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Preface

Finland is committed to EU targets in energy efficiency improvements. New buildings that are in government use or ownership are required to be nearly zero energy buildings from 2018, and after 2020 this will apply to all new buildings. Behind this is the Energy Performance of Buildings Directive (EPBD), which requires member nations to specify near-zero energy buildings.

The common vision of the Finnish construction industry on the EU's requirements for nearly zero energy buildings and suggestions on the energy efficiency requirements of different building types have been announced as the result of the FInZEB project as a base for drafting legislation. The draft will be presented to the Finnish parliament during Autumn 2016.

Finland is a member of IEA Heat Pump Programme, of which Annex 40 “Heat Pump Concepts for Nearly Zero Energy Builidngs” Finland participated with a national project called HP4NZEB. This is the final report of the project. The annex was collaboration project between 9 countries, each participating with their own national project. Annex collaboration has provided an important platform for the international knowledge exchange and exploiting the results of the project.

The results of the HP4NZEB project are surely flattering for the heat pump industry in Finland. Finnish nearly zero energy level for buildings can be achieved more cost-efficiently with concepts utilizing heat pumps than district heating. All studied concepts utilizing heat pumps reached the planned “nearly zero” level. In addition to lower life cycle costs heat pumps can also cool the building and cooling can be done almost without any extra investment needed.

As a conclusion of the project it is safe to point out that investing in a heat pump can bring added value to the building and the user, such as:

- the cooling mode of the heat pump will increase comfort and well-being of the user
- the heat pump investment will increase the market value of the building
- the image of the building gets better
- heat pumps have positive impact on the environment
- heat pumps increase energy independence and decrease the building owner’s dependency on energy pricing

HP4NZEB project has definitely promoted the know-how of the Finnish businesses. All the results of the project were by far excellent for the heat pump business, and they give valuable information for property owners, designers, construction companies and others considering what is the best way to heat your house.

Jussi Hirvonen

Finnish Heat Pump Association SULPU, Executive Director
European Heat Pump Association EHPA, Member of Board

The HP4NZEB project team wish to thank various people and institutions for their contribution to this project:

- Tekes – the Finnish Funding Agency for Innovation which gave the main financing for the project.
- Companies Ensto, Fidelix, Gebwell, Mestariasunnot, Kaukomarkkinat, Suomen Lämpöpumpputekniikka, NIBE, Oilon, Rettig and Scanoffice who contributed in project financing.
- Steering committee members of the project who gave their valuable insight in order to reach successful results of the project:
  - Maria Penttilä (Ensto), Juha Tikka (Nibe Energy Systems), Pasi Hirvijärvi (Scanoffice), Juha Hirvonen (Mestariasunnot / JH Lämpö), Riikka Holopainen (VTT), Petri Virta (Oilon), Tom Palmgren (Ensto), Mikko Iivonen (Rettig Lämpö Oy), Tero Lindén (Kaukomarkkinat Oy), Karri Siren (Kaukomarkkinat Oy), Heikki Lahtinen (Lämpöässä / Suomen Lämpöpumpputekniikka), Tuure Stenberg (Gebwell Oy), Antti Koskinen (Fidelix), Mauri Marjaniemi (Tekes), Jarek Kurnitski (Aalto University), Kai Siren (Aalto University) and Pekka Kalliomäki (Finnish Ministry of the Environment).
- Professor Carsten Wemhoener from Institute of Energy Technologies, HSR University of Applied Sciences in Rapperswil who coordinated the international collaboration in IEA Annex 40.
- All participants in IEA Annex 40.

Contents

Appendices

List of symbols

AAHP	air-to-air heat pump
AWHP	air-to-water heat pump
DH	district heating
DHW	domestic hot water
EAHP	exhaust air heat pump
GSHP	ground source heat pump
HVAC	heating, ventilation and air conditioning
nZEB	nearly zero energy building
PV	photovoltaics
ST	solar thermal collector

1. Introduction

This is the final report of development project “HP4NZEB – Heat Pump Concepts for Nearly Zero Energy Buildings”. The project’s main objective was to define and clarify the role of the heat pumps in nZEB building industry and to offer a realistic view what is the reasonable and cost-effective nZEB level in the Finnish climate.

The project was implemented in 2013–2015 by Green Net Finland (coordinator), VTT Technical Research Centre of Finland Ltd, Aalto University and Finnish Heat Pump Association SULPU. The project was the Finnish national project participating IEA Heat Pump Programme’s Annex 40.

This report includes the calculation material and the main results of the project. The simulation tool utilized in the project was IDA Indoor Climate and Energy (IDA ICE, http://www.equa.se/en/ida-ice).

In this report Chapter 2 (written by VTT) gives an overview of state-of-the art of existing concepts to reach nZEB utilizing heat pumps in residential buildings. The summary of the key factors concerning building energy calculation is presented in Chapter 3 (Aalto University). The detailed data is presented as an appendix. Chapter 4 (Aalto University) introduces the reader the studied system concepts utilizing heat pumps. Chapter 5 (VTT) summarizes all the calculation results – the energy performance and the life cycle costs of each studied concept. Chapter 6 is about conclusions (written by all team members).

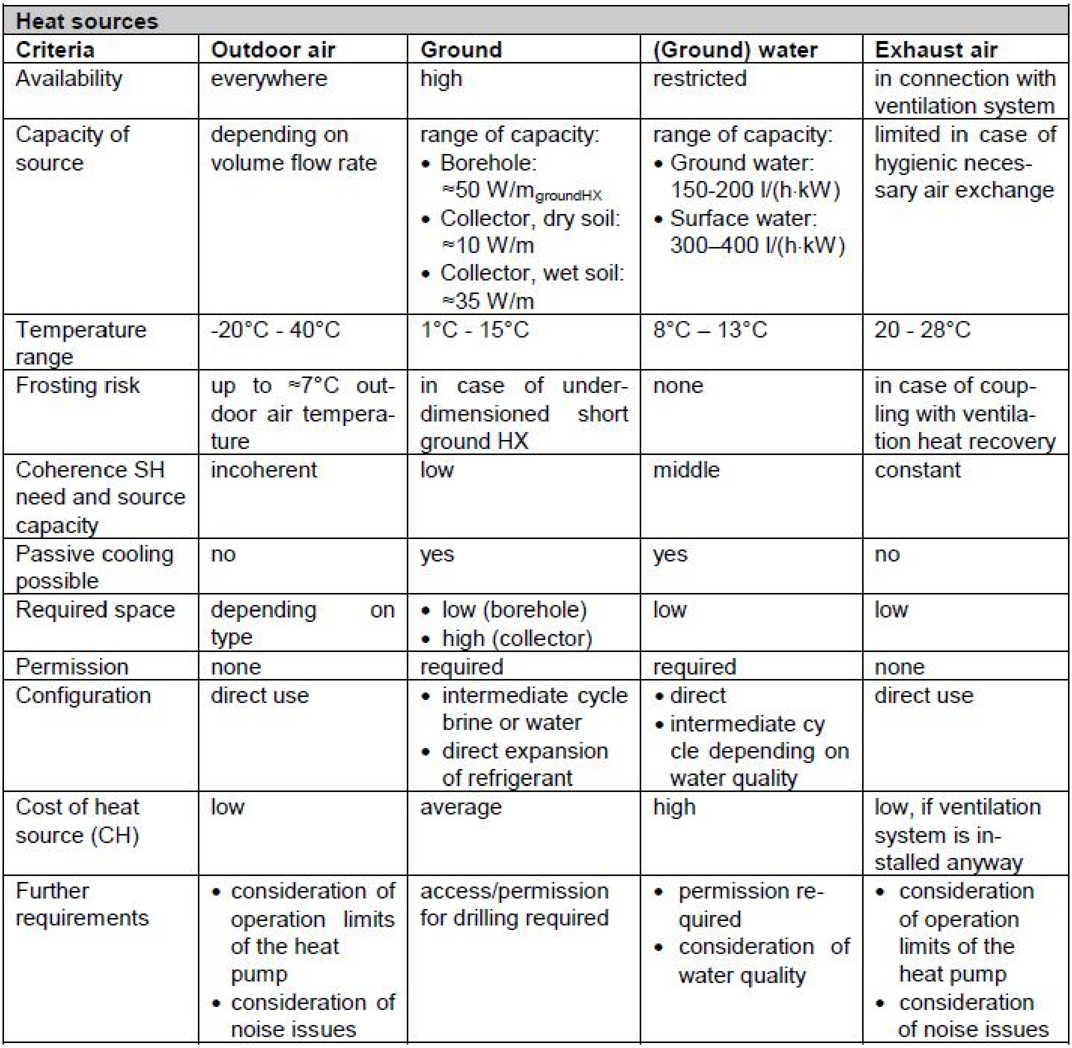
The HP4NZEB project has been implemented in parallel with project FInZEB where the common vision of the Finnish construction industry on the EU's requirements for near-zero energy buildings and suggestions on the energy efficiency requirements of different building types was created as a base for drafting the Finnish nZEB legislation. The preconditions for the calculation and some input data have been harmonized with the preconditions in FInZEB project in order to create commensurate results with FInZEB.

2. State-of-the art of existing concepts to reach nZEB utilizing heat pumps in residential buildings

2.1 Introduction

In low energy houses, loads change significantly, in particular the space heating needs are notably reduced, and the share of domestic hot water (DHW) increases. Moreover, mechanical ventilation may be required to guarantee the necessary air exchange due to the air-tight building construction, and in recent years market development show an increasing integration of a comfort cooling option in the system layouts. An overview of the characteristics of most common heat sources of heat pumps is given in Table 1. (Wemhoener, 2011d.)

Table 1. Characteristics of most common heat sources of heat pipes (Wemhoener, 2011d).



Heat sources				
Criteria	**Outdoor air**	**Ground**	**(Ground) water**	**Exhaust air**
Availability	everywhere	high	restricted	in connection with ventilation system
Capacity of source	depending on volume flow rate	range of capacity: • Borehole: ≈50 $W/m_{groundHX}$ • Collector, dry soil: ≈10 W/m • Collector, wet soil: ≈35 W/m	range of capacity: • Ground water: 150-200 l/(h·kW) • Surface water: 300–400 l/(h·kW)	limited in case of hygienic necessary air exchange
Temperature range	-20°C - 40°C	1°C - 15°C	8°C – 13°C	20 - 28°C
Frosting risk	up to ≈7°C outdoor air temperature	in case of under-dimensioned short ground HX	none	in case of coupling with ventilation heat recovery
Coherence SH need and source capacity	incoherent	low	middle	constant
Passive cooling possible	no	yes	yes	no
Required space	depending on type	• low (borehole) • high (collector)	low	low
Permission	none	required	required	none
Configuration	direct use	• intermediate cycle brine or water • direct expansion of refrigerant	• direct • intermediate cycle depending on water quality	direct use
Cost of heat source (CH)	low	average	high	low, if ventilation system is installed anyway
Further requirements	• consideration of operation limits of the heat pump • consideration of noise issues	access/permission for drilling required	• permission required • consideration of water quality	• consideration of operation limits of the heat pump • consideration of noise issues

In this chapter existing concepts to reach nearly zero energy level by utilizing heat pump solutions in residential buildings in Finland are introduced. Firstly, brief introduction to low-energy and nZEB building definitions is given. Then, both concepts analysed in literature and realized concepts are presented. In addition, concepts presented in finished IEA HPP Annex 32 and on-going IEA HPP Annex 40 are shortly introduced. This work focused on cold climate concepts.

2.2 Definitions

There is no global definition for low-energy buildings; however, different countries have national definitions for low-energy buildings. Low-energy building generally indicates a building that has a better energy performance than the standard alternative/energy efficiency requirements in building codes (EU, 2009). Low-energy buildings are buildings with significantly lower energy demand than buildings just meeting the mandatory building regulations (Blomsterberg et al., 2012). Typical criteria are 25–50% better than minimum requirements. Low-energy buildings typically use high levels of insulation, energy efficient windows, low levels of air infiltration and heat recovery ventilation to lower heating and cooling energy (EU, 2009). They may also use passive solar building design techniques or active solar technologies (EU, 2009). In Finland, a building is called low-energy building if the building energy usage is at least 40% better than of standard buildings (EU, 2009).

National definitions for very low-energy buildings exist in Finland, Sweden, Norway and Denmark (NorthPass, 2012). In Finland, definition of passive house is based on three characteristics: heating energy demand of spaces, total primary energy need of the building, and measured air tightness (Nieminen & Lylykangas, 2009). In Table 2, there is shown the Finnish passive house definitions for different parts of the country.

Table 2. The Finnish passive house definition (Nieminen & Lylykangas, 2009).

	Coastal area including major cities (Helsinki, Espoo, Vantaa & Turku)	**Central Finland**	**North-East Finland + Lapland**
Heating energy demand of spaces (kWh/m^2)	≤ 20	≤ 25	≤ 30
Primary energy demand (kWh/m^2)	≤ 130	≤ 135	≤ 140
Measured air tightness (1/h)	0.6	0.6	0.6

A zero-energy building is a building with zero net energy consumption and zero carbon emissions annually (Kilkis, 2007; Marszal et al., 2011). According to the European Directive on Energy Performance of Buildings (EPBD), “a nearly zero-energy building is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” (European Parliament, 2010). Net ZEBs have the dual role of being energy producers and consumers (“prosumers”) (Salom et al., 2014). In practice, zero-energy building produces as much energy as it consumes. There is no established definition of zero energy building, because there are several comparison principles for energy production and energy usage (Marszal et al., 2011; Sartori et al., 2012). The nearly zero-energy building standard still has to be defined in detail on both European and national level (Flodberg, 2012).

Zero energy buildings have two definitions: Net zero energy building (ZEB) and nearly net zero energy building (nZEB). ZEB has energy use of 0 kWh/(m^2,a) primary energy (Kurnitski, 2013a). The basic concept of a Net Zero Energy Building is that on-site renewable energy generation covers the annual energy load (Berggren et al., 2013). Nearly net zero energy building (nZEB) has technically reasonable achievable national energy use of > 0 kWh/(m^2,a) primary energy achieved with best practice energy efficiency measures and renewable energy technologies which may or may not be cost optimal (Kurnitski, 2013).

Many European countries calculate and compare primary energy instead of end-use energy. End-use energy is the final delivered energy to the building, required for heating, hot water, cooling and electricity, often also referred to as final energy. Primary energy is defined as the total amount of a natural resource needed to produce a certain amount of end-use energy, including extraction, processing, transportation, transformation and distribution losses down the stream (Sartori & Hestnes, 2007; Schimschar et al., 2011; Flodberg, 2012). The system boundary of zero energy building is explained in Figure 1.

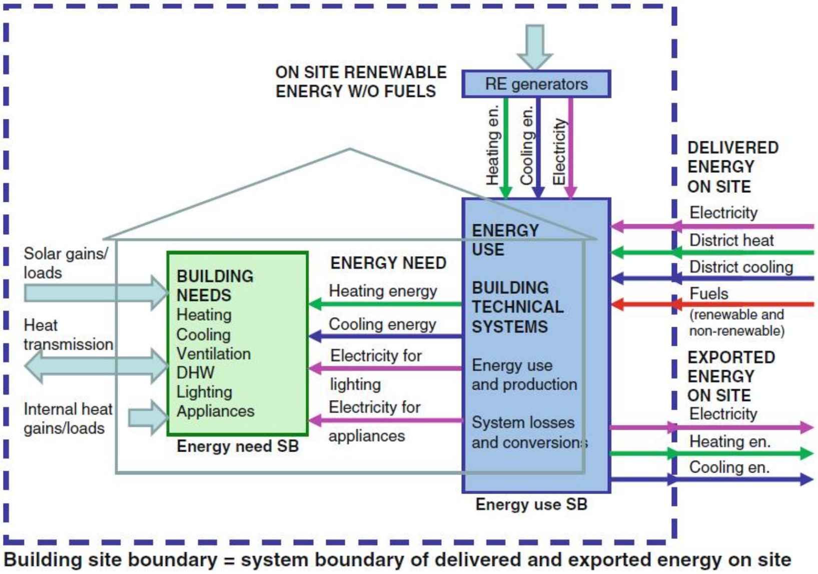


Figure 1. System boundaries for nZEB (Kurnitski, 2013a).

Also other ZEB definitions have been introduced. The +ZEBs produce more energy than their operational needs; Autonomous and NetZEBs produce as much energy as needed and NearZEBs less than needed. In addition, +ZEB category contains the sub-category of Life Cycle ZEB, which is the ZEB that takes into account its embodied energy when calculating the energy needs (Panagiotidou & Fuller, 2013).

2.3 nZEB concepts

Broadly speaking, ZEBs involve two strategies – minimizing the need for energy use in buildings through energy-efficient measures and adopting RETs (renewable energy and other technologies) to meet the remaining energy needs (Li et al., 2013). Even adopting the best energy-efficient measures available, energy will still be required to power the day-to-day running of a building.

In Europe a large variety of (non-governmental) concepts and examples for nearly zero-energy buildings exist (Hermelink et al., 2013). However, even the EPBD does not prescribe a uniform approach for implementing nearly zero-energy buildings and neither does describe the assessment categories in detail.

2.3.1 Concepts analysed in literature

Chwieduk (2012) presents heat pump fundamentals including principles, thermodynamic cycles, classification and renewable heat sources. The simplified idea of utilizing different renewable energy sources for a heat pump at a single-family house is presented in Figure 2. Combining solar thermal systems with heat pumps is popular in modern low-energy buildings, because such heating systems can supply all the heating demand and no auxiliary conventional heating is needed. Classification of solar-assisted heat pump (SAHP) systems is usually made because of the configuration of the system; mainly it is connected with the role of solar collectors and a heat pump for heating and the mutual interaction between them. The following categories can be classified: parallel, series, and dual-source SAHP systems.

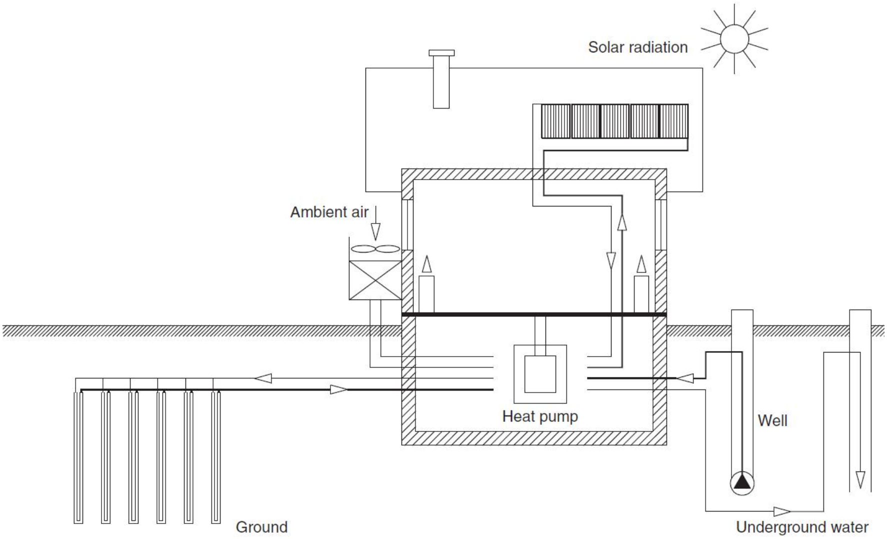


Figure 2. The idea of utilizing different renewable energy sources for a heat pump at a single-family house (Chwieduk, 2012).

Klein et al. (2014) investigated the feasibility of retrofitted hybrid heat pump systems for a German 1970s' single family home as well as a renovated variant of the same building. With the renovated building model, significantly higher efficiencies (SPF 3.88 vs. 3.34) and load factors (0.57 vs. 0.36) were achieved. Medium-sized heat pumps attained the highest SPF values. The volume of the buffer storage tank had very limited impact on system performance.

Thygesen & Karlsson (2013) simulated and analysed three different solar assisted heat pump systems in Swedish near zero energy single-family houses. The analysed systems were: a PV-system and a heat pump, a heat pump and a solar thermal system and a heat pump, a PV-system and a solar thermal system. The conclusion was that a PV system in combination with a heat pump was a superior alternative to a solar thermal system in combination with a heat pump.

Wiberg et al. (2014) investigated whether it is possible to achieve a net Zero Emission Building (nZEB) by balancing emissions from the energy used for operation and embodied emissions from materials with those from on-site renewables for a single-family house in the cold climate of Norway. The residential nZEB concept, mainly based on state-of-the-art-technologies on the market, is a so-called all-electric solution where essentially a well-insulated envelope is heated using a heat pump and where photovoltaic panels (PV) production is used to achieve the CO_{2eq} balance. The results showed that the single-family house had a net export to the electric grid with a need for import only during the coldest months.

Kurnitski et al. (2011) determined cost optimal and nZEB energy performance levels with model calculations. The procedure was tested with Estonian reference buildings and the results of the reference detached house were reported. The concepts also included cases for a ground source heat pump and an air to water heat pump. Cost optimal energy performance level of Estonian reference detached house was 110 kW h/(m^2,a) primary energy including all energy use with domestic appliances. The distance from cost optimal to nearly zero energy performance level was about 239 €/m^2 extra construction cost, i.e. about 20%. Numeric results provided in the study are to be treated as country specific ones applying for Estonian markets with local energy, material and labour prices.

Sarbu & Sebarchievici (2014) provided a detailed literature review of the ground-source heat pump (GSHP) systems, and their recent advances. The operation principle and energy efficiency of a heat pump were defined first. Then, a general introduction on the GSHPs and its development, and a detailed description of the surface water (SWHP), ground-water (GWHP), and ground-couplet (GCHP) heat pumps were performed. The review concentrates to GSHPs only and do not discuss the associated buildings and their properties at all.

Dar et al. (2014) investigated the flexibility of heat pump and photovoltaic combinations that they could offer to the grid. For the purpose, two different hydraulic configurations of heat pump with thermal energy storage and four different control strategies were analysed. The study considered a typical Norwegian detached single-family house whose thermal properties were adjusted to conform to Norwegian passive house requirements. The annual simulation of the house using normative internal gains, heating set-points and occupancy schedules led to space-heating needs of 18 kWh/m^2/y. Results showed that with a proper control: self-consumption of the building could be improved by almost 40%, the annual import bills could be reduced by 20% and hours of peak exchanges with the grid could be reduced by 30%. Overall, significant flexibility in Net-ZEBs is found achievable if a proper control is in place.

