energy price trends, etc.

Step 4: Develop theoretical heat pump concepts based on the best technology for the following cases:

1. New building, single-family houses
2. New building, multifamily houses

Step 5: Implement energy savings and LCC calculations for different system concepts including the building envelope.
The purpose of this step was primarily to theoretically determine which concepts are most competitive in terms of energy savings and LCC. The aim was to select the concepts that will be further developed into physical prototypes.

Step 6: Construction of prototypes by the heat pump manufacturers based on steps 1-7

Step 7: Laboratory testing, from prototype to finished product. *Not performed yet.*
Included in step 7 is to test the performance for heating and DHW production for the prototypes in SPs laboratory.

3 RESULTS

In this chapter the developed type houses are presented as well as the developed heat pump prototypes together with results from the energy savings calculations and the results from the LCC assessment.

3.1 Type Houses and Climate Zones

Included in the development of the requirements specifications in step 2 of the project was also the development of two type houses that the heat pump system concepts should be appropriate for. The type houses where determined to be situated in climate zone three in Stockholm according to the climate zones determined in the Swedish Building Regulations 2013 (BFS 2013:14 BBR 20). Figure 1 shows the geographical positioning of these climate zones. The dimensioning winter outdoor temperature used in this project calculated according to SS-EN ISO 15927-5 (SS-EN ISO 15927-5, 2004) for Stockholm is presented in Table 1.

Table 1 Dimensioning winter outdoor temperature for Stockholm according to SS-EN ISO 15927-5 (SS-EN ISO 15927-5, 2004) used in the calculations in this project

°C	Day 1	Day 2	Day 3	Day 4
Stockholm	-17.8	-17.0	-16.3	-15.8

The type houses were developed by the project group together with the industry partners consisting of both single family house manufacturers, multifamily house manufacturers and heat pump manufacturers. The properties of the developed type houses are summarized in . Table 2.

Table 2: Type houses developed as a basis for the heat pump prototypes

	Single family nZEB	Multifamily nZEB
Nr of houses/apartments	1	40
Nr of residents	4	80
Household electricity	4800 kWh/yr	112 MWh/yr
Specific, household electricity	30 kWh/(yr m^2 A_{temp})	28 kWh/(yr m^2 A_{temp})
Other building electricity	-	8 MWh/yr
Specific other building electricity	-	2 kWh/(yr m^2 A_{temp})
Tempered floor area, A_{temp}	160 m^2	4000 m^2 *
Inner area building envelope, A_{om}	390 m^2	6000 m^2
Nominal airflow; 0,35 dm^3/(s m^2 A_{temp})	56 dm^3/s	1,4 m^3/s
Average heat transfer coefficient (building), U_m	0,2 W/(K m^2 A_{om})	0,3 W/(K m^2 A_{om})
Air tightness (at ±50 Pa)	0,2 dm^3/(s m^2 A_{om})	0,3 dm^3 /(s m^2 A_{om})
Spec. heat loss from ventilation (at dimensioning winter outdoor temperature)	0,14 W/(K m^2 A_{temp})	0,14 W/(K m^2 A_{temp})
Heat loss from ventilation	22,4 W/K	0,56 kW/K
Temperature efficiency, mechanical supply and exhaust air with heat exchange	about 80 %	about 80 %
Specific fan power (SFP) **	≤ 1,5 W/(dm^3/s)	≤ 1,3 kW/(m3/s)
Fan power	≤ 85 W	≤ 1,8 kW
Specific energy to fan	≤ 4,5 kWh/(yr m^2 A_{temp})	≤ 4,0 kWh/(yr m^2 A_{temp})
Energy to fan	≤ 700 kWh/yr	≤ 16 MWh/yr
Specific pump power for heat- and DHW distribution ***	≤ 0,3 W/(m^2 A_{temp})	≤ 0,3 W/(m^2 A_{temp})
Pump power for heat- and DHW distribution	≤ 50 W	≤ 1,2 kW
Specific pump energy for heat- and DHW distribution	≤ 1,5 kWh/(yr m^2 A_{temp})	≤ 1,3 kWh/(yr m^2 A_{temp})
Pump energy for heat- and DHW distribution	≤ 250 kWh/yr	≤ 5 MWh/yr
Specific heat loss DHW/Circulation System at stand-by	≤ 0,5 W/(m^2 A_{temp})	≤ 0,3 W/(m^2 A_{temp})
Heat loss DHW/Circulation System at stand-by	≤ 80 W	≤ 1,2 kW
Specific DHW demand/Circulation System at stand-by	≤ 4,5 kWh/(yr m^2 A_{temp})	≤ 2,5 kWh/(yr m^2 A_{temp})
DHW demand /Circulation System at stand-by	≤ 700 kWh/yr	≤ 10 MWh/yr
Specific heat demand in climate zone III	36,5 kWh/(yr m^2 A_{temp})	34,5 kWh/(yr m^2 A_{temp})
Heat demand in climate zone III	5800 kWh/yr	138 MWh/yr
Maximum power demand, heating system	4 kW	75 kW
Specific DHW demand (excl. heat losses)	21,5 kWh/(yr m^2 A_{temp})	17,5 kWh/(yr m^2 A_{temp})