Georges et al. (2014) investigated the feasibility of the air heating (AH) concept in passive houses in Norway along with its challenges in terms of thermal dynamics: the magnitude of the AH temperature needed, the temperature difference between rooms, the impact of internal gains, the influence of thermal losses from ventilation ducts and the AH control. Results showed limitations related to a centralized AH as well as provide guidelines for a consistent AH design in cold climates. The paper does not directly deal with heat pumps but it could be applied in some heat pump concepts.

Vanhoudt et al. (2014) built a lab test setup to examine the potential of a heat pump for demand response purposes. With this test setup, it is possible to emulate the behaviour of a heat pump in a single Belgian household building equipped with either photovoltaic panels or a residential wind turbine (Figure 3). A market based multi-agent system was developed to control the active heat pump. The goal of this active control was to limit the peak power demands of the building and to maximise the self-consumption of the locally produced electricity. The tests showed that the current heat pump controller is able to shave the power consumption peaks of the building. In this way, active control of the heat pump can diminish extra investment costs for grid reinforcement. Active control also enables self-consumption of locally produced electricity. Any cost analysis of the analysed systems was not made.

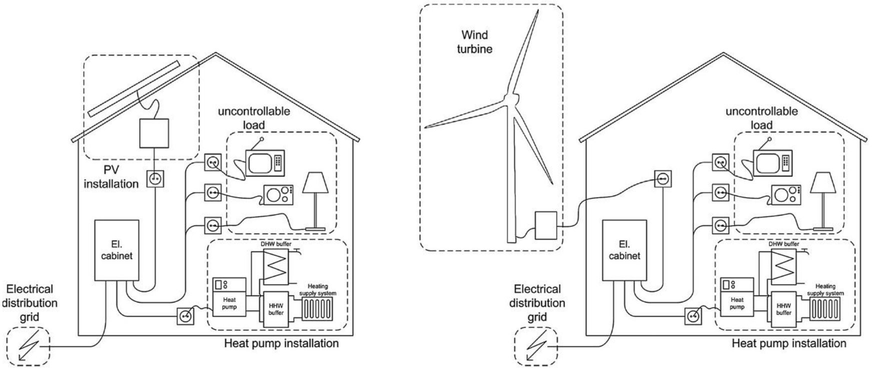


Figure 3. A schematic representation of the emulated buildings.

Marszal et al. (2012) deployed a life cycle cost analysis to define the cost-optimal combination between energy efficiency and renewable energy production for a multi-storey residential Net ZEB from private economy perspective in Denmark. Both on-site and off-site renewable supply options were taken into consideration. Generally from the private economic perspective, the off-site RES (renewable energy supply) options had lower life cycle cost than the on-site RES options. The analysis showed that from the private economy perspective and with the current technologies' cost and energy price, in 4 out of 5 on-site RES options investment in energy efficiency is more cost-effective decision than investment in renewable energy technologies. For the on-site and off-site RES options, the cost-effective system is PV-MiCHP(biomass)[1] and SofW-HP[2] or $El_{100\%}$-HP[3], respectively. Moreover, the SofW-HP and $El_{100\%}$-HP systems are also the cost-effective systems among all ten renewable energy supply options.

2.3.2 Realised concepts

A semidetached house with two apartments and a single-family house were built in two different Finnish locations (Kouhia et al., 2013). Both of them utilized heat pumps. After one year of monitoring, neither of them quite met the defined passive house targets and both of them had problems especially with control and tuning of the building services systems.

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[1] PV-MiCHP(biomass): Building with on-site photovoltaic installations and a micro Stirling biomass CHP. Biomass is transported to the building site.

[2] SofW-HP: Building owning share of a windmill farm and a ground source heat pump.

[3] $El_{100\%}$-HP: Building connected to power grid, which in 100% is supplied with renewable energy sources and a ground source heat pump.

The IEA5 Solar single-family house was built at the Pietarsaari housing fair in 1994, (Nieminen & Kouhia, 1997). The house fulfils the present Finnish passive house and very low-energy houses definitions. The performance of the house has been monitored until the end of 1996 and checked every year since 1996. The results prove that the yearly purchased energy consumption was only 7900 kWh, corresponding to 48 kWh/gross m^2. The average space heating energy consumption was 13 kWh/m^2. The heating system is based on a ground source heat pump with a capacity of 8 kW that is supported by a roof integrated 10 m2 solar thermal collector system. Heat from the 3 m^3 storage tank is distributed to the rooms with a low-temperature floor heating system. The 48 m^2 photovoltaic system consists of 45 solar panels (amorphous silicon modules) with 2 kWp output power.

Salom et al. (2014) monitored six buildings representing different building typologies in different climates and renewable energy technologies. Not all of them fulfilled the zero energy standards. Four of the buildings were single-family houses in Denmark and Sweden and they all included heat pumps. The report gives only a limited description of the actual systems. The most relevant ones are the EnergyFlexFamily house in Denmark and the Finnängen house in Sweden.

The EnergyFlexFamily house (Salom et al., 2014) in Denmark is better than the Low E class 1 defined in the former Danish Building Code from 2008. The annual energy demand for space heating, ventilation, domestic hot water (DHW) and building-related electricity (not including energy for the household) is less than 30 kWh/m². With the PV production, EnergyFlexFamily is energy neutral over the year including the demand for electricity of the household and an electric vehicle. The heating system consists of two heat pumps and a solar heating system. One of the heat pumps produces space heating via the floor heating system. The other heat pump is located in series with the passive heat exchanger of the ventilation system. This heat pump both preheats fresh air and DHW. The solar heating system preheats primarily DHW but may also deliver space heating. The efficiency of the passive heat exchanger is around 85%.

The Finnängen house is the first renovated plus-energy house in Sweden. Finnängen was built in 1976 (Myresjöhus) and renovated in 2010 and added an extension. The building has a wooden structure with brick decoration. The walls were clad with air-tightness layer, external insulation and plaster. The roof tiles were exchanged to steel roof, photovoltaic and solar-thermal. The building envelope can now be classified as a passive-house according to the FEBY criteria (air-tightness 0.13 ACH, U-value roof 0.07 W/m^{2}K wall 0.10 W/m^{2}K, new ground 0.12 W/m^{2}K), except for the old house ground that was not refurbished. Space heating is supplied through hydronic floor heating and radiator system which is heated by solar thermal and horizontal ground source heat pump system. In 2011 the house used 7202 kWh (28.6 kWh/m^2) totally, out of which ~3000 kWh (12 kWh/m^2) is used in the heat pump, ~1000 (4 kWh/m^2) is used for ventilation and heating circulation. The remaining ~3000 kWh (12 kWh/m^2) is household electricity. The power supply through the photovoltaic system was 8356 kWh in 2011, thus a surplus of 1154 kWh. (Salom et al., 2014.)

Molin et al. (2011) presented results and an evaluation of a newly built house in an area with passive houses in Linköping, Sweden. Nine passive houses were built with the aim to be energy efficient, with an annual space heating demand of 21 kWh/m^2, and at the same time to have the same visual appearance as any other building in the surrounding area. The buildings are heated with district heating but heat pump solutions could be applied as well. Some examples of potential improvements for future, similar buildings were found including deficiencies in the insulation of the wall and the roof creating a cold bridge, the insulation of ducts inside the building, the plastic diffusion stops showed signs of worse performance after only one year, and the control of the heat exchanger for sanitary hot water (SHW).

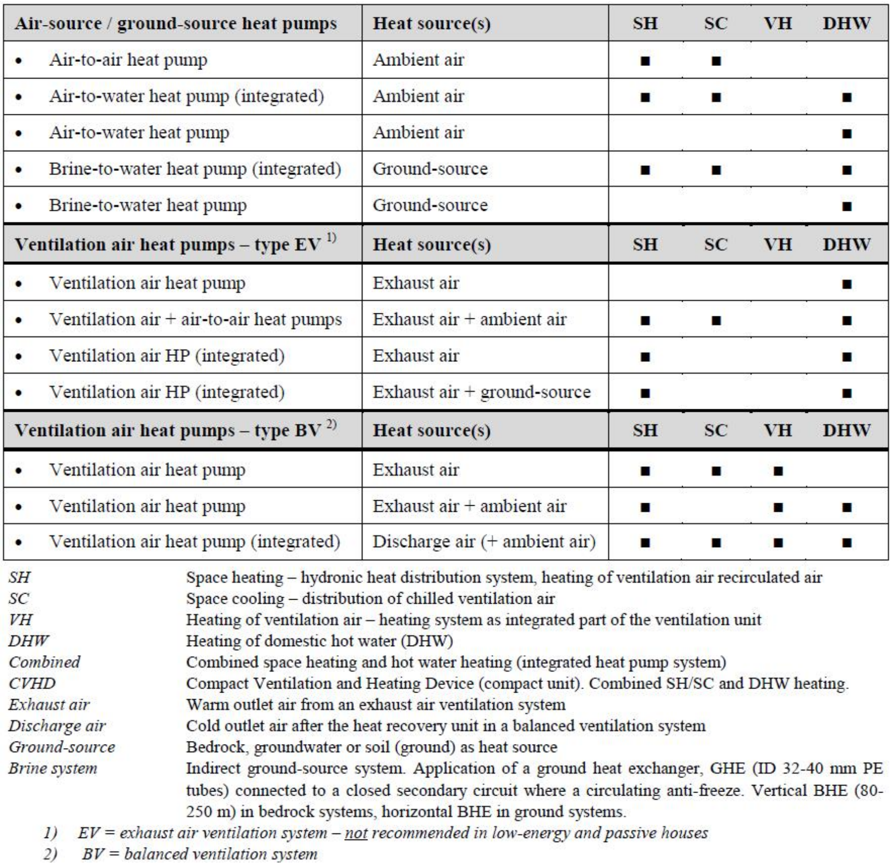
2.3.3 Concepts from IEA HPP Annex 32

Annex 32 in the Heat Pump Programme (HPP) of the International Energy Agency (IEA) entitled "Economical heating and cooling systems for low energy houses" started in 2006 with the participating countries Austria, Canada, France, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland (operating agent) and the USA in order to support the further development of heat pump systems for the use in low- and ultra-low energy buildings and to prove the feasibility and performance benefit of new and marketable systems (Wemhoener, 2011a). Focus of the R&D in the frame of Annex 32 was on the one hand the development of new integrated heat pump concepts including lab-testing, simulation and assessment of respective prototypes.

While Annex 32 concentrated on system integration, current trends also include a building integration, using the building façade and roof as parts of the system technology (Wemhoener, 2011a). This approach opens the scope to even higher integration of the system and building envelope technologies, which may lead, by use of further synergies, to even more comprehensive and high-quality, high performance and low cost sustainable building concepts.

Table 3 gives an overview of heat pump systems of current interest in low-energy and passive houses in Nordic climates and especially in Norway. Justo Alonos & Stene (2010) describe different systems more in detail according to function, design, heating and cooling capacity, typical Seasonal Performance Factor (SPF), heat distribution and impact on the indoor environment.

Table 3. Classification of commercially available heat pump systems for low-energy and passive houses in Nordic climates (Justo Alonso & Stene, 2010).



Air-source / ground-source heat pumps	**Heat source(s)**	**SH**	**SC**	**VH**	**DHW**
• Air-to-air heat pump	Ambient air	■	■		
• Air-to-water heat pump (integrated)	Ambient air	■	■		■
• Air-to-water heat pump	Ambient air				■
• Brine-to-water heat pump (integrated)	Ground-source	■	■		■
• Brine-to-water heat pump	Ground-source				■
Ventilation air heat pumps – type EV [1)]	**Heat source(s)**	**SH**	**SC**	**VH**	**DHW**
• Ventilation air heat pump	Exhaust air				■
• Ventilation air + air-to-air heat pumps	Exhaust air + ambient air	■	■		■
• Ventilation air HP (integrated)	Exhaust air	■			■
• Ventilation air HP (integrated)	Exhaust air + ground-source	■			■
Ventilation air heat pumps – type BV [2)]	**Heat source(s)**	**SH**	**SC**	**VH**	**DHW**
• Ventilation air heat pump	Exhaust air	■	■	■	
• Ventilation air heat pump	Exhaust air + ambient air	■		■	■
• Ventilation air heat pump (integrated)	Discharge air (+ ambient air)	■	■	■	■

SH	Space heating – hydronic heat distribution system, heating of ventilation air recirculated air
SC	Space cooling – distribution of chilled ventilation air
VH	Heating of ventilation air – heating system as integrated part of the ventilation unit
DHW	Heating of domestic hot water (DHW)
Combined	Combined space heating and hot water heating (integrated heat pump system)
CVHD	Compact Ventilation and Heating Device (compact unit). Combined SH/SC and DHW heating.
Exhaust air	Warm outlet air from an exhaust air ventilation system
Discharge air	Cold outlet air after the heat recovery unit in a balanced ventilation system
Ground-source	Bedrock, groundwater or soil (ground) as heat source
Brine system	Indirect ground-source system. Application of a ground heat exchanger, GHE (ID 32-40 mm PE tubes) connected to a closed secondary circuit where a circulating anti-freeze. Vertical BHE (80-250 m) in bedrock systems, horizontal BHE in ground systems.

1) EV = exhaust air ventilation system – not recommended in low-energy and passive houses
2) BV = balanced ventilation system

Extensive field tests accomplished in IEA HPP Annex 32 of above 100 heat pumps installed in low energy houses in Germany and about 10 heat pumps in Austria confirmed that the average performance of air-source heat pumps were in the range of about 2.8 and brine-to-water heat pumps in the range of 4 (Wemhoener, 2011b). So, virtually all measured heat pump systems in low energy house fulfilled the criteria of the European RES Directive to be considered as renewable energies, which is currently a minimum Seasonal Performance Factor of 2.63.

Concerning the system configurations, field results confirmed that modular systems with a rather complex hydronic configuration often do not reach the expected performance. Therefore, the system configuration shall be chosen carefully (Wemhoener, 2011b). Despite this generally good performance in the field operation, also malfunctions and optimisation potentials were encountered. Average temperatures of the system confirmed that performance of the heat pump systems still have performance improvements by lowering the temperature lift and improve design and system layout.

2.3.3.1 EcoTerraTM Home

EcoTerra^{TM} Home is a two-storey detached home of a 234 m^2 floor heating area located in the Eastern Canadian province Québec (Wemhoener, 2011c). The core of the building technology is the 3 kWp building integrated solar PV/thermal (BIPV/T) system, the heat pump and the thermal storage. BIPV/T compared to stand-alone PV or solar thermal systems has the advantage of simultaneous production of heat and electricity.

By a roof top ventilation outdoor air is drawn behind the PV-laminate and heats-up while cooling the PV system to achieve a better electric efficiency. The heated air serves various functions inside the houses, primarily for clothes drying whenever the exiting air temperature is above 15°C. If temperature is below this limit, an air-to-water heat exchanger serves to preheat the DHW or the air is ventilated through a hollow floor slab to store the heat in the concrete. (Wemhoener, 2011c.)

The EcoTerra house is heated or cooled by a two-stage geothermal heat pump (nominal COP at B0/W35 of 4.3). In addition to space heating through a ducted forced air system, the heat pump assists water heating with a desuperheater. Figure 4 depicts the system concept of the EcoTerraTM house. A further component of the building technology is a waste water heat recovery integrated in the drain. Therein, a heat exchanger coil is placed around the waste water pipe. (Wemhoener, 2011c.)

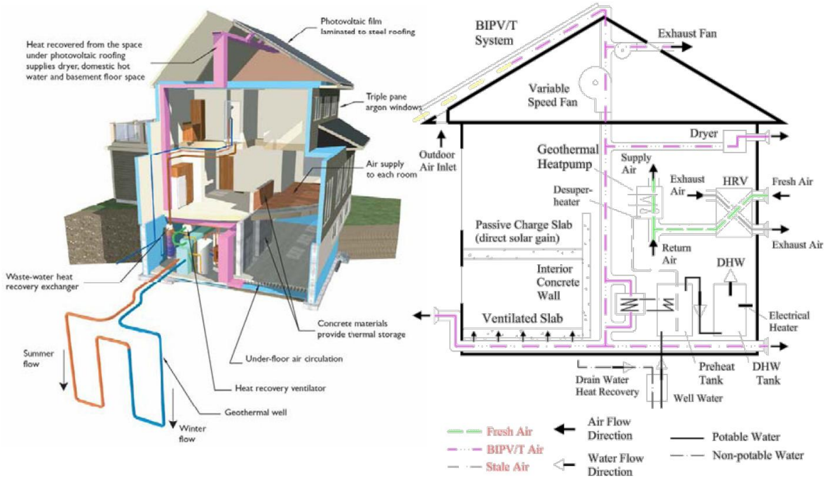


Figure 4. System concept of the EcoTerra^{TM} Home in Eastman (Wemhoener, 2011c).

2.3.3.2 Alstonvale Net Zero Energy House

Pogharian et al. (2008) presented the Alstonvale Net Zero Energy House (AN-ZEH), which strives towards net zero energy lifestyle by integrating efficient on-site food production methods to further reduce the household's energy footprint, and incorporating, as the primary energy generation system, a 7 kW, building integrated, photovoltaic/thermal (BIPV/T) system on its roof to generate both electricity and thermal energy (Figure 5), and of which 1.5 kW is dedicated to balancing the local transportation needs of the household, assuming an electric drive vehicle.

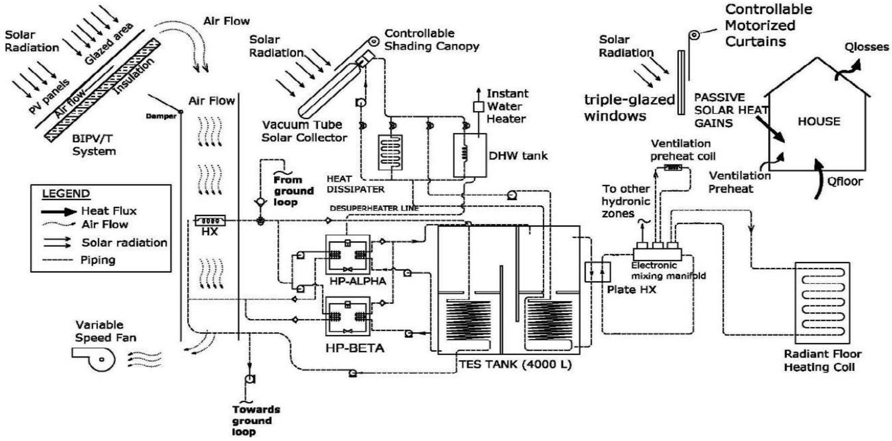


Figure 5. The configuration of the AZEH.

The heat pump system is the most important piece of equipment of the ANZEH. The heat pump chosen had to deliver the required peak heating load (estimated at 12–13 kW). It also had to operate at partial load under varying flow rates and temperatures, with a good coefficient of performance (COP) preferably above 5. (Pogharian et al., 2008.)

2.3.4 Concepts from IEA HPP Annex 40

The IEA HPP Annex 40 "Heat pump concept for Nearly Zero Energy Buildings" deals with the application of heat pumps as core component of the HVAC system for Nearly or Net Zero energy buildings (NZEB) (Baxter & Sikes, 2013). The Task 1 is to give an overview on NZEB on the national level of the participating countries. At the time when writing this report, only two country reports from Task 1 were available – Norway 2007 (Justo Alonso & Stene, 2013) and USA (Baxter & Sikes, 2013). In the following, from them the most relevant heat pump concepts for cold climates are presented.

2.3.4.1 NorOne – the first certified Norwegian passive house & A/W heat pump

The NorOne residence in Sørum, Southern Norway, was the first single-family house in Norway to be certified by the German Passivhaus-Institut in Darmstadt in 2007 (Justo Alonso & Stene, 2013). The 340 m² passive house is equipped with a number of heat recovery and heating systems (Figure 6).

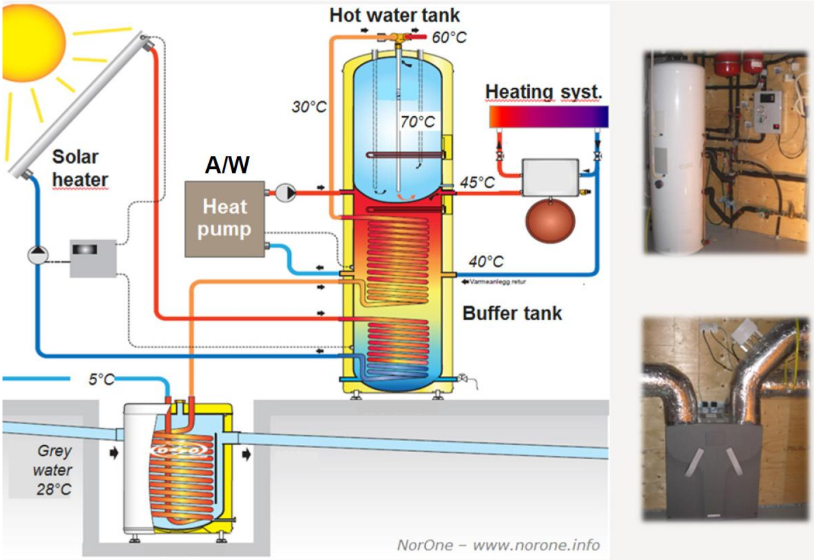


Figure 6. A principle sketch of the heating system including the 5 kW air-to-water heat pump, the grey water heat recovery unit and 6 m² solar collector (www.norone.info).

At the design outdoor temperature (-25 °C), the ground heat exchanger preheats the inlet air by as much as 20 °C. The city water, which circulates in a coil heat exchanger inside a double-shell buffer tank, is preheated to about 35–40 °C by the heat pump unit. An electric immersion heater in the hot water tank reheats the water to the required temperature (min. 65 °C). This kind of integrated heat pump design is not recommended in passive houses since it only covers approx. 50% of the annual domestic hot water (DHW) heating demand, and the supply water temperature from the condenser is maintained at 40–45 °C the entire year. (Justo Alonso & Stene, 2013.)

In 2011 the heat supply from the grey water heat exchanger and the solar heater system was 600 kWh (1,000 kWh) and 1,400 kWh (3,400 kWh), respectively (Justo Alonso & Stene, 2013). ThE-values in the brackets show the calculated (expected) heat supply. The measured total annual energy use was 60 kWh/m², while the annual space heating demand was 7,200 kWh (21 kWh/m²).

2.3.4.2 The Zijdemans Residence – W/W Heat Pump

A 2.9 kW prototype water-to-water heat pump for combined space heating and hot water heating was installed in a 170 m^2 single-family passive house in Flekkefjord (Southern Norway) in 2007. The heat pump unit utilizes lake water as heat source, and propane (R290) is used as working fluid. The heat pump is optimized for energy-efficient DHW and low-temperature space heating. Regarding the DHW heating the heat pump is equipped with a suction gas heat exchanger that increases the heating capacity and temperature of the suction gas as well as a desuperheater for reheating of DHW. Since DHW is preheated by the condenser and reheated by a desuperheater, the system design is denoted "two-stage DHW heating". The main advantage of this system is that the heat pump can cover the entire DHW heating demand at the required temperature (65 °C) without reheating by electric immersion heaters, and still maintain a relatively low condensation temperature. The heat pump is operated in "space heating mode", "DHW heating mode" or "combined heating mode". The average COP for the entire system is 3.1. (Justo Alonso & Stene, 2013.)

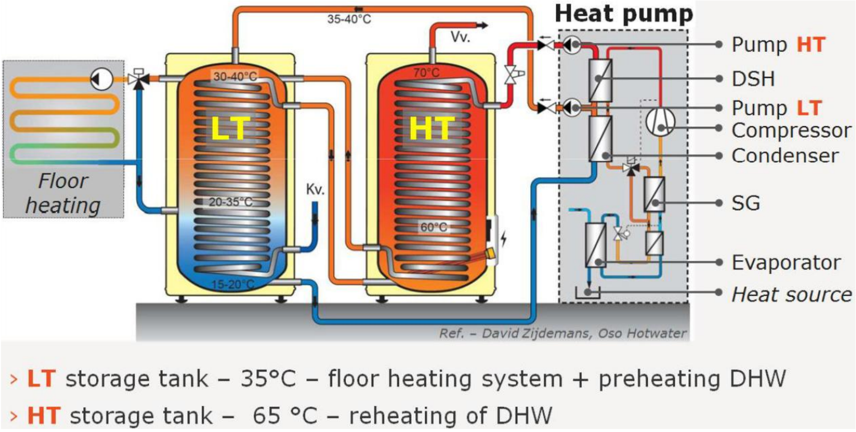


Figure 7. Principle sketch of the 2.9 propane water-to-water heat pump system comprising a 2-stage DHW system with two storage/buffer tanks (Justo Alonso & Stene, 2013).

2.3.4.3 Tveitta Borettslag (Block of Flats) – Heat Pump Water Heater

The three block of flats in Tveitta Borettslag (housing cooperative) in Oslo was built in 1969 and have 819 apartments (Justo Alonso & Stene, 2013). The buildings have recently been refurbished for €40 million, and the specific annual energy use has dropped from 280 to 140 kWh/(m^2a). The building does not meet the Norwegian passive house standard but the hot water heating technology applied represents the most energy efficient and environmentally benign technology for hot water heating.

Each block of flats has a centralized hot water heating system, and the electric immersion heaters have been replaced by heat pump water heaters using carbon dioxide (CO_2, R744) as the working fluid. Each CO_2 heat pump unit has a nominal heating capacity of approx. 100 kW, and the units have been manufactured by Green&Cool in Sweden. The installation is the first large-capacity CO_2 heat pump system in Norway. (Justo Alonso & Stene, 2013.)

The block of flats have an exhaust air ventilation system without heat recovery, and the heat pumps utilize 22 °C exhaust air as heat source. Each brine-to-water heat pump unit is connected to two brine-to-air heat exchangers by means of a secondary circuit. The set-point for the hot water temperature is about 70 °C. However, due to the unique properties of the CO_2 heat pump cycle, the heat pumps can supply water up to approx. 95 °C, i.e. no reheating with electric immersion heaters is required. The average measured COP is above 4. (Justo Alonso & Stene, 2013.)

2.3.4.4 NIST Net Zero Energy Residential Test Facility (NZERTF)

The Net Zero Energy Residential Test Facility, located at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD, USA was designed to ensure that it would meet current and future measurement science needs towards net zero energy homes (NIST, 2012). This 372 m^2 residential building was constructed on the NIST campus and officially opened in summer 2012 (Baxter & Sikes, 2013). The building technical systems include for example a Photovoltaic System and a Solar Thermal/Heat Pump Water Heating System. An overview of the building systems can be seen in Figure 8.

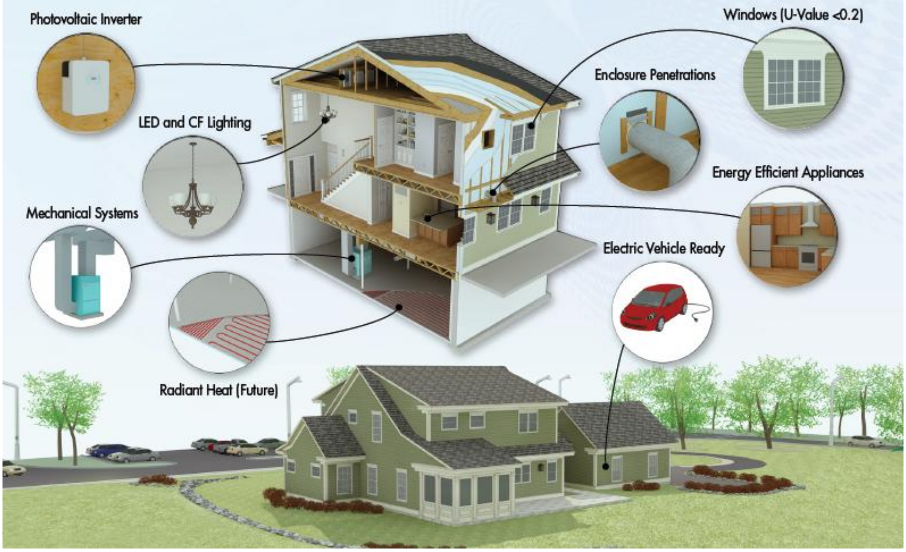


Figure 8. An overview of the key features of the NIST Net Zero Energy Residential Test Facility (NIST, 2012).

3. Description of the studied nZEB buildings and the key factors concerning building energy calculation

3.1 Introduction

The description of the key factors concerning building energy calculation is presented in this chapter. The data includes building envelope structures, the building materials and their features, internal heat gain loads, hot domestic water usage and schedule and other initial data. The detailed data of each case is presented in Appendixes B–D.

The researched buildings are **a new detached house, a new apartment building and an existing apartment building, built in the 1960s**. The data of the new detached house and the 1960s apartment building are based on model buildings defined in a previous Cost Optimal project (Vainio et al., 2012) that has already been completed. The data of the new apartment building is based on a real building that is under construction. The usage profiles and specific powers of the internal heat gains for lighting, persons and household equipment are based on the Finnish building code part D3 (2012). The usage profile of the domestic hot water is based on measured DHW consumption of a Finnish apartment building.

The simulation tool was IDA Indoor Climate and Energy (IDA ICE, http://www.equa.se/en/ida-ice). It is a whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy consumption of the entire building.

3.2 Energy calculation data of the new detached house

The calculation data for the energy simulation model of the new detached house is presented in this section. The detailed data is in Appendix B.

3.2.1 Building’s location and the description of the building

Table 4. Building’s location and general information.

General information	Description / Value	Notifications
Location	Helsinki	60° 19’ north latitude 24° 58’ east longitude
Weatherr	TRY2012	Helsinki-Vantaa test year weather data
Environment	Urban environment	
Total inner dimensions of the building		
Width	8.8 m	From inner surface to the inner surface of the external walls
Length	10.6 m	From inner surface to the inner surface of the external walls
Floor height	2.75 m	
Room height	2.60 m	
Outer dimensions of the building		
Width	9.9 m	From outer surface to the outer surface of the external walls
Length	11.8 m	From outer surface to the outer surface of the external walls
Areas and volumes		
Heated net floor area	180.0 m^2	
Gross floor area	233.6 m^2	
The total area of the building envelope	383.2 m^2	
The heated volume of the building	468.1 m^3	

3.2.2 Building’s geometry and layout

The main geometry of the building and the layout of the floor plans are shown in Figures 9–11.

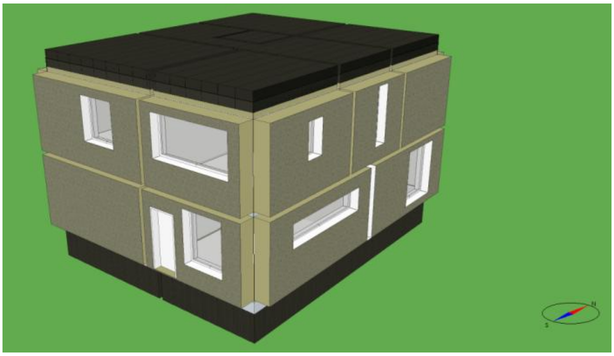


Figure 9. The geometry of the detached house building.

Figure 10.The floor layout of the first floor.

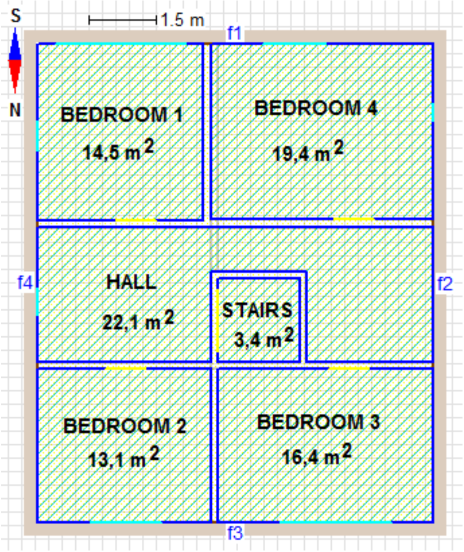


Figure 11. The floor layout of the second floor.

3.3 Energy calculation data of the new apartment building

The calculation data for the energy simulation model of the new detached house is presented in this section. The detailed data is in Appendix C.

3.3.1 Building’s location and the description of the building

Table 5. Building’s location and general information.

General information	**Description / Value**	**Notifications**
Location	Järvenpää	60° 28' 0" North latitude 25° 6' 0" East longitude
Weather	TRY2012	Helsinki-Vantaa test year weather data
Environment	Urban environment	
Total inner dimensions of the building		
Width		From inner surface to the inner surface of the external walls
Length		From inner surface to the inner surface of the external walls,
Floor height	3.0 m	According to the sectional drawing (A-A) of the building
Room height	2.6 m	According to the sectional drawing (A-A) of the building
Outer dimensions of the building		
Width	44.2 m	Maximum from outer surface to the outer surface of the external walls, **not a rectangle shape,** According to the floor plan of the building
Length	17.8 m	Maximum from outer surface to the outer surface of the external walls, **not a rectangle shape**, According to the floor plan of the building
Areas and volumes		
Heated net floor area	3098.5 m^2	According to the ground plan of the building
Gross floor area	3959 m^2	According to the ground plan of the building
Gross floor area of main storeys	696 m^2	According to the ground plan of the building (storeys 2–4; cellar, and storeys 1 and 5 are a bit different)
The total area of the building envelope	1908.8 m^2	123.95 m (building circle) *15,4 m (building height excluding cellar)
The heated volume of the building	8056.1 m^3 (13233 m^3 according to the building specification)	heated net floor area (3098,5 m^2) * room height (2,6 m)

The building has 5 storeys and a cellar, which includes a parking hall.

3.3.2 Building’s geometry and layout

The main geometry of the building and the layout of the floor plans are shown in Figures 12–14.

Figure 12. The geometry of the new apartment building.

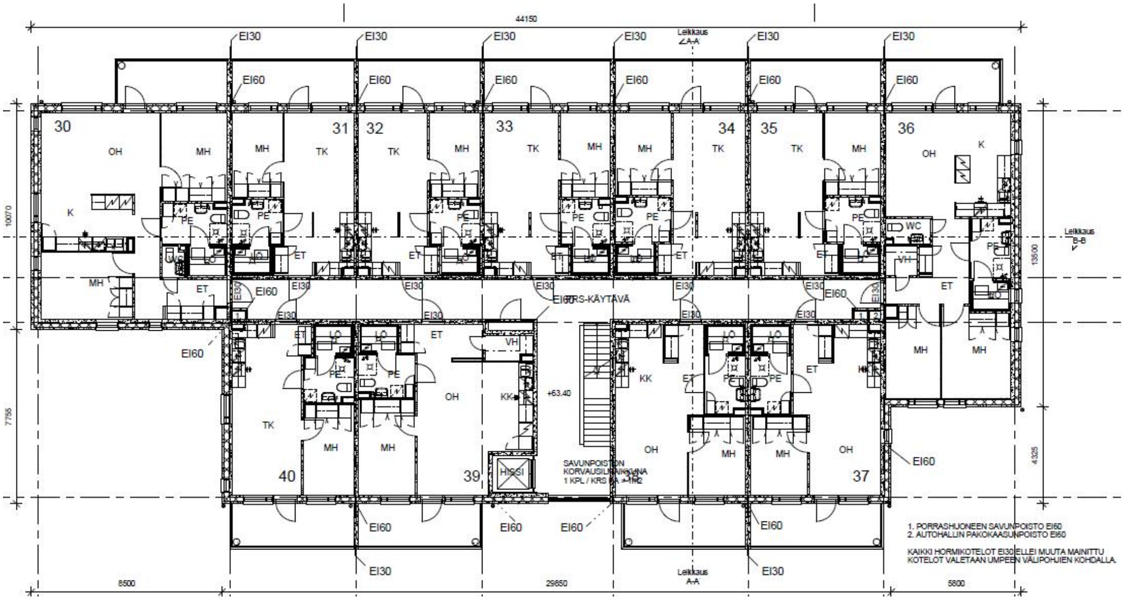


Figure 13. The floor layout of the apartment floors (4th storey).

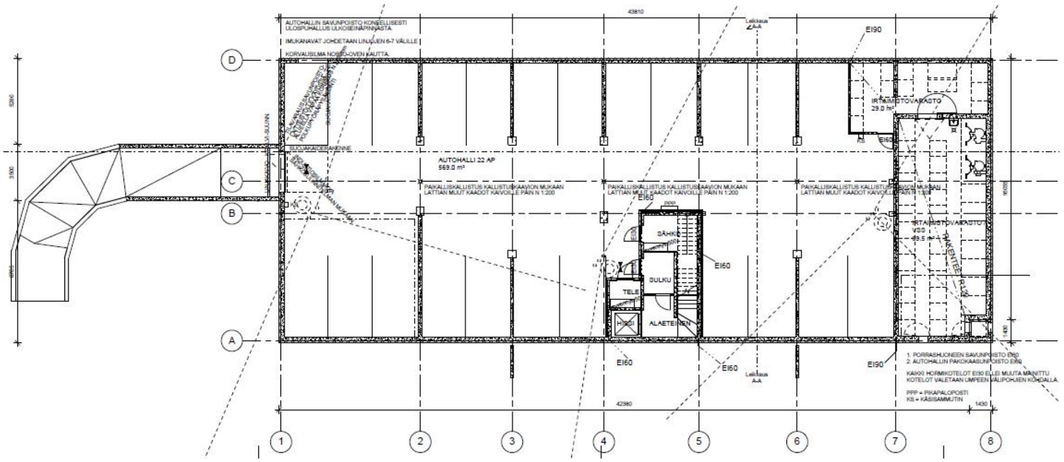


Figure 14. The floor layout of the basement floor, which is used as a parking hall.

3.4 Energy calculation data of the 1960s apartment building

The calculation data for the energy simulation model of the existing 1960s apartment building is presented in this section. The detailed data is in Appendix D.

3.4.1 Building's location and the description of the building

Table 6. Building's location and general information.

General information	Description / Value	Notifications
Location	Helsinki	60° 19' north latitude 24° 58' east longitude
Weather	TRY2012	Helsinki-Vantaa test year weather data
Environment	Urban environment	
Total inner dimensions of the building		
Width	12.0 m	From inner surface to the inner surface of the external walls
Length	50.0 m	From inner surface to the inner surface of the external walls
Floor height	3.00 m	
Room height	2.60 m	
Outer dimensions of the building		
Width	12.6 m	From outer surface to the outer surface of the external walls
Length	50.6 m	From outer surface to the outer surface of the external walls
Areas and volumes		
Heated net floor area	3697 m^2	
Gross floor area	4463 m^2	
The total area of the building envelope	3586 m^2	
The heated volume of the building	10 497 m^3	

3.4.2 Building’s geometry and layout

The main geometry of the building and the layout of the floor plans are shown in Figures 15–17.

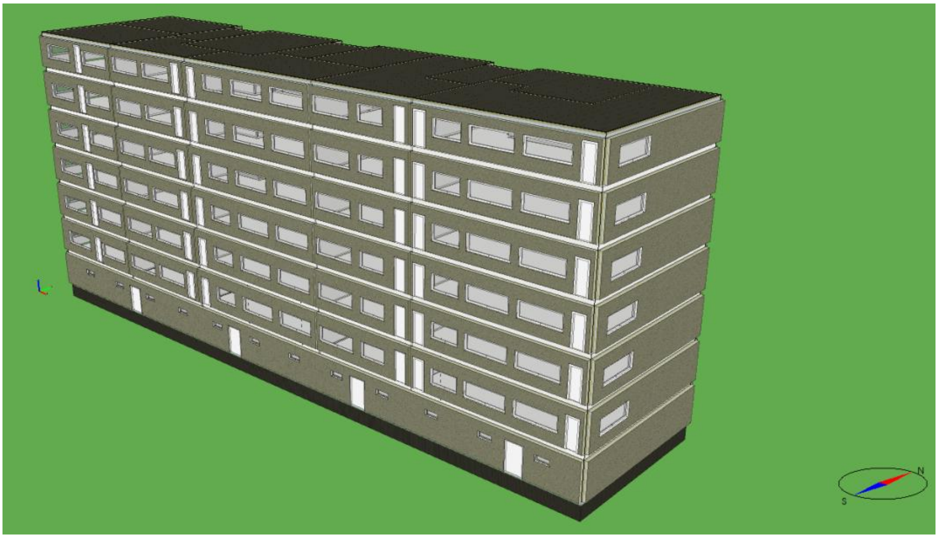


Figure 15. The geometry of the 1960s apartment building

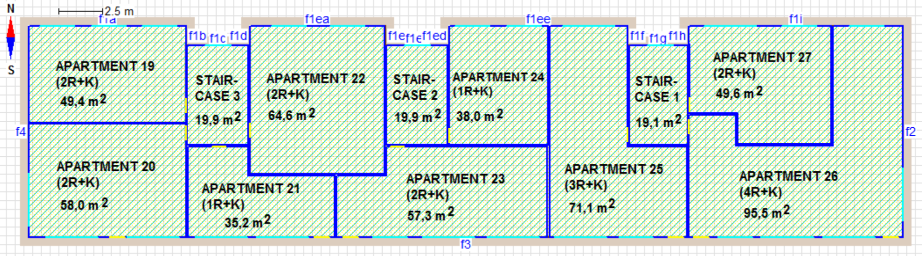


Figure 16. The floor layout of the apartment floors (r = room, k = kitchen).

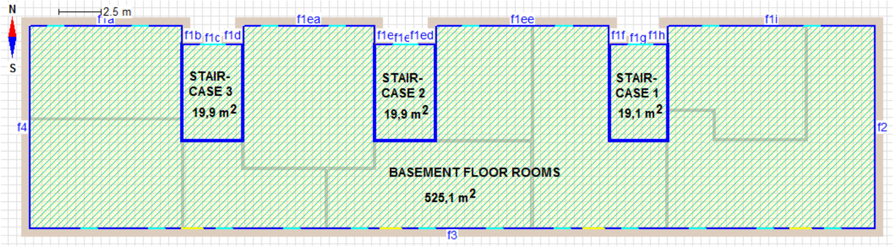


Figure 17. The floor layout of the basement floor.

4. The studied system concepts of the nZEB buildings

4.1 General information

The different system concepts utilizing heat pumps that were used in the energy simulation and calculation are presented in this chapter. There are three different system concepts for the new apartment building and four different system concepts for the new detached house and for the 1960s apartment building. The total number of different system concepts is eleven and the total number of different simulation cases is 44, because the system concepts are simulated both without and with the solar energy systems, using a few different dimensioning options for the solar systems.

The idea of the selection of different system concepts was to make a clear difference between different factors that influence to the energy efficiency of the building. This was done by choosing a different kind of heat pump for system concepts and by adding solar energy production, electricity and thermal, along with the heat pump. The building's envelope, exterior structures and their insulation levels were fixed and kept constant in all system concepts and simulation cases and the cases concentrate on the energy efficiency of the heat pump and HVAC systems. The selection of different system concepts for different nZEB buildings was mainly based on the results of previous research projects concerning energy efficiency of buildings and also on the expertise of the project and steering groups of the HP4nZEB project.

4.2 Simulation method

Dynamic energy performance simulations were carried out using IDA-ICE 4.6.1 building simulation software in this study. This software allows modelling of the multi-zone building, HVAC-systems, internal and solar loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and mass flows. It is a suitable tool for the simulation of thermal comfort, indoor air quality, and energy consumption in all kinds of buildings. A modular simulation environment, IDA-ICE, has originally been developed by the Division of Building Services Engineering, KTH, and the Swedish Institute of Applied Mathematics, ITM (Sahlin, 1996; Björsell et al., 1999). IDA-ICE has been tested against measurements for example in Moinard et al. (1999) and several independent inter-model comparisons have been made (Achermann & Zweifel, 2003). In the comparisons, the performance of radiant heating and cooling systems using five simulation programs (CLIM2000, DOE, ESP-r, IDA-ICE and TRNSYS) were compared and IDA ICE showed a good agreement with the other programs. IDA-ICE was validated according to the European Standard prEN 13791 by Kropf and Zweifel (2001). The IDA-ICE software has been successfully used and validated in numerous studies before, for example in Travesi et al. (2001) and Loutzenhiser et al. (2007).