DHW demand (excl. heat losses)	3400 kWh/yr	70 MWh/yr
Net specific energy demand, incl. household electricity	100 kWh/(yr m^2 A_{temp})	90 kWh/(yr m^2 A_{temp})
Net energy demand, incl. household electricity	16 000 kWh/yr	360 MWh/yr
Specific energy use (bought energy), incl. household el. ****	60 kWh/(yr m^2 A_{temp})	55 kWh/(yr m^2 A_{temp})
Energy use (bought energy), incl. household el.	9 600 kWh/yr	220 MWh/yr
Specific energy use (bought energy), excl. household el.	30 kWh/(yr m^2 A_{temp})	27 kWh/(yr m^2 A_{temp})
Energy use (bought energy), excl. household el.	4 800 kWh/yr	108 MWh/yr

*) incl. stairs etc. (i.e. about 80 m^2/apartment)

**) excl. fan in outdoor part if air to water heat pump

***) excl. pump for brine

****) excl. on site produced electricity from PV

The derived figures for the specific energy consumption for the type houses, presented in . Table 2, are on par with the figures suggested by the Swedish Energy Agency in the report (ER 2010:39). These figures for specific energy use proposed by the Swedish Energy Agency can be seen in Table 3.

Table 3: Specific energy consumption (Swedish Energy Agency 2009)

	Non electrically heated [kWh/m^2yr]			Electrically heated (including heat pumps) [kWh/m^2yr]		
	Geographical zone					
Type of building	**1**	**2**	**3**	**1**	**2**	**3**
Residential	75	65	55	50	40	30
Non residential	70	60	50	50	40	30
Non residential with add. highest air flow rate for hygiene	(120-192)	(100-159)	(80-126)	(95-131)	(75-104)	(55-78)

Figure 1: Climate zones in Sweden according to the Swedish Board of Housing

3.2 The Developed Heat Pump Systems

In an iterative process together with the whole project group the type houses were chosen to have the following system solutions for both the single family house and the multifamily house.

Heat source: Vertical ground source (with bore hole)
The manufacturers of single family houses in Sweden want a single solution with a heat pump that works in all climate zones in Sweden for economic reasons. They also wanted a solution that could cover the whole heating demand the year around. By experience it was known that it is reasonable to design an ASHP to cover the whole heating demand down to about -5°C but not at lower outdoor temperatures. Therefore solutions with ASHP won't be a possible solution in this project due to the low dimensioning winter outdoor temperature. When also taking into account for lack of space for horizontal ground source systems in areas with new built houses the only option is a vertical ground source with bore whole.

Heat recovery: Mechanical supply and exhaust air with heat exchange
For this type of building the air tightness (0.2 $dm^3/(s\ m^2\ A_{om})$) is better than for many other buildings which leads to a need for forced ventilation, otherwise it would be problems with indoor air quality. Many new built houses in Sweden today, are equipped with an inverter controlled exhaust air heat pump (mechanical exhaust air). However, this solution was disqualified due to two reasons. Firstly, by experience it was known that it is really hard to meet the tough requirements on energy use in an exhaust air ventilated house (no direct heat recovery between supply and exhaust air). Secondly, a balanced ventilated house is much "slower" when it comes to interrupters in the heating and is thus better adapted to future smart electricity grids.

Heat distribution system: Floor heating
Floor heating is the best alternative from an energy saving point of view due to the low distribution temperature. Earlier there have been problems with installing floor heating on the second floor in single family houses due to settings in load bearing beams but new research has solved these problems. Further on floor heating was preferred by house manufacturers from an esthetical point of view which is also very important.