The validation studies and the successful use in various studies before are the main reasons why IDA-ICE was selected as a simulation tool of this study. Furthermore, the recent implementation of the ESBO Plant model in IDA-ICE made detailed energy simulation of heating system possible. Detailed simulation of heat pumps, hot water storage tank and solar-based energy production was performed by means of ESBO Plant model in this study. Main features of the ESBO plant energy production system are presented in Figure 18.

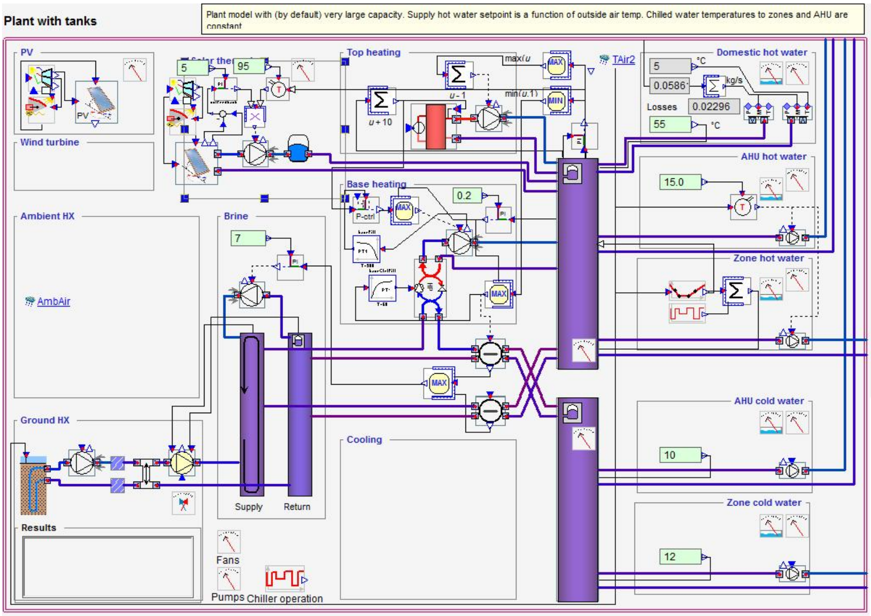

Plant model with (by default) very large capacity. Supply hot water setpoint is a function of outside air temp. Chilled water temperatures to zones and AHU are constant

Figure 18. Main features of the ESBO Plant model with ground source heat pump and boreholes, heat storage tank, solar collectors and PV-electricity production system.

Real room heating and cooling units with data of existing products, such as water radiators, floor heating, chilled beams and fan coil was used to simulate heating and cooling energy consumption. Furthermore, losses of the heat distribution system were simulated in IDA-ICE.

4.3 The target levels for energy performance in different building types

According to the Finnish building code, energy performance of buildings is calculated by means of E-value, which is total delivered energy consumption of the building weighted by the energy carrier factors (D3, 2012). The official Finnish definition of E-value is

$$E_{D3(2012)} = \frac{\sum_i \left(E_{DE,i} \cdot f_{DE,i}\right)}{A_{net}} \qquad (1)$$

where

$E_{DE,i}$ = delivered energy i (district heating, electricity, fuels used for energy production of the building and district cooling), kWh/a
$f_{DE,i}$ = weighing factors of delivered energy form i (0,7 for district heating, 1,7 for electricity, 1,0 for fossil fuels, 0,5 for renewable fuels, 0,4 for district cooling), -
A_{net} = heated net floor area of the building, m^2.

There is no official definition for the nZEB level of buildings in the Finnish building code yet. A proposal of the Finnish nZEB levels was done in FInZEB-project in 2015 (see Table 7).

Table 7. The current Finnish requirement levels of E-value for new buildings and the proposed requirement levels of Finnsh nZEB-buildings by the FInZEB-project (Reinikainen et al., 2015).

Building type	Current max. E-value of new buildings, $E_{D3(2012)}$, kWh/m²,a	Proposal for the nZEB level of E-value, kWh/m²,a
Detached house[1]	160…204	120…204
Apartment building	130	116
Office	170	90
School	170	104
Kindergarten	170	107
Commercial building	240	143
Sports hall	170	115
Commercial accom-	240	182

modation building		
Hospital	450	418

[1] The requirement levels depend on the heated net floor area of the detached house. The levels are presented for the houses with 270–100m² floor area.

One of the most important goals of this research project was to define and clarify the role of the heat pumps in nZEB building industry and to offer a realistic view what is the reasonable and cost-effective nZEB level in the Finnish climate. For this reason, the target level for energy performance ($E_{D3(2012)}$) was set to 0 kWh/m^2 for all three building types of this project. By doing this, one could study what energy performance level can be achieved in all three different building types and what could be the cost-optimal level. In this study, the E-value is calculated with its current definition (Equation 1) and also with a definition by REHVA (Kurnitski, 2013b) which takes exported energy into account (Equation 2).

$$E_{Exp} = \frac{\sum_i \left(E_{DE,i} \cdot f_{DE,i}\right) - \sum_i \left(E_{Exp,i} \cdot f_{Exp,i}\right)}{A_{net}} \tag{2}$$

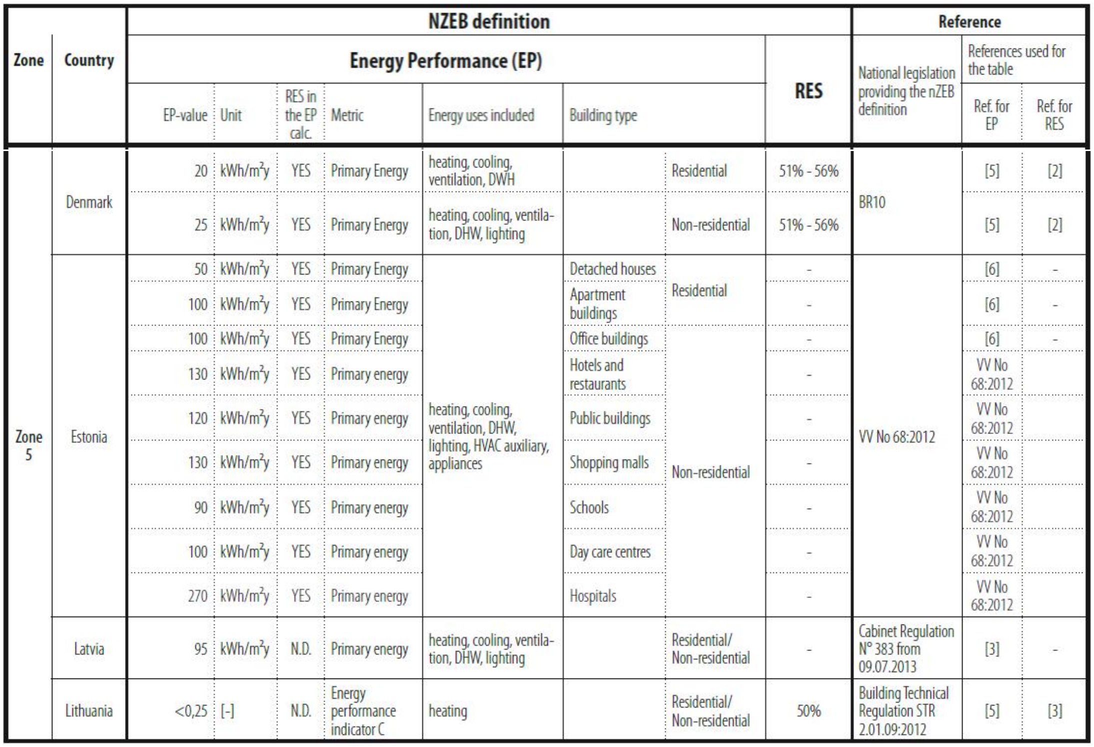
where

$E_{Exp,i}$ = annual energy i, that is exported from the building, kWh/a
$f_{Exp,i}$ = weighing factors of exported energy form i, -
A_{net} = heated net floor area of the building, m^2

Two different definitions of E-value are studied in order to show how surplus electricity which is produced by PV-system and exported to grid impacts on E-value. The weighting factor of exported electicity f_{Exp} is assumed to be same as the factor of delivered electricity f_{DE} (1.7) in this study, because there is no national definition for the weighing factors of exported energy in Finland yet.

Examples of different nZEB definitions in different countries are shown in Table 8 for a reference.

Table 8. Different energy performance levels for different nZEB building types in Denmark, Estonia, Latvia and Lithuania (Kurnitski et al., 2014).



Zone	Country	NZEB definition								Reference		
		Energy Performance (EP)							RES	National legislation providing the nZEB definition	References used for the table	
		EP-value	Unit	RES in the EP calc.	Metric	Energy uses included	Building type				Ref. for EP	Ref. for RES
Zone 5	Denmark	20	kWh/m^{2}y	YES	Primary Energy	heating, cooling, ventilation, DWH		Residential	51% - 56%	BR10	[5]	[2]
		25	kWh/m^{2}y	YES	Primary Energy	heating, cooling, ventilation, DHW, lighting		Non-residential	51% - 56%		[5]	[2]
	Estonia	50	kWh/m^{2}y	YES	Primary Energy	heating, cooling, ventilation, DHW, lighting, HVAC auxiliary, appliances	Detached houses	Residential	-	VV No 68:2012	[6]	-
		100	kWh/m^{2}y	YES	Primary Energy		Apartment buildings		-		[6]	-
		100	kWh/m^{2}y	YES	Primary Energy		Office buildings	Non-residential	-		[6]	-
		130	kWh/m^{2}y	YES	Primary energy		Hotels and restaurants		-		VV No 68:2012	
		120	kWh/m^{2}y	YES	Primary energy		Public buildings		-		VV No 68:2012	
		130	kWh/m^{2}y	YES	Primary energy		Shopping malls		-		VV No 68:2012	
		90	kWh/m^{2}y	YES	Primary energy		Schools		-		VV No 68:2012	
		100	kWh/m^{2}y	YES	Primary energy		Day care centres		-		VV No 68:2012	
		270	kWh/m^{2}y	YES	Primary energy		Hospitals		-		VV No 68:2012	
	Latvia	95	kWh/m^{2}y	N.D.	Primary energy	heating, cooling, ventilation, DHW, lighting		Residential/ Non-residential	-	Cabinet Regulation N° 383 from 09.07.2013	[3]	-
	Lithuania	<0,25	[-]	N.D.	Energy performance indicator C	heating		Residential/ Non-residential	50%	Building Technical Regulation STR 2.01.09:2012	[5]	[3]

4.4 The system concepts of the new detached house

The main system concepts used in the energy simulation cases of the new detached house are presented in this section.

4.4.1 Recent studies

According to Vainio et al. (2012) the ground source heat pump is a good option for main heating system in a detached house, especially when combined with solar thermal and solar electricity systems. The downside is obviously its high investment costs. It seems to be reasonable to integrate solar systems with all the heat pump solutions, if one wants to achieve the coming nZEB requirements in a new detached house.

Pan and Cooper (2011) state that when choosing the heat pump concept for a detached house, one should always consider the economical aspects and the total life-cycle costs of the entire building, because the energy consumption of a passive house level detached house is small in the first place and the extra investment in different heat pump systems may not actually be profitable, especially in the Southern Finland or warmer climates.

Hamdy et al. (2012) states that the ground source heat pump system is dominating over the other conventional heating systems in detached houses in the Southern Finland, when the optimization is based on primary energy consumption and life-cycle costs.

When choosing the heat pump system to the specific situation, an important point is also the annual energy consumption level of the building. The main benefits of the heat pump systems are realized when the heating energy consumption is relatively high. In an energy efficient building, for instance a detached passive house, the difference in energy savings between the ground source heat pump and the air source heat pump (air to water) becomes smaller. According to Saari et al. (2010) the higher investment costs of the ground source heat pump may not be justified anymore and the actual life cycle costs of the ground source heat pump may actually be higher than the life cycle costs of the air source heat pump.

For further notice with the solar based energy, the usage profiles of lighting, household equipment and domestic hot water use have a significant impact on the solar based energy production, electricity and thermal. The production and demand should match as close as possible to obtain the maximum benefits of the solar based energy production. (Liljeström et al., 2014.)

The auxiliary heat energy is produced by electricity for all four heat pump types.

4.4.2 System concepts for energy simulation cases

The structures and the insulation thicknesses of the new detached house are kept constant in every calculation case. The exterior structures are at the Finnish passive house level (RIL 249, 2009) as shown in Chapter 3 and the system concepts concentrate on different types of heat pumps and on the use of solar energy systems. The heat recovery unit of the ventilation system is also kept similar in each system concept, as it is reasonable to install a ventilation system with high supply air temperature efficiency in every new detached house. The heat distribution system is water-based floor heating system with dimensioning temperatures of 40/30 °C in system concepts 1–3 and supply air heating system with electric floor heating in the bathroom in system concept 4.

The selected system concepts and their properties are shown in Table 9. The properties of the systems shown in Table 9 are based on the product information of the existing systems.

Table 9. The system concepts and their properties used in the energy simulation for the new detached house (DH).

Properties of the new detached house	**DH CONCEPT 1:**	**DH CONCEPT 2:**	**DH CONCEPT 3:**	**DH CONCEPT 4:**
Main heating system	Ground source heat pump	Air source heat pump (air to water)	Exhaust air heat pump	Air source heat pump (outdoor air to ventilation supply air)
Heating power and COP of the heat pump in a test point	8.9kW COP: 4.85 (0/35°C)	8.0kW COP: 4.4 7/35°C	4.9kW COP: 3.0 (20/35°C)	1.9 kW COP: 3.8 (-10/37°C)
Heat distribution system	Floor heating (40/30°C)	Floor heating (40/30°C)	Floor heating (40/30°C)	Supply air heating + El. floor heating in bathroom
Cooling system	Free cooling with boreholes	Free cooling with horizontal ground loop	Free cooling with horizontal ground loop	The main heating system in a cooling mode and an additional air to air heat pump for cooling in a bedroom
Cool distribution system	Brine/Water-based cooling system for supply air (10/15°C) and a a fan coil in a single bedroom	Brine/Water-based cooling system for supply air (10/15°C) and a a fan coil in a single bedroom	Brine/Water-based cooling system for supply air (10/15°C) and a a fan coil in a single bedroom	Cooling for supply air and a split unit in a bedroom
Ventilation system (temp. efficiency of heat recovery)	Mec. sypply and exhaust ventilation (80%)	Mec. sypply and exhaust ventilation (80%)	Mec. sypply and exhaust ventilation N/A	Mec. sypply and exhaust ventilation (80%)
Level of thermal insulation	Passive (RIL 249, 2009)	Passive (RIL 249, 2009)	Passive (RIL 249, 2009)	Passive (RIL 249, 2009)
On-site energy production	Solar collectors PV-panels	Solar collectors PV-panels	Solar collectors PV-panels	Solar collectors PV-panels

The different simulation cases are shown in Table 10 below. Total of 16 simulation cases are selected from these proposed concepts, as shown in Table 10. There is also an extra simulation case with LED-based lighting. The extra LED-lighting simulation is performed to the most energy efficient simulation case of the four system concepts.

Table 10. The simulation cases for the selected detached house system concepts.

Description of the simulation cases	**DH CONCEPT**			
	1	**2**	**3**	**4**
1: concepts without the solar based energy systems	X	X	X	X
2: concepts with the solar collectors	X	X	X	X
3: concepts with the solar collectors (see case 2) and PV-panels, typical panel area is selected	X	X	X	X
4: concepts with the solar collectors (see case 2) and PV-panels, large panel area is selected	X	X	X	X

The selected solar collector area for simulation cases is 12 m^2. The criterion of selection for solar collectors was to dimension the collector area so that approximately 50% of the needed annual domestic hot water heating energy is produced by the solar collectors. With the 12 m^2 collector area approximately 54% of the annual DHW heating energy is produced.

The selected PV-panel area is 18 m^2 for simulation case 3 and 36 m^2 for simulation case 4. The 18 m^2 PV-panel area represents a typical PV-area that is installed to a detached house and was chosen for that reason. The 36 m^2 PV-panel area was selected to demonstrate how the large panel area affects to the solar electricity production and to the E-value of the building.

The solar based energy systems are dimensioned so that the total solar collector and large PV-panel area is not more than 50% of the building's total roof area, as the panels and collectors begin to shade each other, if the total area is increased beyond 50%.

4.5 The system concepts of the new apartment building

The main system concepts used in the energy simulation cases of the new apartment building are presented in this section.

4.5.1 Recent studies

According to Vainio et al. (2012) the ground source heat pump is a good option for main heating system in a new apartment building as well, especially when combined with solar thermal and solar electricity systems. The downside is obviously its high investment costs when compared to the district heating system. It seems to be reasonable to integrate solar systems with the ground source heat pump solution, if one wants to achieve the coming nZEB requirements in a new apartment building.

Saari et al. (2010) states that it seems to be a smart decision to choose the low energy standard level (RIL 249, 2009) or the 2012 Finnish building code part D3 reference level of thermal insulation with the ground source heat pump system and integrate solar systems along with it rather than choosing the passive house standard level structures in a new apartment building. The reason is that when one compares the investment costs between the passive house standard level and the low energy standard level, it can be seen that the increase in investment costs is substantial, almost three times larger. In addition, the specific energy consumption is smaller in apartment buildings than in detached buildings, so the actual benefits of making the structures more energy efficient are also smaller.

It is also not a very common solution to choose an air to water heat pump for the primary heating system to a new apartment building. The air source heat pumps work well in detached house sized buildings, but the substantially larger heat demand of an apartment building requires a much larger heat pump system to cover the heat demand of the building, especially the dimensioning of the outdoor unit is a key factor with the air source heat pump system. Also, the need of the auxiliary heating energy during winter time would be substantial as well, as the performance of the heat pump decreases on cold outdoor temperatures. However, according to the Finnish Heat Pump Association (SULPU) and a group of Finnish heat pump manufacturers the air source heat pump technology is currently developing at a fast pace and could be a very potential heating system in the near future also in new apartment buildings. Additionally, its investment costs are substantially lower than for example the ground source heat pump’s investment costs. For these reasons, it is reasonable to study the air to water heat pumps in new apartment buildings as well.

The district heating is a common and probable heating system in almost every new apartment building, when it is available. For this reason, it is reasonable to choose the district heating as a reference concept of this building type.

The auxiliary heat energy for the ground source and air source (air to water) heat pumps is produced by electricity.

4.5.2 System concepts for energy simulation cases

The structures and the insulation thicknesses of the new apartment building are similar in every system concept. Even if the level of thermal insulation of the new apartment building almost fulfills the low energy level defined in (RIL 249, 2009), the system concepts are simulated with the reference level of thermal insulation defined in D3 (2012). This lower level of thermal insulation was used because it has been shown for example in Vinha et al. (2013) that the better thermal insulation level brings negligible energy savings in apartment buildings in Southern Finland. The system concepts concentrate on different types of heat pumps and on the use of solar energy systems. The heat recovery unit of the ventilation system is also similar in every system concept, as it is reasonable to install a ventilation system with high supply air temperature efficiency in every new apartment building. The heat distribution system is water-based low-temperature radiator heating system with dimensioning temperatures of 45/35 °C in every system concept and in every simulation case. The low temperature heating system benefits all heat pump types, making the heat pump’s COP-value higher, and also the district heating system by allowing lower return water temperatures in the heating system and also in the district heating network.

The heat pumps used in the concepts are selected as a result of the current trend in the heat pump market and the selection is also based on the experience and opinions of a group of professionals that are involved both in Finnish and in international heat pump markets. According to this group’s opinion, it is reasonable to choose both ground source and air to water heat pumps as the main heating system in a new apartment building, rather than choosing an exhaust air heat pump for example. The market and the technology is developing fast at the moment and there are new solutions and system concepts coming, especially in the air source heat pump category, making the air source heat pump a potential main heating system also in new apartment buildings in the near future. Ground source heat pumps are already known to be a very potential main heating system in new apartment buildings, as well as in almost any type of building.

The selected system concepts and their properties are shown in Table 11. The properties of the systems shown in Table 11 are based on the product information of the existing systems.

Table 11. The system concepts and their properties used in the energy simulation for the new apartment building (AB).

Properties of the new apartment building	**AB CONCEPT 1:**	**AB CONCEPT 2:**	**AB CONCEPT 3:**
Main heating system	Ground source heat pump	Air source heat pump (air to water)	District heating
Heating power and COP of the heat pump in (a test point)	61 kW COP: 3.6 (0/45°C)	64 kW COP: 4.2 (7/45°C)	-
Heat distribution system	Low temperature radiators (45/35 °C)	Low temperature radiators (45/35 °C)	Low temperature radiators (45/35 °C)
Cooling system	Free cooling with boreholes	Mechanical water chiller system	Mechanical water chiller system
Cool distribution system	Water-based cooling system for supply air (10/15°C)	Water-based cooling system for supply air (10/15°C)	Water-based cooling system for supply air (10/15°C)
Ventilation system (temp. efficiency of heat recovery)	Mec. sypply and exhaust ventilation (AB: 80%) (Parking hall: 75%)	Mec. sypply and exhaust ventilation (AB: 80%) (Parking hall: 75%)	Mec. sypply and exhaust ventilation (AB: 80%) (Parking hall: 75%)
Level of thermal insulation	Reference level 2012 (D3, 2012)	Reference level 2012 (D3, 2012)	Reference level 2012 (D3, 2012)
On-site energy production	Solar collectors PV-panels	Solar collectors PV-panels	Solar collectors PV-panels

The different simulation cases are shown in Table 12 below. Total of 12 simulation cases are selected from these proposed concepts, as shown in Table 12. There is also an extra simulation case with LED-based lighting. The extra LED-lighting simulation is performed to the most energy efficient simulation case of the three system concepts.

Table 12. The simulation cases for the selected new apartment building system concepts.