3.3 Energy Use

The heat pump prototypes developed in the project, presented in Table 4, gave the following input to the assessment of specific energy use using the software TMF Energy.

Table 4: Input, energy use assessment single family house and multifamily house

Heat pump single family house			Heat pump multifamily house		
P HP heat, 0/35°C	4750	(W)	P HP heat, 0/35°C	90980	(W)
COP, heat, 0/35°C	4.24	(-)	COP, heat, 0/35°C	4.60	(-)
P HP heat, 0/45°C	4500	(W)	P HP heat, 0/45°C	87040	(W)
COP, heat, 0/45°C	3.28	(-)	COP, heat, 0/45°C	3.66	(-)
De-superheater	no		De-superheater	no	
A-labeled brine pump	yes		A-labeled brine pump	yes	
Standby power consumption	55	(W)	Standby power consumption	1201.6	(W)
Installed electric power	4500	(W)	Installed electric power	35880	(W)

Using the type houses defined in the project, presented in .
Table 2 together with the input presented in Table 4 and the software TMF Energy gives us the specific energy use for the single family house presented in Figure 2 and for the multifamily house in Figure 3. The specific energy use has been assessed for four different cases. In addition to the baseline with the type house and the heat pump prototypes three various cases with the heat pump prototype and PV, solar thermal collectors and both PV and solar thermal collectors respectively has been assessed. For the single family house a PV installation of about 3000 kWh and 25% reduction of the heating demand according to the levels in the Building Legislations by the Swedish board of Housing whereas the solar thermal installation has been assumed to cover 40% of the DHW demand and 10% of the heating demand for the type house. For the multifamily house a PV installation of about 40 000 kWh and 25% reduction of the heating demand according to the levels in the Building Legislations by the Swedish board of Housing whereas the solar thermal installation has been assumed to cover 40% of the DHW demand and 10% of the heating demand for the type house. For the single family house it can be seen in Figure 2 that the specific energy use in the baseline case without solar installations is below the proposed levels in Table 3. It should be noted that the alternative with PV gives a lower specific energy use than the alternative with solar thermal collectors. For the multifamily house it can be seen in Figure 3 that the specific energy use in the baseline case without solar installations is also below the proposed levels in Table 3.

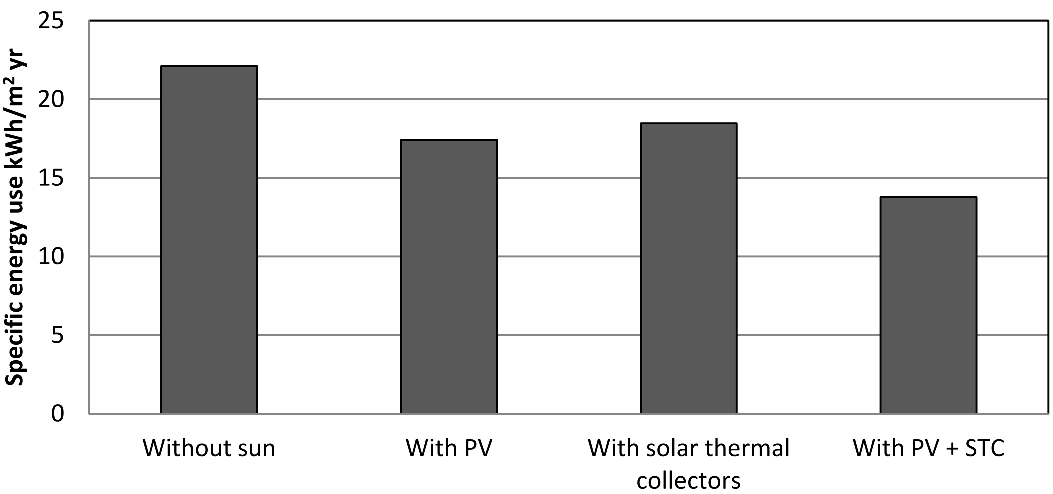

Figure 2: Specific energy use for the single family house estimated using the software TMF.

From the energy savings calculation for the GSHP system prototype for the single family house with the software TMF it can be seen that the specific energy use is well below the proposed levels in Table 3. The result from the energy savings calculation for the GSHP system prototype for multifamily house can be seen in Figure 3. Both the baseline results for the singe family house are below the target levels in Table 2.