Description of the simulation cases	**AB CONCEPT**		
	1	**2**	**3**
1: concepts without the solar based energy systems	X	X	X
2: concepts with the solar collectors, typical collector area is selected, so that a reasonable amount of domestic hot water heating energy is produced by the solar collectors, considering the domestic hot water consumption and the roof area of the building	X	X	X
3: concepts with the solar collectors (see case 2) and PV-panels, typical panel area is selected	X	X	X
4: concepts with the solar collectors (see case 2) and PV-panels, large panel area is selected	X	X	X

The selected solar collector area for simulation cases is 78 m^2. The criterion of selection for solar collectors was to dimension the collector area so that approximately 40–50% of the needed annual domestic hot water heating energy is produced by the solar collectors. One criteria of selection was also to dimension the system according to the typical dimensioning of solar thermal systems in apartment buildings. With the 78 m^2 collector area approximately 47% of the annual DHW heating energy is produced.

The selected PV-panel area is 66 m^2 for simulation case 3 and 200 m^2 for simulation case 4. The 66 m^2 PV-panel area represents a typical PV-area that is installed to an apartment building of this size and was chosen for that reason. The 200 m^2 PV-panel area was selected to demonstrate how the large panel area affects to the solar electricity production and to the E-value of the building.

The solar based energy systems are dimensioned so that the total solar collector and large PV-panel area is not more than 50% of the building's total roof area, as the panels and collectors begin to shade each other, if the total area is increased beyond 50%.

4.6 The system concepts of the 1960s apartment building

The main system concepts used in the energy simulation cases of the existing 1960s apartment building are presented in this section.

4.6.1 Recent studies

The ground source heat pump is a good option for main heating system in new detached houses and in new apartment buildings, as stated in the previous chapters, and it is even more profitable to choose it as the main heating system in an existing 1960s apartment building as well, because the existing building consumes more heating energy than the new building, so the potential heating energy savings are even higher. The downside is obviously its high investment costs. It seems to be reasonable to integrate solar energy systems with the ground source heat pump solution, according to the recent studies mentioned before.

According to Vainio et al. (2012), the exhaust air heat pump is also a considerable option in an existing apartment building. The investment costs are smaller than with the ground source heat pump and the savings in heating energy are high. Previous research projects indicate that the exhaust air heat pump is a valuable addition to improve building's energy efficiency, even when the building's primary heating system is district heating.

Saari et al. (2010) state, that it doesn't seem very profitable to improve either the level of thermal insulation or energy efficiency of the ventilation system of an existing apartment building, unless it is necessary along with other renovation processes.

It is also not a very common solution to choose an air source heat pump for the primary heating system to an existing apartment building for the same reason as with the new apartment buildings. The air source heat pumps work well in detached house sized buildings, but the substantially larger heat demand of an apartment building requires a much larger heat pump system to cover the heat demand of the building, especially the dimensioning of the outdoor unit is a key factor with the air source heat pump system. Also, the need of the auxiliary heating energy during winter time would be substantial as well, as the performance of the heat pump decreases on cold outdoor temperatures. There are several systems on the market for larger air to water heat pump applications at the moment (Danfoss, Mitsubishi and Nibe for example), but the air source heat pump system is generally not a very typical heating solution to be installed in an existing apartment building at the moment. However, according to the Finnish Heat Pump Association (SULPU) and a group of Finnish heat pump manufacturers the air source heat pump technology is currently developing at a fast pace and could be a very potential heating system in the near future also in existing apartment buildings.

Additionally, its investment costs are substantially lower than for example the ground source heat pump's investment costs. For these reasons, it is reasonable to study the air to water heat pumps in existing apartment buildings as well.

The auxiliary heat energy for the ground source, exhaust air and air source (air to water) heat pumps are produced by district heating.

As it is stated before, one should carefully select the energy efficiency improvement options and their features to be carried out to maximize the total benefits of the renovation process, especially in the nZEB building cases. There have been carried out multiple research projects in Sweden to determine the most cost-optimal energy performance improving methods for existing apartment buildings that have been built in the 1950s to 1970s. These research results and conclusions can be used to help the selection of reasonable and cost-optimal system concepts for the 1960s apartment building. There are numerous different energy performance improving combinations and variations for the existing apartment buildings and one can't carry them all out at the same time, because the investment costs of the energy saving measures would then be too high. However, if one wants to achieve the EPBD-2020 standards with the renovation process, then these energy performance improving measures need to be reconsidered.

The different energy performance improving measures and their impact on the building's life-cycle costs and energy consumption are shown in Figure 19. The figure shows the results of the Swedish research projects to determine the cost-optimal energy performance improving measures for the existing 1950s to 1960s apartment buildings.

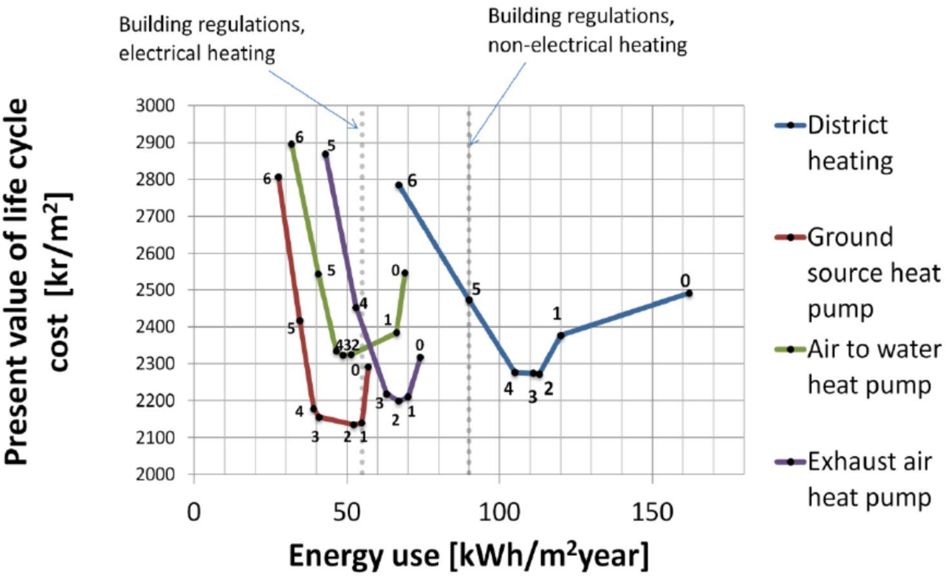


Figure 19. Different energy performance improving measures for the existing apartment buildings. Present value of life-cycle cost for different packages of energy efficient measures in combination with different heating systems at renovation of a low-rise apartment blocks in climate zone 3 built in 1950–1960. (CIT Energy Management, 2013.)

4.6.2 System concepts for energy simulation cases

The structures and the insulation thicknesses of the 1960s apartment building are similar in every system concept. The exterior structures are at the initial level as shown in Chapter 3 and Annexes B–D and the system concepts concentrate on different types of heat pumps and on the use of solar energy systems. The heat distribution system will be renovated from the original high-temperature water-based radiator system to a water-based low-temperature radiator heating system with dimensioning temperatures of 45/35 °C in every system concept and in every simulation case, except in the initial base case simulation cases, where the heat distribution system is the original high temperature radiator heating system with dimensioning temperatures of 80/50 °C.

The selected system concepts and their properties are shown in Table 13. The selection of the concepts is based on the personal view and on the experience of the authors and also on the results of the recent research projects that have been carried out in Sweden, considering the cost-optimal energy performance improvement measures in existing apartment buildings. The properties of the systems shown in Table 13 are based on the product information of the existing systems.

Table 13. The system concepts and their properties used in the energy simulation for the 1960s apartment building (EAB).

Properties of the 1960s apartment building	**EAB CONCEPT 1:**	**EAB CONCEPT 2:**	**EAB CONCEPT 3:**	**EAB CONCEPT 4:**
Main heating system	District heating	Exhaust air heat pump	Ground source heat pump	Air source heat pump (air to water)
Heating power and COP of the heat pump in a test point	-	39kW COP: 3.7 (0/45°C)	156kW COP: 3.7 (0/45°C)	128 kW COP: 4.2 (7/45°C)
Heat distribution system	Original radiators (80/50 °C)	Low temperature radiators (45/35 °C)	Low temperature radiators (45/35 °C)	Low temperature radiators (45/35 °C)
Ventilation system	Mec. exhaust ventilation	Mec. exhaust ventilation	Mec. exhaust ventilation	Mec. exhaust ventilation
Level of thermal insulation	Original	Original	Original	Original
On-site energy production	Solar collectors PV-panels	Solar collectors PV-panels	Solar collectors PV-panels	Solar collectors PV-panels

The different simulation cases are shown in Table 14. Total of 16 simulation cases are selected from these proposed concepts, as shown in Table 14. There is also an extra simulation case with LED-based lighting. The extra LED-lighting simulation is performed to the most energy efficient simulation case of the four system concepts.

Table 14. The simulation cases for the selected 1960s apartment building system concepts.

Description of the simulation cases	**EAB CONCEPT**			
	1	**2**	**3**	**4**
1: concepts without the solar based energy systems	X	X	X	X
2: concepts with the solar collectors, typical collector area is selected, so that a reasonable amount of domestic hot water heating energy is produced by the solar collectors, considering the domestic hot water consumption and the roof area of the building	X	X	X	X
3: concepts with the solar collectors (see case 2) and PV-panels, typical panel area is selected	X	X	X	X
4: concepts with the solar collectors (see case 2) and PV-panels, large panel area is selected	X	X	X	X

The selected solar collector area for simulation cases is 90 m^2. The criterion of selection for solar collectors was to dimension the collector area so that approximately 40–50% of the needed annual domestic hot water heating energy is produced by the solar collectors. One criteria of selection was also to dimension the system according to the typical dimensioning of solar thermal systems in apartment buildings. With the 90 m^2 collector area approximately 42% of the annual DHW heating energy is produced.

The selected PV-panel area is 66 m^2 for simulation case 3 and 200 m^2 for simulation case 4. The 66 m^2 PV-panel area represents a typical PV-area that is installed to an apartment building of this size and was chosen for that reason. The 200 m^2 PV-panel area was selected to demonstrate how the large panel area affects to the solar electricity production and to the E-value of the building.

The solar based energy systems are dimensioned so that the total solar collector and large PV-panel area is not more than 50% of the building’s total roof area, as the panels and collectors begin to shade each other, if the total area is increased beyond 50%.

5. Energy performance of the concepts

This chapter shows the detailed energy simulation results of each concept of the studied buildings. Tables 15–17 show annual energies of the solar systems, breakdown of the annual delivered energy and the E-value calculated by two different definitions. The E-value was calculated according to the official Finnish definition ($E_{D3(2012)}$) and using the definition of REHVA (E_{exp}), which takes exported energy into account (see Chapter 4.2, Equations 1 and 2).

In Tables 15–17, energy of solar thermal (ST) system is heat energy which is used in the heating of DHW, space heating and heating of ventilation supply air. Energies of the solar electricity system (PV) are the total amount of on-site electricity production and the produced electricity which is used in the building. Surplus electricity can be exported to the grid.

The tables show delivered energy consumption of heat pump and auxiliary heater separately. Electricity consumption of heat pump and electric auxiliary heater is shown in the cases of the new detached house and the new apartment building. District heating is used as the auxiliary heating system in the cases of the 1960s apartment building with heat pumps. District heating was selected to be the auxiliary heating system, because district heating is the original heating system of the studied building and the district heating connection is available in the building.
The new buildings are equipped with a mechanical cooling or a free cooling depending on the studied concept (see Tables 9 and 11). The delivered energy of cooling includes electricity consumption of the mechanical cooling system or a pump of the free cooling system.

Electricity consumption of HVAC auxiliary devices in the tables includes fans and pumps of the ventilation system and pumps of the heat distribution system. Lighting and equipment includes inside lighting and all the household devices as defined in D3 (2012).

5.1 Energy performance of the studied system concepts of new detached house

Table 15 shows the detailed energy simulation results of the new detached house.

Table 15. Annual energy simulation results of the new detached house.

Case	Solar system energy, kWh/m²,a			Delivered energy, kWh/m²,a						E-value, kWh/m²,a	
	ST[1]	PV		Electricity						$E_{D3(2012)}$	E_{exp}
	Utilized	Produced	Utilized	Heat pump	Aux. heater	Cooling	HVAC-aux. devices	Lighting+ equip.	Total[2]		
Ground source heat pump											
No solar systems	0	0	0	16.7	0.4	0.1	6.1	22.8	46	78.2	78.2
+ST (12m2)	19.0	0	0	14	0.4	0.1	6.1	22.8	43.3	73.7	73.7
+ST (12m2)+PV (18m2)	19.0	20.9	9.8	14	0.4	0.1	6.1	22.8	33.6	57.1	38.1
+ST (12m2)+PV (36m2)	19.0	41.9	12.1	14	0.4	0.1	6.1	22.8	31.2	53.1	2.5
+ST (12m2)+PV (36m2)+LED	19.0	41.9	11.1	13.8	0.4	0.1	6.1	20	29.3	49.9	-2.5
Air-to-water heat pump											
No solar systems	0	0	0	21	1.1	0.1	6.1	22.8	51	86.7	86.7
+ST (12m2)	19.0	0	0	14.6	1.1	0.1	6.1	22.8	44.6	75.9	75.9
+ST (12m2)+PV (18m2)	19.0	20.9	9.6	14.6	1.1	0.1	6.1	22.8	35	59.5	40.3
+ST (12m2)+PV (36m2)	19.0	41.9	11.8	14.6	1.1	0.1	6.1	22.8	32.8	55.8	4.7
Exhaust air heat pump											
No solar systems	0	0	0	39.7	2.7	0.1	6.1	22.8	71.4	121.3	121.3
+ST (12m2)	19.0	0	0	33.6	2.7	0.1	6.1	22.8	65.3	111	111
+ST (12m2)+PV (18m2)	19.0	20.9	10.8	33.6	2.7	0.1	6.1	22.8	54.5	92.6	75.4
+ST (12m2)+PV (36m2)	19.0	41.9	14	33.6	2.7	0.1	6.1	22.8	51.3	87.2	39.8
Air-to-air heat pump											
No solar systems	0	0	0	6.7	38.9	0.1	6	22.8	74.5	126.6	126.6
+ST (12m2)	19.0	0	0	6.7	23.1	0.1	6	22.8	58.6	99.7	99.7
+ST (12m2)+PV (18m2)	19.0	20.9	10.4	6.7	23.1	0.1	6	22.8	48.2	82	64.1
+ST (12m2)+PV (36m2)	19.0	41.9	13.4	6.7	23.1	0.1	6	22.8	45.2	76.8	28.4

[1] Solar thermal collectors

[2] Utilized PV electricity has been subtracted from the total electricity consumption.

The results show that the lowest total delivered energy consumption can be achieved with GSHP. Compared to the GSHP without the solar systems, the total delivered energy consumption is 11% (5kWh/m²,a) higher with AWHP, 55% (25 kWh/m²,a) higher with EAHP or 62% (28kWh/m²,a) higher with AAHP.

The delivered energy saving by the solar systems depends on the energy efficiency of the main heating system. The achieved maximum saving with the solar systems is the lowest with GSHP (15 kWh/m²,a) and highest (29kWh/m²,a) with AAHP. The saving is lower with GSHP because the heating electricity consumption is lower and because DHW is heated by the GSHP.

The E-value ($E_{D3(2012)}$) of all the studied concepts fulfill the proposed Finnish nZEB level of the detached house (see Table 7). The proposed nZEB level of the studied detache house with 180m² heated net floor area is 128kWh/m²,a.

If the exported electricity is taken into account the E_{exp} is significantly lower than $E_{D3(2012)}$ with the studied PV areas. The E_{exp} reach even -2.5 kWh/m²,a with GSHP and maximum studied PV area and LED lights. But, it should be noted that, the same energy carrier factors were assumed for delivered and exported electricity.

5.2 Energy performance of the studied system concepts of new apartment building

Table 16 shows the detailed energy simulation results of the new apartment building.

Table 16. Annual energy simulation results of new apartment building.

Case	Solar system energy, kWh/m²,a			Delivered energy, kWh/m²,a								E-number, kWh/m²,a	
	ST[1]	PV		District heating	Electricity						Total delivered energy	$E_{D3(2012)}$	E_{exp}
	Utilized	Produced	Utilized		Heat pump	Aux. heater	Cooling	HVAC-aux. devices	Lighting+ equip.	Total[2]			
Ground source heat pump													
No solar systems	0	0	0	0	13.1	0.5	0.1	12	30.6	56.3	56.3	95.7	95.7
+ST (78m2)	15.7	0	0	0	10.2	0.5	0.1	12	30.6	53.3	53.3	90.7	90.7
+ST (78m2)+PV (66m2)	15.7	3.9	3.9	0	10.2	0.5	0.1	12	30.6	49.5	49.5	84.1	84.1
+ST (78m2)+PV (200m2)	15.7	11.7	9.5	0	10.2	0.5	0.1	12	30.6	43.9	43.9	74.6	70.7
+ST (78m2)+PV (200m2)+LED	15.7	11.7	8.9	0	10.9	0.5	0.1	12	25.2	39.9	39.9	67.8	62.9
Air-to-water heat pump													
No solar systems	0	0	0	0	15.3	1.8	0.7	12	30.6	60.4	60.4	102.6	102.6
+ST (78m2)	15.7	0	0	0	11.3	1.8	0.7	12	30.6	56.5	56.5	96	96
+ST (78m2)+PV (66m2)	15.7	3.9	3.9	0	11.3	1.8	0.7	12	30.6	52.6	52.6	89.4	89.4
+ST (78m2)+PV (200m2)	15.7	11.7	9.8	0	11.3	1.8	0.7	12	30.6	46.7	46.7	79.4	76.1
Distric heating													
No solar systems	0	0	0	48.4	0	0	0.7	12	30.6	43.3	91.8	107.6	107.6
+ST (78m2)	15.7	0	0	32.2	0	0	0.7	12	30.6	43.3	75.6	96.2	96.2
+ST (78m2)+PV (66m2)	15.7	3.9	3.9	32.2	0	0	0.7	12	30.6	39.5	71.7	89.7	89.7
+ST (78m2)+PV (200m2)	15.7	11.7	9.5	32.2	0	0	0.7	12	30.6	33.8	66.1	80.1	76.3

[1] Solar thermal collectors

[2] Utilized PV electricity has been subtracted from the total electricity consumption.

The results show that the lowest total delivered energy consumption can be achieved with GSHP. Compared to the GSHP without the solar systems, the total delivered energy consumption is 7% (4kWh/m²,a) higher with AWHP or 63% (35 kWh/m²,a) higher with district heating.

The delivered energy saving by the solar systems depends on the main heating system. The achieved maximum saving with the solar systems is the lowest with GSHP (12 kWh/m²,a) and highest (26kWh/m²,a) with district heating. The saving is lower with GSHP especially because DHW is heated by the GSHP.

The E-value ($E_{D3(2012)}$) of all the studied concepts fulfill the proposed nZEB level (116 kWh/m²,a) of the new apartment building (see Table 7).

According to the results, almost all the produced electricity can be used in the building, so the difference between the $E_{D3(2012)}$ and E_{exp} is minor.

5.3 Energy performance of the studied system concepts of 1960s apartment building

Table 17 shows the detailed energy simulation results of the 1960s apartment building.

Table 17. Annual energy simulation results of the 1960s apartment building.

Case	Solar system energy, kWh/m²,a			Delivered energy, kWh/m²,a						E-number, kWh/m²,a	
	ST[1]	PV		District heating (aux. heating)	Electricity				Total delivered energy	$E_{D3(2012)}$	E_{exp}
	Utilized	Produced	Utilized		Heat pump	HVAC-aux. devices	Lighting + equipment	Total[2]			
Distric heating											
No solar systems	0	0	0	144.3	0	5.5	30.6	36.1	180.4	162.4	162.4
+ST (90m2)	17.2	0	0	126.6	0	5.5	30.6	36.1	162.7	150	150
+ST (90m2)+PV (66m2)	17.2	3.7	3.7	126.6	0	5.5	30.6	32.5	159	143.8	143.7
+ST (90m2)+PV (200m2)	17.2	11.3	8	126.6	0	5.5	30.6	28.1	154.7	136.4	130.7
Exhaust air heat pump											
No solar systems	0	0	0	74.3	15.5	5.3	30.6	51.5	125.8	139.5	139.5
+ST (90m2)	17.2	0	0	74.3	11.8	5.4	30.6	47.8	122.1	133.2	133.2
+ST (90m2)+PV (66m2)	17.2	3.7	3.7	74.3	11.8	5.4	30.6	44	118.4	126.9	126.9
+ST (90m2)+PV (200m2)	17.2	11.3	8.4	74.3	11.8	5.4	30.6	39.4	113.7	119	114
Ground source heat pump											
No solar systems	0	0	0	2.7	39.9	5.6	30.6	76.1	78.8	131.2	131.2
No solar systems+LED	0	0	0	3.1	40.8	5.6	25.2	71.6	74.6	123.8	123.8
+ST (90m2)	17.2	0	0	2.7	36.7	5.6	30.6	72.9	75.6	125.8	125.8
+ST (90m2)+PV (66m2)	17.2	3.7	3.7	2.7	36.7	5.6	30.6	69.2	71.8	119.4	119.4
+ST (90m2)+PV (200m2)	17.2	11.3	8.6	2.7	36.7	5.6	30.6	64.3	67	111.2	106.5
Air-to-water heat pump											
No solar systems	0	0	0	17.1	38.5	5.5	30.6	74.6	91.7	138.8	138.8
+ST (90m2)	17.2	0	0	17.1	32.9	5.6	30.6	69.1	86.1	129.4	129.4
+ST (90m2)+PV (66m2)	17.2	3.7	3.7	17.1	32.9	5.6	30.6	65.3	82.4	123	123
+ST (90m2)+PV (200m2)	17.2	11.3	8.6	17.1	32.9	5.6	30.6	60.5	77.5	114.8	110.1
+ST (90m2)+PV (200m2)+LED	17.2	11.3	8	18	33.4	5.6	25.2	56.2	74.2	108.2	102.5

[1] Solar thermal collectors

[2] Utilized PV electricity has been subtracted from the total electricity consumption.