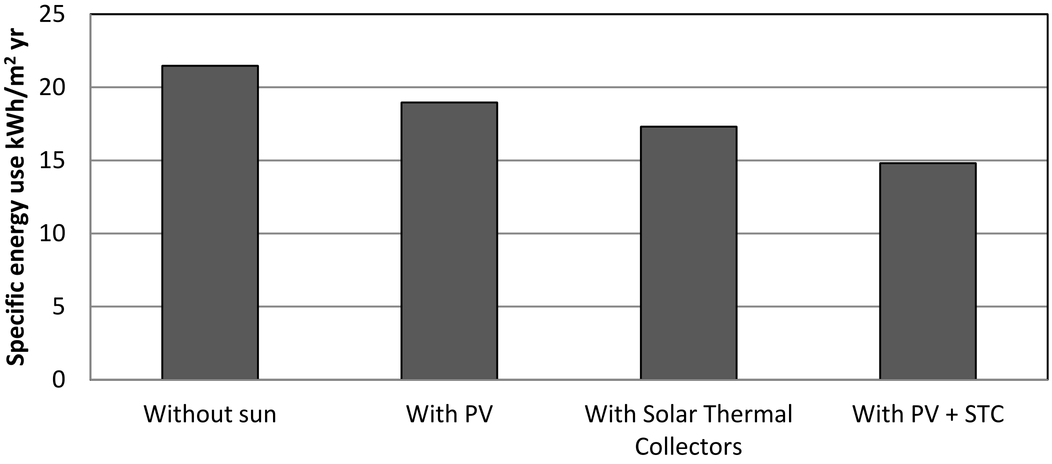

Figure 3: Specific energy use for the multifamily house estimated using the software TMF.

3.4 LCC Analysis

An LCC-analysis was performed for the developed system prototypes together with the type houses developed in the project. Table 5 shows the calculation conditions for the LCC analysis. For the electricity price, district heating (DH) price and pellet price monthly variations throughout the year have been used. Table 5 gives mean prices of electricity, DH and pellet. The investment cost for the pellet boiler has been assumed without a storage tank due to that being the most common case in Sweden.

Table 5: Calculation conditions for the LCC-analysis

Variable	Value	Unit
Discount rate	4.0%	
Time of the cash flow	30	yr
Mean electricity price	1.46	SEK/kWh
Mean price for DH	0.67	SEK/kWh
Mean pellet price	0.55	SEK/kWh
Increase in electricity price per year	3.0%	
Increase in heat price per year	2.0%	
Increase in cost for pellet per year	2.0%	

The assumed investment costs and lifetime expectation used in the LCC calculations are presented in Table 6 and Table 7 below.

Table 6: Investment cost and lifetime expectation for the single family house

Single family house		
Investment	**Investment (SEK)**	**Life expectancy (yr)**
GSHP	73 500	15
Bore hole	37 500	75
ASHP	80 800	15
District heating sub station	20 600	20
Pellet boiler	43 750	20

Solar thermal collector + accumulator tank	56 250	20
Furnace	18 750	20
Piping etc.	6 250	30
PV- installation, total per kWp	20 000	
PV-module:, per kWp	12 000	25
Inverter, per kWp	2 000	15
PV-modules: additional costs, per kWp	6 000	25
PV-installation: subsidy, per kWp	-7 000	25

Table 7: Investment cost and lifetime expectation for the multifamily house

Multifamily house	**Investment (SEK)**	**Life expectancy (yr)**
GSHP	440 000	15
Bore hole	308 000	75
District heating sub station	60 000	20
Solar thermal collector + accumulator tan	100 000	20
PV-installation, total per kWp	20 000	
PV-module:, per kWp	12 000	25
Inverter, per kWp	2 000	15
PV-modules: additional costs, per kWp	6 000	25
PV-installation: subsidy, per kWp	-7 000	25

From the LCC-analysis it can be seen that the net present value for the GSHP system prototype developed for the single family house in this project is slightly better than the air source heat pump (ASHP) and the DH alternatives. The alternative with pellet comes out a little bit better than the prototype GSHP alternative as can be seen in Figure 4. For the cases with PV it has been assumed that the electricity that can't be used in the house can be sold to the net at the Nordpool spot electricity price plus the electricity certificate. The Nordpool spot electricity price has been calculated from statistical data from 2008 to 2012 with monthly variations. This ends up with a mean spot price at 0.43 SEK/kWh and the electricity certificate has been assumed to be able to be sold at 0.20 SEK/kWh.

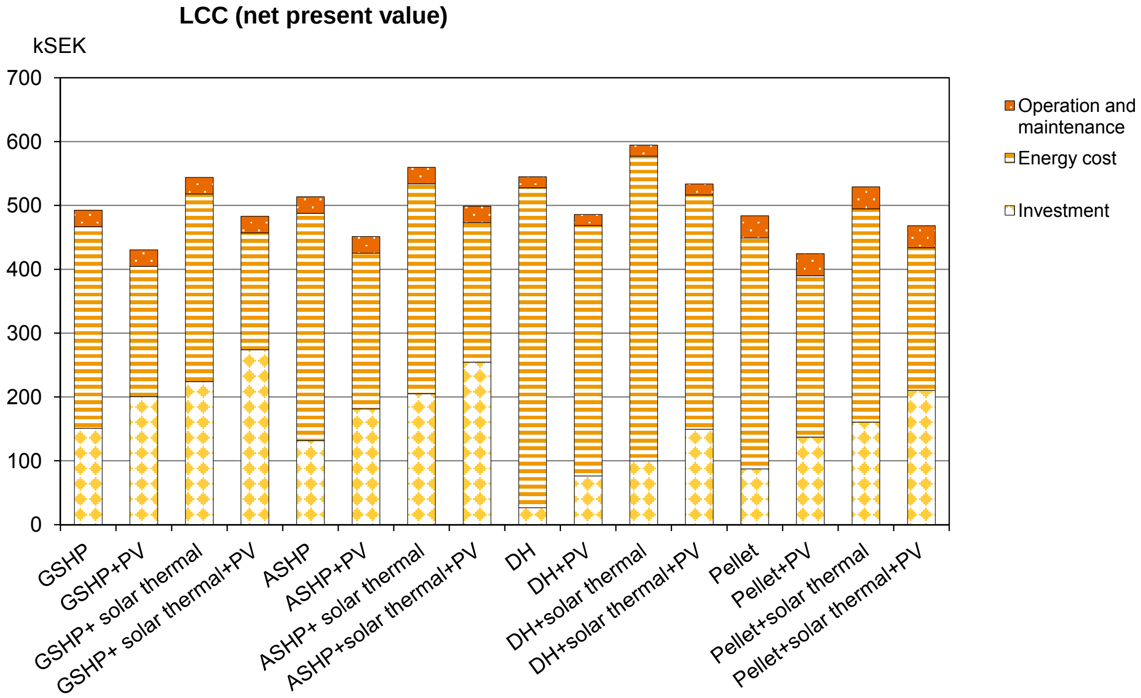

Figure 4: LCC-analysis for the single family house with various installations

From the LCC-analysis it can be seen that the net present value for the GSHP system prototype developed for the multifamily house in this project is on par with the district heating (DH) alternative as can be seen in Figure 5.