The results show that the lowest total delivered energy consumption can be achieved with GSHP. Compared to the GSHP without the solar systems, the total delivered energy consumption is 16% (13kWh/m²,a) higher with AWHP, 59% (47 kWh/m²,a) higher with EAHP or 129% (102kWh/m²,a) higher with district heating.

The delivered energy saving by the solar systems depends on the main heating system. The achieved maximum saving with the solar systems is the lowest with GSHP (12 kWh/m²,a) and highest (26kWh/m²,a) with district heating.

It is notable that the E-value ($E_{D3(2012)}$) of the most energy efficient concepts of GSHP and AWHP fulfill the proposed Finnish nZEB level (116 kWh/m²,a) of the new apartment building (see Table 7). The most of the heat pump concepts and the district heating concept with the maximum studied ST and PV areas fulfill the current Finnish requirement of major renovation.

According to the requirement, the E-value of the building after the major renovation should be ($E_{D3(2012)} \leq 0.85 \times E_{initial}$) where $E_{initial}$ is the E-value of the building before the renovation (Decree for the improvement of the energy efficiency of the building by repairs and modifications, 2013). The E-value of the studied building before the renovation is 162.4 kWh/m²,a. The concept fulfills the requirement, if it is less or equal than 138 kWh/m²,a after the renovation.

According to the results, the most of the produced electricity can be used in the building, so the difference between the $E_{D3(2012)}$ and E_{exp} is minor.

6. Life cycle cost analysis

This chapter summarizes the life cycle cost analysis and its results implemented for all studied system concepts included into the project and descripted in the previous chapters. The total number of different system concepts is eleven and the total number of different simulation cases is 44, as described in Chapter 4. The system concepts are simulated both without and with solar energy systems, using a few different dimensioning options for the solar systems.

6.1 Calculation methods

The Life Cycle cost (LCC) analysis takes the capital and the life cycle cost impacts into account by using net present value. The resulting value will be the cost effect of different options.

The life cycle calculations are carried out during the following 25 year period which is in line with the average of the calculation period used in FInZEB project (Reinikainen et al., 2015) (20 years and 30 years). In addition, a sensitivity analysis for life cycle of 20 years was made.

The following issues have been taken into account in the calculation (corresponding output values are presented in Appendix E):

- The investment cost covering the design and construction costs
- Capital cost (= investment cost + financial cost – residual value)
- Service and maintenance cost
- Heating energy cost based on the average month tariffs and the average basic fees (Vantaan Energia Ltd., 3/2015). The selling price of electrical energy is estimated to be about 1/3 compared to the consumer price.
- Electrical energy cost (based on the prices of Vantaan Energia Ltd., 6/2014)

The detailed output data is presented in Appendix E.

As basic rate of interest has been chosen to be 0%, due the calculation was done in the point of view of the property owner. The interest rate of 2% is included in the sensitivity analysis. Also possible taxation advantages and other supports for use of renewable energy resources and rise of energy prices have not been included. However the importance of these has been taken in account by means if sensitivity analysis. The results of sensitivity analysis are almost as probable as results of basic calculation.

This way the most important factors effecting on the development of energy prices as the most difficult prediction factor have been noticed:

- ending the use of coal energy
- investments on renewable energy
- rise of energy taxation
- competition of energy companies

The variations of electricity prices are supposed to be remarkable and the importance of call compliance will increase.

The life cycle cost and its sensitivity regarding different heating systems are depicted in the following paragraphs. The utilization of maximal solar energy is also taken into account (the new detached house: 12m² solar heat, 36m² PV and apartment buildings: 90m² solar heat, 200m² PV). The reason for this is that life cycle costs are almost the same with every building type and their heating system concepts. The benefits of solar energy and additional panel costs refute each other's positive effect. Therefore it is justified to choose the system concepts with the best return of solar energy. This way it is also possible to have the lowest possible E-value.

Every concept (heating system) also has its own result column where the maximum solar energy (Sol/S) is calculated.

6.2 LCC analysis results of the new detached house

The detailed calculation results of different heating systems are presented in table 18 and corresponding optimization curves in Figure 20.

Table 18. Life cycle costs of new detached house.

Life cycle costs and E-values of new detached house

Heated netto area: 180 m2

	Acquisition cost and life cycle cost €/m²/25 y								E-value
	Acquisition cost	Renewing	Residual value	Capital	Maintenance	Heating energy	Electrical energy	Summary	kWh/m²,v
Ground source heat pump									
No solar systems	86.0	22.0	50.0	58.0	22.0	46.0	74.0	200.0	78.2
+ST (12m2)	110.0	46.0	69.0	87.0	35.0	41.0	74.0	237.0	73.7
+ST(12m2)+PV (18m2)	114.0	46.0	69.0	91.0	37.0	41.0	47.0	214.0	57.1
+ST (12m2)+PV (36m2)	118.0	46.0	69.0	95.0	39.0	41.0	31.0	206.0	53.1
+ST(12m2)+PV (36m2)+LED	124.0	46.0	69.0	101.0	39.0	42.0	27.0	209.0	49.9
Air-water heat pump									
No solar systems	60.0	16.0	11.0	65.0	22.0	56.0	73.0	216.0	86.0
+ST (12m2)	84.0	40.0	30.0	94.0	35.0	40.0	73.0	242.0	75.9
+ST(12m2)+PV (18m2)	89.0	40.0	30.0	99.0	38.0	40.0	49.0	226.0	59.5
+ST(12m2)+PV (36m2)	94.0	40.0	30.0	104.0	41.0	40.0	33.0	218.0	55.8
Exhaust-air heat pump									
No solar systems	55.0	55.0	42.0	68.0	21.0	108.0	73.0	270.0	121.3
+ST(12m2)	84.0	79.0	61.0	102.0	34.0	93.0	73.0	309.0	111.0
+ST(12m2)+PV (18m2)	89.0	79.0	61.0	107.0	37.0	93.0	47.0	284.0	92.6
+ST(12m2)+PV (36m2)	94.0	79.0	61.0	112.0	40.0	93.0	28.0	273.0	87.2
Air-air heat pump									
No solar systems	60.0	17.0	12.0	65.0	23.0	116.0	73.0	277.0	126.6
+ST(12m2)	89.0	36.0	31.0	94.0	36.0	78.0	69.0	277.0	99.7
+ST(12m2)+PV (18m2)	94.00	36.0	31.0	99.0	39.0	78.0	44.0	261.0	82.0
+ST(12m2)+PV (36m2)	99.0	36.0	31.0	104.0	42.0	78.0	26.0	250.0	76.8

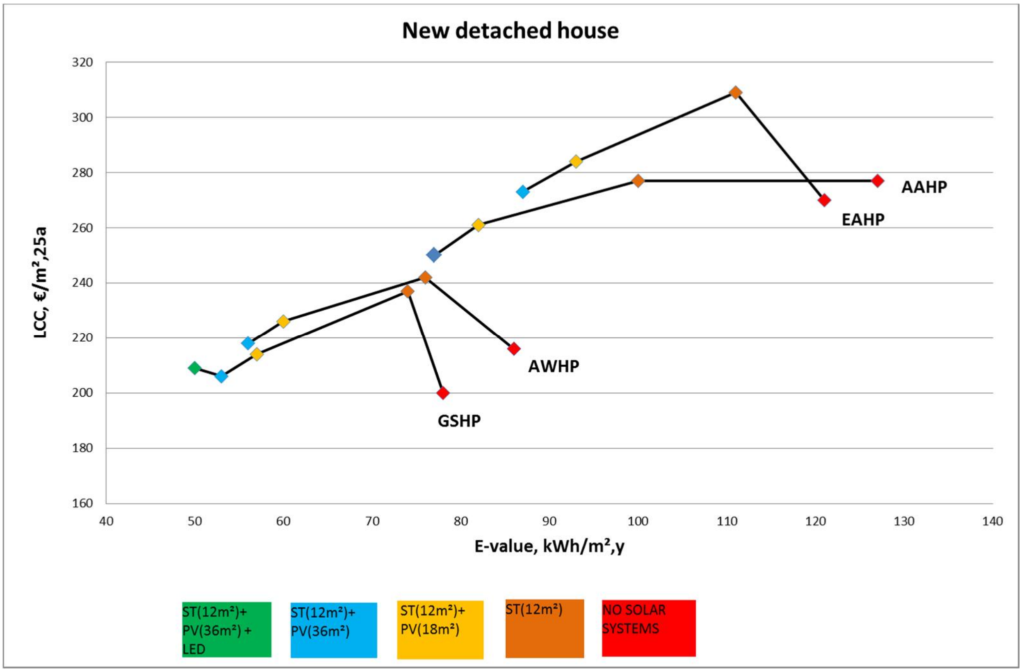


Figure 20. Life cycle costs (€/m²/25 years) and corresponding E–values of the heating systems in the new detached house. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, EAHP = exhaust air heat pump, AAHP = air-to-air heat pump, S = solar energy, E = E-value.)

4 different heat pump types and GSHP with maximum amount of solar energy were chosen for more thorough analysis as shown in Figure 20. Then maximum rate is the most economical choice of solar energy.

The life cycle cost of the ground source heat pump (GSHP E78) is the most inexpensive solution/heating system – even when solar energy is included (GSHP/S E53). In this case it is also possible to reach a very low E-value. Even the air-to-water heat pump (AWHP E87) has a good energy and cost efficiency. The results are reported in order of E-value starting with the lowest (Figure 21). The maximum use of solar energy and its effects to the life cycle cost are also shown in the results.

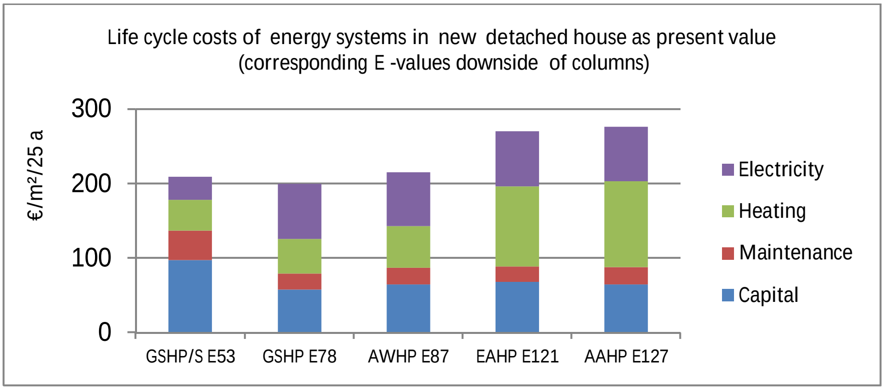


Figure 21. Life cycle costs of energy systems in the new detached house. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, EAHP = exhaust air heat pump, AAHP = air-to-air heat pump Sol = solar energy, E = E-value.)

Capital costs are in every case approximately at the same level, excluding the solution where solar energy is included (GH/S E53). Utilizing solar energy also raises costs of maintenance and service. In the other solutions these costs are approximately equivalent. The air heat pumps are slightly cheaper to buy but don't save as much energy as for example the ground source heat pump. This is why the exhaust air heat pump (EAHP E121) has heating costs of almost twice the size of the other solutions. Also the air-to-air heap pump's (AAHP E127) heating costs are high. The reason for this is that the heating solution needs extra electric heating.

The lower heating costs of the ground source heat pump (GH) and the air-to-water heat pump (AW) are explained by their better seasonal performance factor (SPF). By using solar energy it is possible to achieve electricity consumption that is less than half of what the other solutions consume. The benefits of solar energy are small when taking the investments into account.

It is possible to reduce the E-value significantly by maximum use of solar energy (12m² ST, 36m² PV).

The life cycle cost savings of ground source heat pump (GSHP) and air water heat pump (AWHP) in house with 150 m² are over 10 000 € compared to air-air water pumps or exhaust-air heat pumps.

6.2.1 Sensitivity of life cycle costs in new detached house

The economic order of the solutions depicted before doesn't change when the results are sensitized. The sensitivity analysis includes factors: capital cost growth +30% (because of higher price of money, shorter use time of heat pumps etc.), capital cost reduction -30% (because of technological development etc.), and annual energy cost rise +4.0% and using a counting period of 20 years instead of 25 years. The economic efficiency of the ground source heat pump is even better when energy costs rise. The results are reported in order of E-value starting with the lowest (Figure 22).

However if the capital cost of both ground source heating pump and solar energy become lower, then the life cycle costs are almost equal with those of pure ground source heating pump.

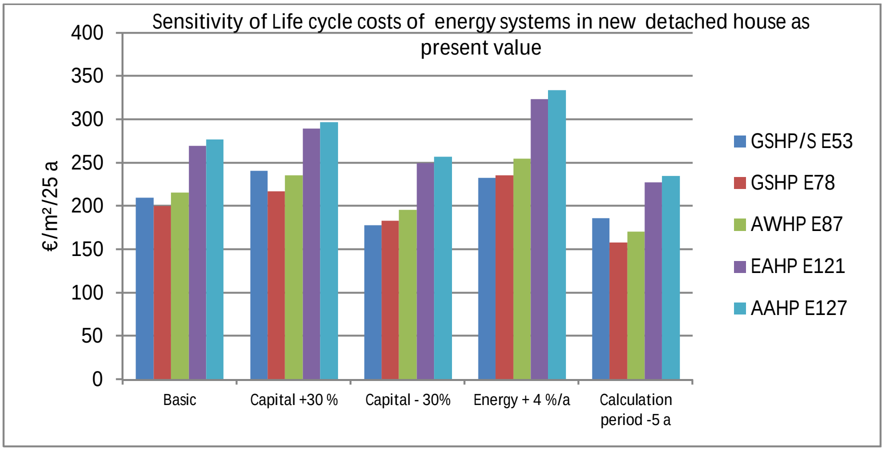
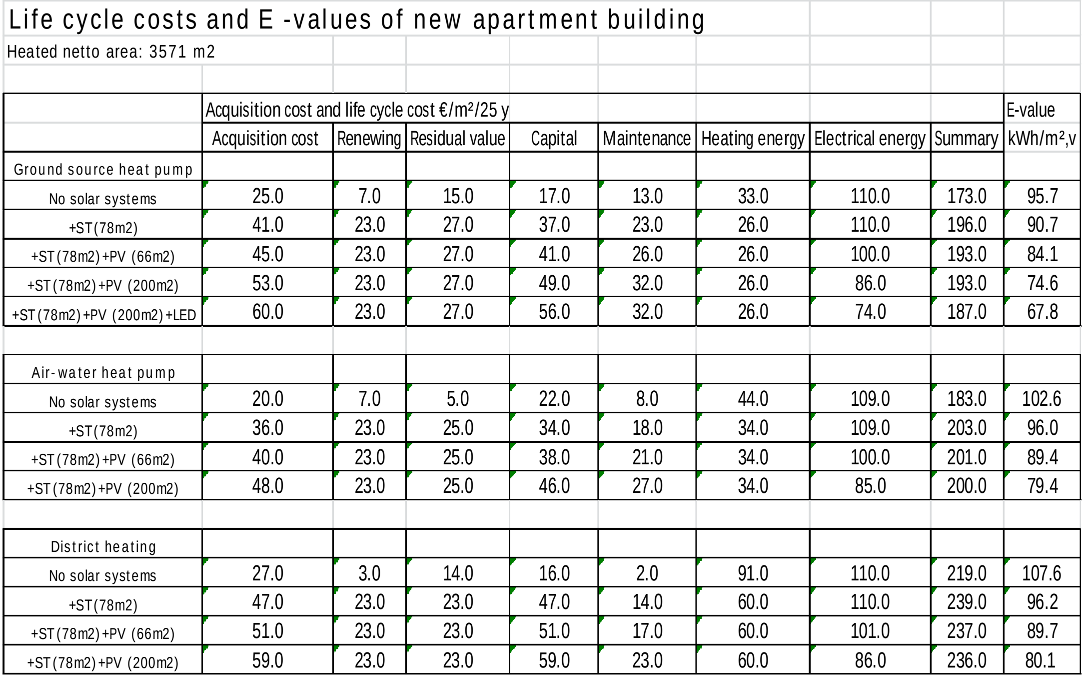


Figure 22. Sensitivity of life cycle costs (€/m²/25 years) of the energy systems in the new detached house. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, EAHP = exhaust air heat pump, AAHP = air-to-air heat pump, Sol = solar energy, E = E-value.)

6.3 LCC analysis results of the new apartment building

The detailed costing results of different heating systems are presented in Table 19 and corresponding optimization curves in Figure 23.

Table 19. Life cycle costs of new apartment building.



Life cycle costs and E -values of new apartment building

Heated netto area: 3571 m2

	Acquisition cost and life cycle cost €/m²/25 y								E-value
	Acquisition cost	Renewing	Residual value	Capital	Maintenance	Heating energy	Electrical energy	Summary	kWh/m²,v
Ground source heat pump									
No solar systems	25.0	7.0	15.0	17.0	13.0	33.0	110.0	173.0	95.7
+ST(78m2)	41.0	23.0	27.0	37.0	23.0	26.0	110.0	196.0	90.7
+ST(78m2)+PV (66m2)	45.0	23.0	27.0	41.0	26.0	26.0	100.0	193.0	84.1
+ST(78m2)+PV (200m2)	53.0	23.0	27.0	49.0	32.0	26.0	86.0	193.0	74.6
+ST(78m2)+PV (200m2)+LED	60.0	23.0	27.0	56.0	32.0	26.0	74.0	187.0	67.8
Air-water heat pump									
No solar systems	20.0	7.0	5.0	22.0	8.0	44.0	109.0	183.0	102.6
+ST(78m2)	36.0	23.0	25.0	34.0	18.0	34.0	109.0	203.0	96.0
+ST(78m2)+PV (66m2)	40.0	23.0	25.0	38.0	21.0	34.0	100.0	201.0	89.4
+ST(78m2)+PV (200m2)	48.0	23.0	25.0	46.0	27.0	34.0	85.0	200.0	79.4
District heating									
No solar systems	27.0	3.0	14.0	16.0	2.0	91.0	110.0	219.0	107.6
+ST(78m2)	47.0	23.0	23.0	47.0	14.0	60.0	110.0	239.0	96.2
+ST(78m2)+PV (66m2)	51.0	23.0	23.0	51.0	17.0	60.0	101.0	237.0	89.7
+ST(78m2)+PV (200m2)	59.0	23.0	23.0	59.0	23.0	60.0	86.0	236.0	80.1

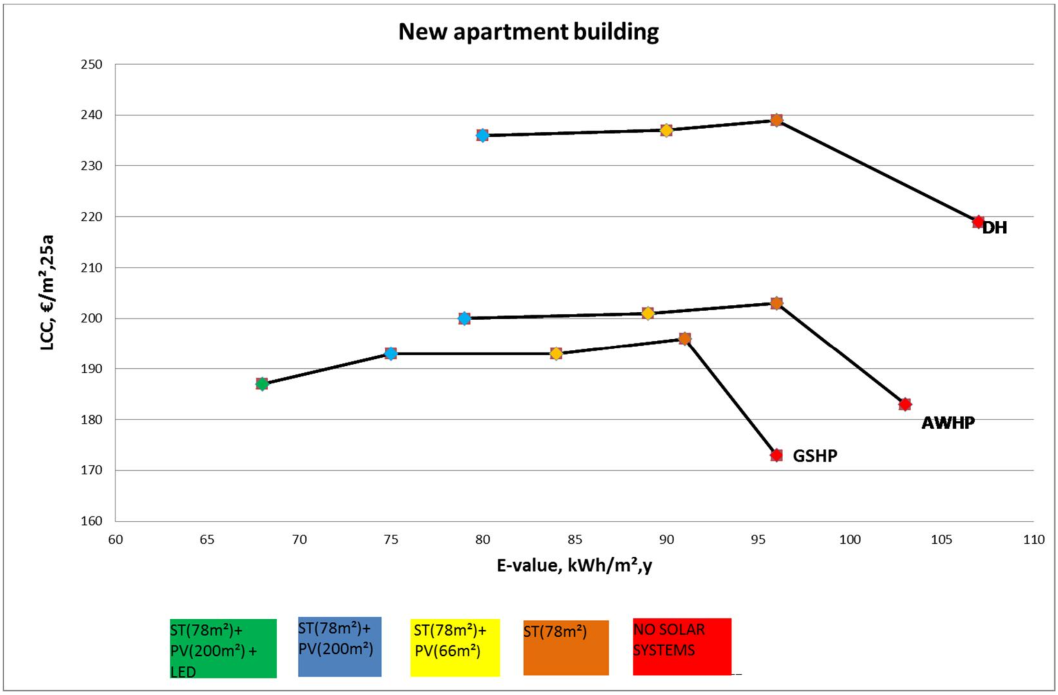


Figure 23. Life cycle costs (€/m²/25 years) and corresponding E-values of the heating systems in the new apartment building. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, EAHP = exhaust air heat pump, AAHP = air-to-air heat pump, S = solar energy, E = E-value.)

4 different heat pump types and GSHP with maximum amount of solar energy were chosen for more thorough analysis as shown in Figure 24.

The life cycle cost of the ground source heat pump (GH E96) is the most inexpensive solution and the air-to-water heat pump (AWHP E103) is almost as good as the ground source heat pump. In addition, when solar energy (GH/S E53) is taken into account with the ground source heat pump, it is also possible to reach a very low E-value. The results are reported in order of E-value starting with the lowest.

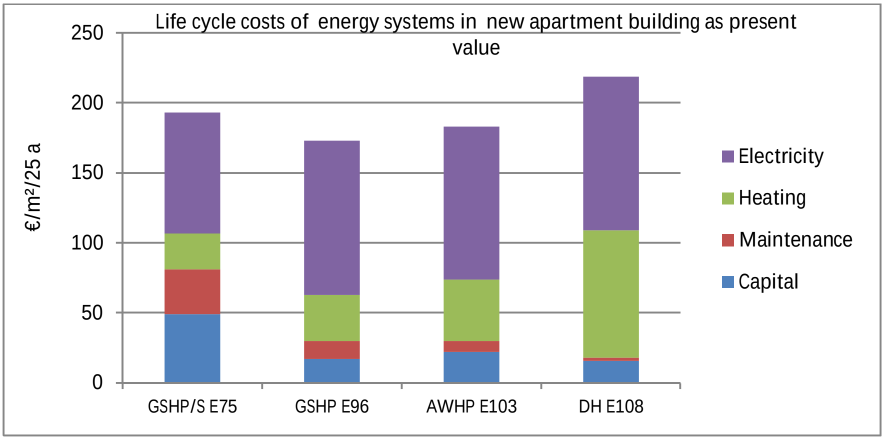


Figure 24. Life cycle costs of energy systems in new apartment building. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, DH = district heating, S = solar energy, E = E-value.)

In each case, capital costs are approximately at the same level, excluding the solution where solar energy is included (GSHP/S E75). Utilizing solar energy also raises costs of maintenance and service. In the other solutions these costs are lower and approximately equivalent. The district heating solution (DH E108) has low costs of maintenance and service compared to the other solutions. Also, there is no need to replace any components during the 25 year period. This lowers capital costs because the residual value is bigger than in the other cases. On the other hand, the energy costs of the district heating solution are much higher than with the heat pump solutions. The portion of "free energy" with the heat pump solutions (especially the ground heat solution) is bigger when heating costs are compared with district heating. Investing in solar energy (GSHP/S E75) reduces electricity consumption. The difference of heating costs between ground heat (GH E96) and air-to-water heat pump solution (AWHP E103) is explained by the better seasonal performance factor (SPF) of ground source heat.

The air-to-water heat pump (AWHP E103) is cheaper to buy but doesn't save as much energy as does for example the ground source heat pump. This is explained by their lower seasonal performance factor (SPF). This is why the air-to-water heat pump has higher heating costs than the ground source heat pump. By using solar energy it is possible to achieve lower electricity and heating consumption but correspondingly other costs are higher, such as service, maintenance and capital costs. So, the benefits of solar energy are relatively small when taking the investments into account.

The maximum use of solar energy and its effects to the life cycle cost are also shown in the results (Figure 23). It is possible to reduce the E-value significantly by maximum use of solar energy (78m² solar heat, 200m² PV). The other combinations of solar energy cause higher life cycle costs than maximum use so every solution in case of other building types are shown in the results with and without maximum amount solar energy.

6.3.1 Sensitivity of life cycle costs in new apartment building

The economic order of the solutions depicted before doesn't change when the results are sensitized (Figure 25). The sensitivity analysis includes factors: capital cost growth +30%, annual energy cost rise +4.0% and using a counting period of 20 years instead of 25 years. The economic efficiency of the ground source heat pump is even better when energy costs rise.

However if the electricity cost rise is higher, the life cycle costs of AWHP become even higher than those of district heating.

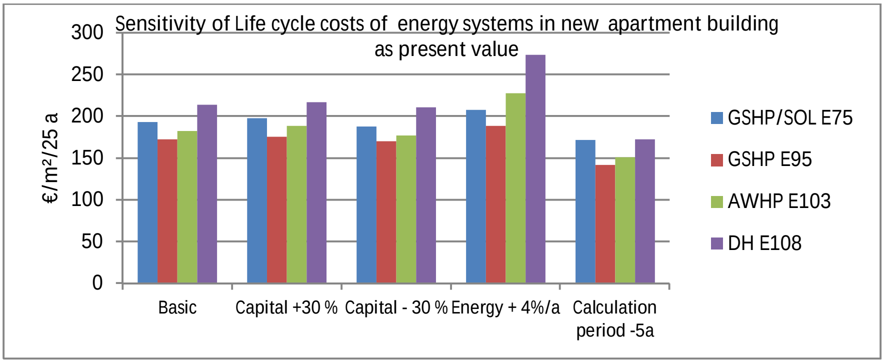


Figure 25 Sensitivity of life cycle costs (€/m²/25 years) of the energy systems in the new apartment building. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, DH = district heating, Sol = solar energy, E = E-value.)

6.4 LCC analysis results of the 1960s apartment building

The detailed costing results of different heating systems are presented in Table 20 and corresponding optimization curves in Figure 26. As seen in Figure 26, the economic profitability with the solar systems is lower in case of GSHP compared to other systems, since the system has high energy performance level. Due the high COP of the GSHP, the domestic hot water is mainly produced by the heat pump system and the profitability of adding solar energy is lower.

Table 20. Life cycle costs results of the 1960s apartment building.

Life cycle costs and E-values1960s apartment building									
Heated netto area: 3697 m2									
				Capital = acquisition + renewing - residual value					
	Acquisition cost and life cycle cost €/m²/25 y								E-value
	Acquisition cost	Renewing	Residual value	Capital	Maintenance	Heating energy	Electrical energy	Summary	kWh/m²,v
District heating									
No solar systems	22.0	0.0	11.0	11.0	4.0	270.0	92.0	377.0	162.4
+ST(90m2)	47.0	25.0	31.0	41.0	20.0	237.0	92.0	390.0	150.0
+ST(90m2)+PV (66m2)	51.0	25.0	31.0	45.0	22.0	237.0	83.0	387.0	143.8
+ST(90m2)+PV (200m2)	59.0	25.0	31.0	53.0	26.0	237.0	71.0	387.0	136.4
Exhaust-air heat pump									
No solar systems	61.0	37.0	33.5	64.5	9.0	179.0	91.0	343.5	139.5
+ST(90m2)	86.0	62.0	53.5	94.5	25.0	169.0	91.0	341.5	133.2
+ST(90m2)+PV (66m2)	90.0	62.0	53.5	98.5	27.0	169.0	82.0	343.5	126.9
+ST(90m2)+PV (200m2)	98.0	62.0	53.5	96.5	31.0	169.0	70.0	343.5	119.0
Ground source heat pump									
No solar systems	81.0	9.0	44.0	46.0	23.0	105.0	92.0	266.0	131.2
No solar systems+LED	87.0	9.0	44.0	52.0	23.0	108.0	80.0	263.0	123.8
+ST(90m2)	101.0	20.0	60.0	61.0	36.0	98.0	92.0	287.0	125.8
+ST(90m2)+PV (66m2)	106.0	20.0	60.0	66.0	38.0	98.0	83.0	285.0	119.4
+ST(90m2)+PV (200m2)	116.0	34.0	60.0	90.0	45.0	98.0	70.0	303.0	111.2
Air-water heat pump									
No solar systems	64.0	8.0	8.0	64.0	24.0	130.0	92.0	310.0	138.8
+ST (90m2)	84.0	19.0	24.0	79.0	37.0	116.0	92.0	324.0	129.4
+ST(90m2)+PV (66m2)	88.0	19.0	24.0	83.0	39.0	116.0	83.0	321.0	123.0
+ST(90m2)+PV (200m2)	96.0	19.0	24.0	91.0	43.0	116.0	70.0	320.0	114.8
+ST(90m2)+PV (200m2)+LED	102.0	19.0	24.0	97.0	43.0	119.0	58.0	317.0	108.2

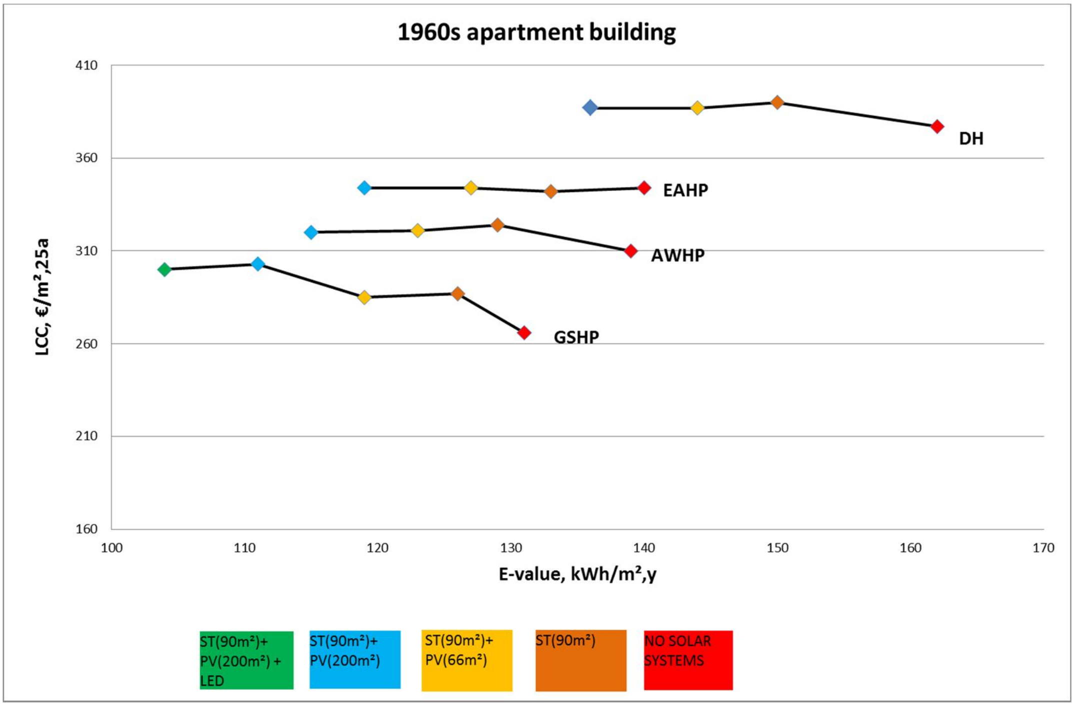


Figure 26. Life cycle costs (€/m²/25 years) of the heating systems in 1960s apartment building. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat pump, AWHP = air-to-water heat pump, DH = district heating, EAHP = exhaust air heat pump, S = solar energy, E = E-value.)

4 different heat pump types and GSHP with maximum amount of solar energy were chosen for more thorough analysis as shown in Figure 27.

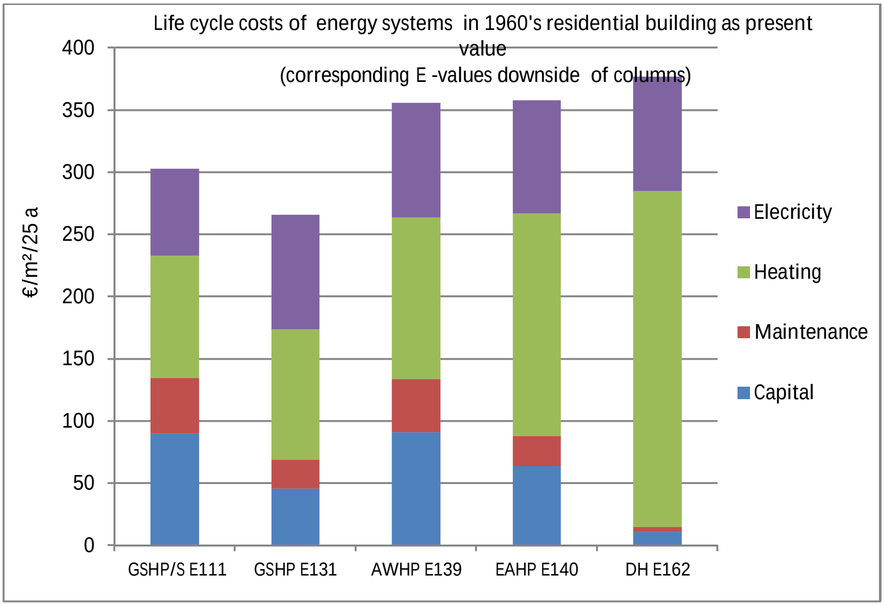


Figure 27. Life cycle costs of energy systems in 1960s apartment building. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = ground source heat Pump, AWHP = air-to-water heat pump, EAHP = exhaust air heat pump, DH = district heating, S = solar energy, E = E-value.)

The capital cost of district heating (DH E162) is low compared to the other solutions. This is due to high residual value. It is also important to take into account the big differences between investment costs regarding different solutions. When it comes to district heating, only adjustment of radiator heating has been executed. In other solutions the whole radiator system has been replaced with low temperature radiators. The latter is ten times more expensive as an investment. So even though the investment costs of district heating are much lower, the other solutions are still much more profitable.

The air-to-water heat pump (AWHP E139) is more expensive than the other solutions, which is due to the heating method’s low residual value. District heating is used in every solution as a back-up system, which weakens the other solutions’ competitive power. This induces the other solutions extra costs because the back-up system has to be fitted to match the maximum design power of the building.

The district heating solution (DH E162) has low costs of maintenance and service compared to the other solutions. Also, there is no need to replace any components during the 25 year period. This lowers capital costs because the residual value is bigger than in the other cases. On the other hand, the energy costs of the district heating solution are much higher than with the heat pump solutions.

The benefits of the ground source heat pump may be even greater the more energy the building consumes. The portion of “free energy” with the heat pump solutions (especially the ground heat solution) is bigger when heating costs are compared with district heating.

The difference of heating costs between the ground source heat pump (GSHP E131) and air heat pumps (EAHP E140A and AWHP E139) is explained by the good seasonal performance factor (SPF) of ground heat. The air heat pumps are cheaper to buy but don't save as much energy as does for example the ground source heat pump. This is why the air heat pumps have higher heating costs than the ground source heat pump. Investing in solar energy (GH/S E111) reduces electricity consumption increasing capital costs relatively much.

The maximum use of solar energy and its effects to the life cycle cost are also shown in the results (Figure 26). It is possible to reduce the E-value significantly by maximum use of solar energy (90m² ST, 200m² PV). Every solution is shown in the results with and without solar energy.

6.4.1 Sensitivity of life cycle costs of 1960s apartment buildings

The economic order of the solutions depicted before doesn't change when the results are sensitized. The sensitivity analysis includes factors: capital cost growth +30%, capital cost decrease -30% (based on technological development), annual energy cost rise +4.0% and using a counting period of 20 years instead of 25 years. The economic efficiency of the ground source heat pump is even better in two cases: when energy costs rise and/or the ground source heat pump's investment costs decrease at the same time when the investment costs of district heating stay the same. The results are reported in order of E-value starting with the lowest (Figure 28).

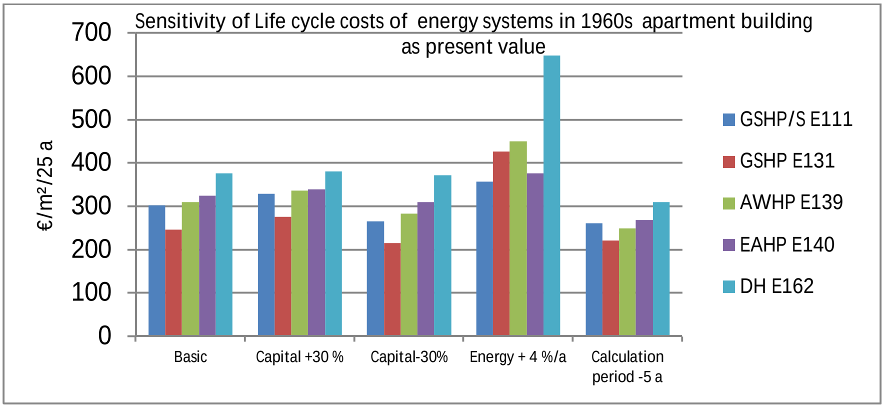


Figure 28. Sensitivity of life cycle costs (€/m²/25 years) of the energy systems in 1960s apartment building. Present values of the different solutions are reported in order of E-value starting with the lowest. (GSHP = Ground source heat pump, AWHP = air-to-water heat pump, DH = district heating, EAHP = exhaust air heat pump, S = solar energy, E = E-value.)

7. Conclusions

The analysis presented in this report shows that Finnish nearly zero energy level for buildings can be achieved more cost-efficiently with concepts utilizing heat pumps than district heating.

In HP4NZEB project three different building types were studied: typical Finnish new detached house, new apartment building and the renovation of a 1960s apartment building.

All the studied concepts of new buildings fulfill the suggested Finnish nZEB levels. The delivered energy consumption is significantly lower with the studied heat pump solutions compared with district heating. The ground source heat pump and air to water heat pumps are the most efficient solutions to save delivered energy within the studied concepts.

When calculating life cycle costs using output values of the energy performance calculation of the different concepts (as presented in the chapter 5), the ground source heat pump is the best choice in all three different types of buildings: a new detached house, a new apartment building and an existing apartment building, built in the 1960s.

Even after sensitivity analyses the ground source heat pump is the most profitable solution, when taking all life cycle costs into account. The economic efficiency of the ground source heat pump is even better in two cases: when energy costs rise and/or the ground source heat pump’s investment costs decrease at the same time when the investment costs of district heating stay the same.

In addition to lower life cycle costs heat pumps can also cool the building and no extra investment for cooling is needed. The simulation of all studied building types showed that there can be a demand for cooling in Finnish nearly zero energy building in order to ensure the comfortable indoor environment conditions throughout the year. The cooling demand can be decreased through solar shading. The cooling feature of a heat pump brings added value to the investment since no additional investment for cooling is needed when utilizing heat pump. Heat pump is able to cool the building in an energy efficient way.

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Appendix A: Domestic hot water consumption profile

The domestic hot water consumption profile is based on a measured data of a Finnish apartment building. It is essential to take into account the monthly usage profiles of the DHW consumption in addition to the hourly usage profiles when simulating the NZEB buildings to achieve realistic results, as the consumption of the DHW is higher in winter time than in summer time. The hourly and monthly usage profiles are shown in Tables A1 and A2.

Table A1. Hourly usage profile $P_h(t)$ of domestic hot water.

Time t, hour	1	2	3	4	5	6	7	8	9	10	11	12
$P_h(t)$	0.87	0.52	0.52	0.52	0.67	0.82	0.92	0.97	1.02	1.02	1.02	1.02
Time t, hour	13	14	15	16	17	18	19	20	21	22	23	24
$P_h(t)$	0.97	0.97	1.02	1.07	1.17	1.27	1.42	1.52	1.52	1.42	1.12	0.72

Table A2. Monthly usage profile $P_m(t)$ of domestic hot water.

Time t , month	1	2	3	4	5	6	7	8	9	10	11	12
$P_m(t)$	1.17	1.11	1.02	0.94	0.87	0.84	0.85	0.89	0.97	1.05	1.13	1.18

The hourly consumption of the domestic hot water (m^3/h) is calculated using the hourly and monthly usage profile multipliers according to Equation (A1) shown below.

$$DHW(t) = \frac{DHW_a \cdot A_{building}}{8760h} \cdot P_h(t) \cdot P_m(t) \tag{A1}$$

where

$DHW(t)$ = hourly consumption of the domestic hot water, m^3/h
DHW_a = total specific consumption of the domestic hot water in one year, $m^3/m^2,a$
$A_{building}$ = total heated net floor area of the building, m^2
$P_h(t)$ = hourly usage profile multiplier of the DHW consumption, -
$P_m(t)$ = monthly usage profile multiplier of the DHW consumption, -.

Appendix B: Detailed energy calculation data for the new detached house

Structures

Table B1. Structures and their main features.

Structure	Description / Value	Notifications
External wall	U-value: 0.08 W/m^{2}K	Gypsum board 13 mm Wooden frame (at 600 mm) + mineral wool 540 mm Wind shield board 9 mm
Roof	U-value: 0.05 W/m^{2}K	Mineral wool 570 mm Wooden frame (at 600 mm) + mineral wool 150 mm Gypsum board 13 mm
Base floor (connected to the ground)	U-value: 0.10 W/m^{2}K	Parquet 14 mm Concrete slab 80 mm EPS-insulation 365 mm Ground layer 1000 mm
Internal wall	U-value: 2.42 W/m^{2}K	Gypsum board 13 mm Wooden frame (at 600 mm) + air gap 50 mm Gypsum board 13 mm
Intermediate floor	U-value: 0.36 W/m^{2}K	Wooden panel 15 mm Particle board 22 mm Wooden frame (at 600 mm) + mineral wool 100 mm Gypsum board 13 mm
External door	U-value: 0.80 W/m^{2}K	Wooden panel 12 mm Wooden frame + mineral wool 40,5 mm Wooden panel 12 mm
Windows	U-value: 0.81 W/m^{2}K Orientation of the windows: *North: 11.9 m^2* *East: 9.2 m^2* *South: 8.9 m^2* *West: 0.2 m^2*	Window type: MS2E-170 (two-frame and four-glazing structure, opened inwards, argon filled inner and outer low-e glazing elements) Glazing U-value: 0,80 W/m^{2}K g-value: 0,26 ST-value: 0,21 Internal/external emissivity: 0,90 Frame depth: 170 mm Frame fraction of the total window

		area: 0.15 (15%)
Integrated window shading	Blinds between the outer panes	Multiplier for g-value: 0.33 Multiplier for ST-value: 0.12
Air-tightness of the building	q_{50}-value = 0.60 $m^3/(m^2\ h)$	

Table B2. Thermal bridges of the structure joints and their conductances.