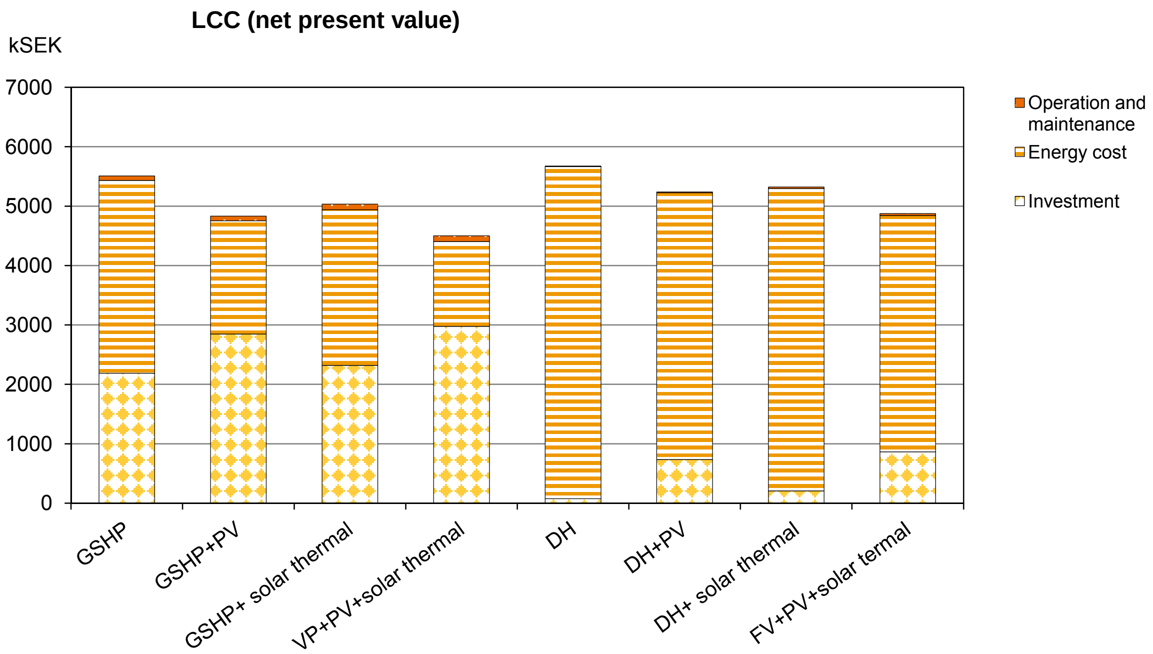

Figure 5: LCC-analysis for the multifamily house with various installations

A sensitivity analysis has been done where the variables in Table 5 were varied. From the sensitivity analysis it can be concluded that the net present values presented in Figure 4 and Figure 5 will change quite a lot with small variations in the variables in Table 5. This shows that the future prices on electricity and heat as well as the discount rate will affect weather the developed prototypes will be cost effective or not.

3.5 Future Work

The last step in the development process is to verify the energy savings performance of the developed system prototypes for both the single family house and the multifamily house in SPs laboratory. Included in this step is to label the system prototypes according to the Energy Labeling Directive. The system prototype for the single family house will be tested according to the Eco Design/Energy Labeling Directive for space heaters and for water heaters with the tapping cycle “large” which fits the type house quite good. The system prototype for the multifamily house will be tested according to Eco Design/Energy Labeling Directive for water heaters with the tapping cycle 2XL and an additional project-developed tapping cycle based on field measurements in similar multifamily houses in Sweden. This is due to the relatively bad fit between the larger tapping cycles 3XL and 4XL in the Eco Design/Energy Labeling Directive and the user behavior observed in the field measurements.

4. DISCUSSION

The relatively low heating demand that we see in single family nZEB leads to relatively low power requirements on the heat pump. This means that a too large heat pump will start and stop quite often and deliver unnecessarily high leaving water temperatures when running, when combined with an nZEB. The challenge is then to construct a heat pump that is small enough and that can handle the low heating demand in the house but at the same time is cheap enough to be cost effective when only delivering about 6000 kWh per year. One way of solving this is to go for a variable speed controlled compressor that can handle the low heating demand but this might be too expensive leading to a solution that is not cost effective. Another solution is to combine a slightly larger heat pump with a large tank between the heat pump and the heat distribution system allowing the heat pump to run for longer periods resulting in less starts and stops per year which will result in a longer life time of the compressor. The drawback with choosing a solution with an extra tank between the heat pump and the heating system is that the extra tank will use floor area witch needs to be taken into consideration when comparing the LCC for the various alternatives. These questions will be further assessed in the project.

Regarding the multifamily house the heat demand is large enough to relatively easy produce a cost effective system solution which has been shown in previous research projects. In this project the focus has rather been on the development of the dimensioning criteria’s for the heap pump system for the multifamily house. Little research has been done on dimension criteria’s and user behaviors for multifamily houses and judging from common “rules of thumb” and design criteria’s used when dimensioning both DH system and HP system for multifamily houses many systems are too large. This leads to too large heat losses from DHW tanks, too expensive system solutions and too an overuse of material. When comparing the 3XL and 4XL tapping cycles in the Eco Design /Energy Labeling Directive with user behaviors from field measurements in Sweden it is quite clear that these tapping cycles are quite over dimensioned. Of course one should take into account for the possibility of some residents in a multifamily house take a shower at the same time at some heavily loaded time periods each day but to design a DHW system for all residents in a multifamily house to take a shower at exactly the same time does not make sense from an energy performance point of view neither from a cost effective point of view. This is simply due to the fact that this situation statistically occurs very seldom which has also been shown by the field measurements used in this project. This needs to be further assessed with more field measurements of user behaviors in various types of multifamily houses with various numbers of residents.

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