Structure joint	Conductance	Notifications
External wall / external wall, outer corner	0.05 W/mK	
External windows perimeter	0.04 W/mK	
External doors perimeter	0.04 W/mK	
Roof / external walls	0.05 W/mK	
Base floor / external walls	0.08 W/mK	

External wall

	Structure	D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Thermal resistance (inner)					0.13
2	Gypsum board	13	0.22	970	1090	0.059
3	Wooden frame (at 600 mm) + mineral wool	540	0.044	56	1720	12.273
4	Wind shield board	9	0.22	970	1090	0.041
5	Thermal resistance (exterior)					0.04
Total	**U-value**	**0.08**	**W/m²K**			

Roof

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^2K/W
1	Thermal resistance (exterior)					0.04
2	Mineral wool	570	0.035	20	750	16.286
3	Wooden frame (at 600 mm) + mineral wool	150	0.044	56	1720	3.409
4	Wind shield board	13	0.22	970	1090	0.059
5	Thermal resistance (inner)					0.10
Total	**U-value**	**0.05**	**W/m^2K**			

Base floor (connected to the ground)

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^2K/W
1	Thermal resistance (inner)					0.17
2	Parquet	14	0.14	460	2300	0.100
3	Concrete	80	1.70	2300	880	0.047
4	EPS-insulation	365	0.040	20	750	9.125
5	Ground layer	1000	2.00	2000	1000	0.500
Total	**U-value**	**0.10**	**W/m^2K**			

Internal wall

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^2K/W
1	Thermal resistance (inner)					0.13
2	Gypsum board	13	0.22	970	1090	0.059
3	Wooden frame (at 600 mm) + air gap	50				0.035
4	Gypsum board	13	0.22	970	1090	0.059
5	Thermal resistance (inner)					0.13
Total	**U-value**	**2.42**	**W/m^2K**			

Intermediate floor

Structure		D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Thermal resistance (inner)					0.10
2	Parquet	14	0.14	460	2300	0.100
3	Particle board	22	0.13	1000	1300	0.169
4	Wooden frame (at 600 mm) + mineral wool	100	0.044	56	1720	2.273
5	Gypsum board	13	0.22	970	1090	0.059
6	Thermal resistance (inner)					0.10
Total	**U-value**	**0.36**	**W/m²K**			

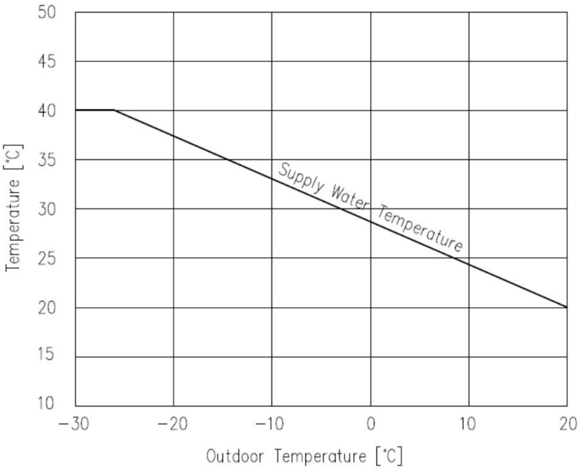
External door

Structure		D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Thermal resistance (inner)					0.13
2	Wooden panel	12	0.14	460	1360	0.086
3	Wooden frame + mineral wool	40.5	0.045	56	1720	0.910
4	Wooden panel	12	0.14	460	1360	0.086
5	Thermal resistance (exterior)					0.04
Total	**U-value**	**0.80**	**W/m²K**			

HVAC systems

	Description / Value	**Notifications**
Ventilation system		
Mechanical supply and exhaust ventilation system		With heat recovery system
Operation schedule	Monday–Sunday 00:00–24:00	Same operation schedule throughout the year
Supply and exhaust air flow rate	0.4 $dm^3/(s, m^2)$	CAV-ventilation system
Supply air temperature in	18.0 °C / 17.0 °C	Constant temperature control, 18.0 °C in the

rooms		heating season, 17.0 °C from 1.6 to 31.8
Temperature increase in the supply air fan	1.0 °C	
Heat recovery unit	Supply air temperature efficiency: 0.80	Defined according to Standard BS EN 13141-7:2010
The SFP-value of the ventilation system	1.70 kW/(m^3/s)	
Heat distribution and heating system		
Type of the heat distribution system	Water-based underfloor heating system	
Dimensioning temperatures of the heat distribution system	40/30 °C	Supply water temperature control according to the outdoor temperature
Room temperature set point for heating	21.0 °C	
Supply water temperature of the heating system	According to the figure 4	
Cool distribution and cooling system		
Type of the cool distribution system	Brine/Water-based cooling system for supply air cooling and for bedroom 1 fan coil cooling	There is a fan coil (1000 W) in bedroom 1 and a cooling coil in the supply air duct for supply air cooling
Dimensioning temperatures of the cool distribution system	10/15 °C	Constant supply water temperature control when the cooling system is operating (from 1.6. to 31.8.)
Room temperature set point for cooling	27.0 °C	Room temperature doesn’t exceed 27.0 °C for more than 150 degree hours between 1.6.–31.8.



Internal heat gains from lighting, persons and household equipment

The usage of the building, including usage profiles and specific internal gain power outputs, is assumed to be according to the Finnish building code part D3. The internal gains from lighting, persons and household equipment are shown in Table B3. The heat gains presented are used in every room of the building.

Table B3. The internal gains from lighting, persons and household equipment in the detached house.

Internal heat gain	**Specific power / Notifications**
Persons	2.0 W/m^2, which equals to 1 person per 43 m^2 with activity level of 1,2 met and clothing 0.75 ± 0.25 clo
Lighting	8.0 W/m^2
Household equipment	3.0 W/m^2

Hourly internal heat gains from household equipment and persons are calculated by multiplying the specific powers (W/m^2) shown in Table B3 by the constant usage rate 0.6 and hourly internal heat gain from lighting by the constant usage rate of 0.1, according to the Finnish building code part D3.

Appendix C: Detailed energy calculation data for the new apartment building

Structures

Table C1. Structures and their main features.

Structure	Description / Value	Notifications
External wall	U = 0.13 W/m^{2}K	US1: 100 mm concrete, 200 mm insulation + 80 mm concrete
Roof	U = 0.09 W/m^{2}K	YP1: 50 catwalk mm, 400 mm blowing wool, 100 mm mineral wool, vapor barrier, + 265 mm hollow core concrete slab (According to the sectional drawing B-B)
Base floor (connected to the ground)	U = 0.27 W/m^{2}K	AP1: 120 mm concrete, 120 mm EPS insulation + 1000 mm ground layer
Internal walls between staircases and apartments	U = 0.6 W/m^{2}K	VS10: tiling, waterproofing, 200 mm concrete + surface material (According to the sectional drawing B-B)
Internal walls between apartments	U = 2.09 W/m^{2}K	VS3 (200 mm concrete, no info on finishing layers)
Intermediate floor	U = 1.73 W/m^{2}K	VP1, concrete 370 mm + screeding 20 mm + parquet 15 mm
External door	1.0 W/m^{2}K	Aluminum profile entrance doors with at least 3-glazing windows (g=0,37), balcony doors wood-aluminum with triple glazings including Argon (According to the building speci-

		fication)
Windows	0.8 W/m^{2}K (in the apartments) g-value at least 0.37 ST-value 0.31 Orientation of the windows: *Northeast: 15.0 m^2* *Southeast: 113.7 m^2* *Southwest: 28.5 m^2* *Norhwest: 146.9 m^2*	wooden-aluminium MSE, total U-value including glazings and frames (According to the building specification)
Integrated window shading	Blinds between the outer panes	Multiplier for g-value: 0.33 Multiplier for ST-value: 0.12
Air-tightness of the building	n_{50} = 0.4 q_{50} = 1.43	typical for Finnish low-energy apartment buildings (Vainio et al., 2012) not measured q_{50} = n_{50}×air volume (13233 m^3)/envelope area (3708,12 m) including base floor and roof (m^3/h/m^2)

The thermal bridges between the structure joints and their conductances used in the energy simulation are shown in Table C2.

Table C2. Thermal bridges of the structure joints and their conductances (according to Heikkinen, 2011).

Structure joint	**Conductance**	**Notifications**
External wall / external wall, outer corner	0.06	
External windows perimeter	0.04	
External doors perimeter	0.04	
Roof / external walls	0.08	
Base floor / external walls	0.23	

A more detailed description of the structure materials and their main features are shown in the tables below.

External wall (US1)

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
	Thermal resistance (inner)					0.13
1	Concrete	100	2	2400	1000	0.050
2	Polyurethane	200	0.026	35	1450	7.692
3	Concrete	80	2	2400	1000	0.040
	Thermal resistance (exterior)					0.04

U-value 0.13 W/m^{2}K

Roof

Structure		D,mm	λ, W/mK	ρ, kg/m^3	cp, J/kgK	R, m^{2}K/W
	Thermal resistance (exterior)					0.04
1	Blowing wool	400	0.045	30	1030	8.889
2	Mineral wool	100	0.041	20	750	2.439
3	Vapor barrier	5	0.040	1100	1000	0.125
4	Hollow core slab	265	2	1400	1000	0.133
	Thermal resistance (inner)					0.1

U-value 0.09 W/m^{2}K

Base floor (connected to the ground)

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
	Thermal resistance (inner)					0.17
1	Concrete	120	2	2400	1000	0.060
2	EPS-insulation	120	0,040	20	750	3.000
3	Ground layer	1000	2	2000	1000	0.500

U-value 0.27 W/m^{2}K

Internal walls between apartments

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
	Thermal resistance (inner)					0.13
1	Plaster	10	0.9	1700	1000	0.011
2	Concrete	200	2.000	2400	1000	0.100
3	Plaster	10	0.9	1700	1000	0.011

	Thermal resistance (inner)					0.13

U-value 2.62 W/m^{2}K

Internal wall (VS10 between apartments and staircases)

Structure		D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
	Thermal resistance (inner)					0.13
1	Ceramic tiles	5	0.9	1700	1000	0.006
2	Concrete	200	0.145	2400	1000	1.379
3	Plaster	10	0.9	1700	1000	0.011
	Thermal resistance (inner)					0.13

U-value 0.60 W/m^{2}K

Intermediate floor (VP1)

Structure		D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
	Thermal resistance (inner)					0.1
1	Parquet	15	0.14	460	2300	0.107
2	Levelling	20	1.2	2000	1000	0.017
3	Concrete slab	370	2.000	2400	1000	0.185
	Thermal resistance (inner)					0.17

U-value 1.73 W/m^{2}K

External door

Structure		D,mm	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
	Thermal resistance (inner)					0.13
1	Aluminum panel	13	220	2700	900	0.0001
2	EPS-insulation	34	0.041	20	750	0.829
3	Aluminum panel	13	220	2700	900	0.0001
	Thermal resistance (exterior)					0.04

U-value 1.00 W/m^{2}K

HVAC systems

The building will be heated with a ground source heat pump (According to building services work specification). The HVAC systems, their main features, operational functions and set points are shown below.

	Description / Value	Notifications
Ventilation system		
Mechanical supply and exhaust ventilation system	Apartment specific systems in the 5th floor, centralized in other floors.	According to building services work specification
Operation schedule	Monday-Sunday 00:00-24:00	Same operation schedule throughout the year
Supply and exhaust air flow rate	0,5 $dm^3/(s,m^2)$	
Supply air temperature in rooms	18.0 °C	Constant temperature control in simulation cases, 18,0 °C throughout the year (cooling is applied from 1.6. to 31.8.), in the real building there is only supply air cooling in the top floor apartments that is controlled according to the outdoor temperature, in this study the supply air cooling was applied to all apartments of the building
Temperature increase in the supply air fan	1.0 ºC	
Heat recovery unit	> 75%	(defined) temperature efficiency of the supply air Defined according to Standard BS EN 13141-7: 2010
The SFP-value of the ventilation system	max 2.0 $kW/m^3/s$	
Heat distribution and heating system		
Type of the heat distribution system	low-temperature radiator and floor heating system	Floor heating system in bathrooms and saunas, radiator heating system in

		other spaces
Dimensioning temperatures of the main heat distribution system	45/35 ºC	Supply water temperature control according to the outdoor temperature
Room temperature set point for heating	21.0 ºC / 17.0 ºC	21.0 ºC (living spaces) 17.0 ºC (cellar and stair case) 17.0 ºC (parking hall)
Supply water temperature of the heating system	According to the figure 8	
Cool distribution and cooling system		
Type of the cool distribution system	Water-based cooling system for supply air cooling	There is a cooling coil in the supply air duct for supply air cooling
Dimensioning temperatures of the cool distribution system	10/15 °C	Constant supply water temperature control when the cooling system is operating (from 1.6. to 31.8.)
Room temperature set point for cooling	27.0 °C	Room temperature doesn´t exceed 27.0 °C for more than 150 degree hours between 1.6.–31.8.

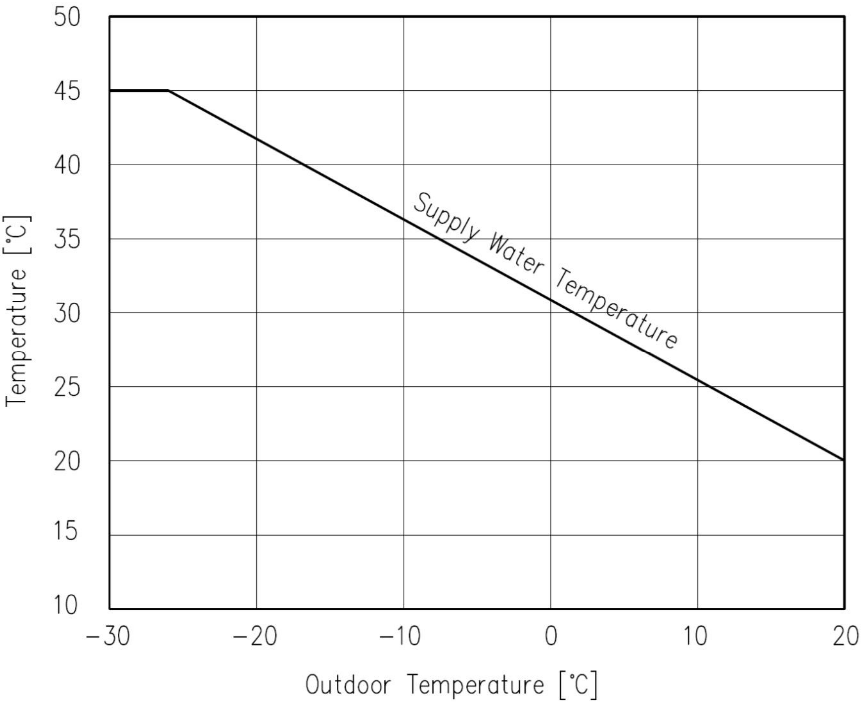


Figure C1. Supply water temperature control of radiators according to the outdoor temperature.

	Description / Value	Notifications
Domestic hot water system		
Domestic hot water consumption	0.500 $m^3/(m^2$, year)	Area-based consumption (based on ongoing FInZEB-project)
Domestic hot water circulation system	yes	
DHW circulation system temperatures	58/55 ºC	
DHW circulation system water flow	0.13 dm^3/s	Assuming well insulated pipes

The usage profile of the domestic hot water consumption is presented in Appendix A.

Internal heat gains from lighting, persons and household equipment

The usage of the building, including usage profiles and specific internal gain power outputs, is assumed to be according to the Finnish building code part D3. The internal gains from lighting, persons and household equipment are shown in Table C3. The heat gains presented are used in every room of the building.

Table C3. The internal gains from lighting, persons and household equipment in the new apartment building.

Internal heat gain	Specific power / Notifications
Persons	3.0 W/m^2, which equals to 1 person per 28 m^2 with activity level of 1.2 met and clothing 0.75 ± 0.25 clo
Lighting	11.0 W/m^2
Household equipment	4.0 W/m^2

Hourly internal heat gains from household equipment and persons are calculated by multiplying the specific powers (W/m^2) shown in Table C3 by the constant usage rate 0.6 and hourly internal heat gain from lighting by the constant usage rate of 0.1, according to the Finnish building code part D3.

Appendix D: Detailed energy calculation data for 1960s apartment building

Structures

Table D1. Structures and their main features.

Structure	Description / Value	Notifications
External wall	U-value: 0.60 W/m^{2}K	Plaster 10 mm Burnt tile 120 mm Thermal insulation 75 mm Burnt tile 60 mm Plaster 10 mm
Roof	U-value: 0.34 W/m^{2}K	Burnt tile 20 mm Foamed plastic insulation 107 mm Concrete slab 150 mm Plaster 10 mm
Base floor (connected to the ground)	U-value: 0.40 W/m^{2}K	Plastic carpet 5 mm Lightweight concrete block 20 mm Concrete slab 200 mm Polystyrene insulation 72 mm Ground layer 500 mm
Internal wall	U-value: 1.78 W/m^{2}K	Gypsum board 13 mm Wooden frame (at 600 mm) + air gap 70 mm Gypsum board 13 mm
Intermediate floor	U-value: 1.78 W/m^{2}K	Plastic carpet 5 mm Lightweight concrete block 20 mm Concrete slab 250 mm
External door	U-value: 1.41 W/m^{2}K	Wood 70 mm
Windows	U-value: 2.50 W/m^{2}K Orientation of the windows: *North: 202.1 m^2* *East: 19.8 m^2* *South: 222.6 m^2* *West: 19.8 m^2*	Window type: MS-170 (two-frame and two-glazing structure, opened inwards) Glazing U-value: 2.50 W/m^{2}K g-value: 0.76 ST-value: 0.69 Internal/external emissivity: 0.90 Frame depth: 170 mm Frame fraction of the total window area: 0.10 (10%)

Integrated window shading	Blinds between panes	Multiplier for g-value: 0.39 Multiplier for ST-value: 0.12
Air-tightness of the building	q_{50}-value = 6.00 m^3/(m^2 h)	

The thermal bridges between the structure joints and their conductances used in the energy simulation are shown in Table D2.

Table D2. Thermal bridges of the structure joints and their conductances.

Structure joint	**Conductance**	**Notifications**
External wall / external wall, outer corner	0.06 W/mK	
External windows perimeter	0.04 W/mK	
External doors perimeter	0.04 W/mK	
Roof / external walls	0.08 W/mK	
Base floor / external walls	0.24 W/mK	

A more detailed description of the structure materials and their main features are shown on the tables below.

External wall

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (inner)					0.13
2	Plaster	10	1	1800	1000	0.010
3	Burnt tile	120	0.650	1500	1000	0.185
4	Thermal insulation	75	0.063	25	1030	1.190
5	Burnt tile	60	0.650	1500	1000	0.092
6	Plaster	10	1	1800	1000	0.010
7	Thermal resistance (exterior)					0.04
Total	**U-value**	**0.60**	**W/m²K**			

Roof

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (exterior)					0.04
2	Burnt tile	20	0.650	1500	1000	0.031
3	Foamed plastic insulation	107	0.040	20	1450	2.675
4	Concrete	150	2.000	2400	1000	0.075
5	Plaster	10	0.9	1700	1000	0.011
6	Thermal resistance (inner)					0.10
Total	**U-value**	**0.34**	**W/m^{2}K**			

Base floor (connected to the ground)

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (inner)					0.17
2	Plastic carpet	5	0.17	1200	1400	0.029
3	Lightweight concrete block	20	0.14	500	1000	0.148
4	Concrete	200	2.000	2400	1000	0.100
5	Polystyrene insulation	72	0.04	20	1450	1.800
6	Ground layer	500	2	2000	1000	0.250
Total	**U-value**	**0.40**	**W/m^{2}K**			

Internal wall

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (inner)					0.13
2	Gypsum board	13	0.21	700	1000	0.062
3	Wooden frame (at 600 mm) + air gap	70	0.390	1.2	1006	0.179
4	Gypsum board	13	0.21	700	1000	0.062
5	Thermal resistance (inner)					0.13
Total	**U-value**	**1.78**	**W/m^{2}K**			

Intermediate floor

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (inner)					0.13
2	Plastic carpet	5	0.17	1200	1400	0.029
3	Lightweight concrete block	20	0.14	500	1000	0.148
4	Concrete	250	2.000	2400	1000	0.125
5	Thermal resistance (inner)					0.13
Total	**U-value**	**1.78**	**W/m^{2}K**			

External door

Structure		D,mm	λ, W/mK	ρ, kg/m^3	c_p, J/kgK	R, m^{2}K/W
1	Thermal resistance (inner)					0.13
2	Wood	70	0.13	500	1600	0.538
3	Thermal resistance (exterior)					0.04
Total	**U-value**	**1.41**	**W/m^{2}K**			

HVAC systems

The HVAC systems, their main features, operational functions and set points are shown below.

	Description / Value	**Notifications**
Ventilation system		
Mechanical exhaust ventilation system		Without heat recovery system
Operation schedule	Monday-Sunday 00:00–24:00	Same operation schedule throughout the year
Supply and exhaust air flow rate	0.4 dm^3/(s, m^2)	CAV-ventilation system
Supply air temperature in rooms	-	According to the outdoor temperature
Temperature increase in the supply air fan	-	No supply air fan
Heat recovery unit	-	No heat recovery unit
The SFP-value of the ventilation system	1.50 kW/(m^3/s)	

Heat distribution and heating system		
Type of the heat distribution system	Water-based radiator heating system	
Dimensioning temperatures of the heat distribution system	80/50 °C (with the district heating) / 45/35 °C (with the heat pumps)	Supply water temperature control according to the outdoor temperature
Room temperature set point for heating	21.0 ºC / 17.0 ºC	21.0 ºC (living spaces) 17.0 ºC (cellar and stair cases)
Supply water temperature of the heating system	According to the figures D1 and D2	

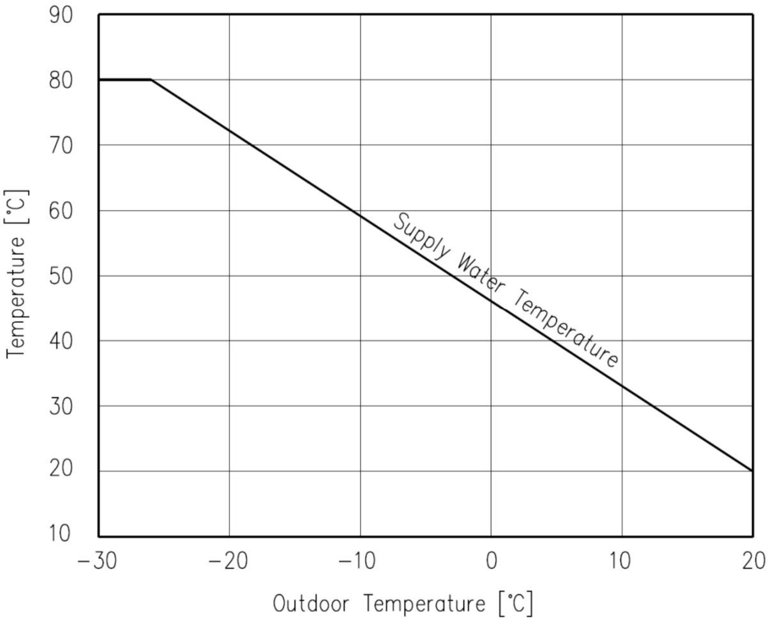


Figure D1. Supply water temperature control with the district heating according to the outdoor temperature (original high-temperature radiator heating system).

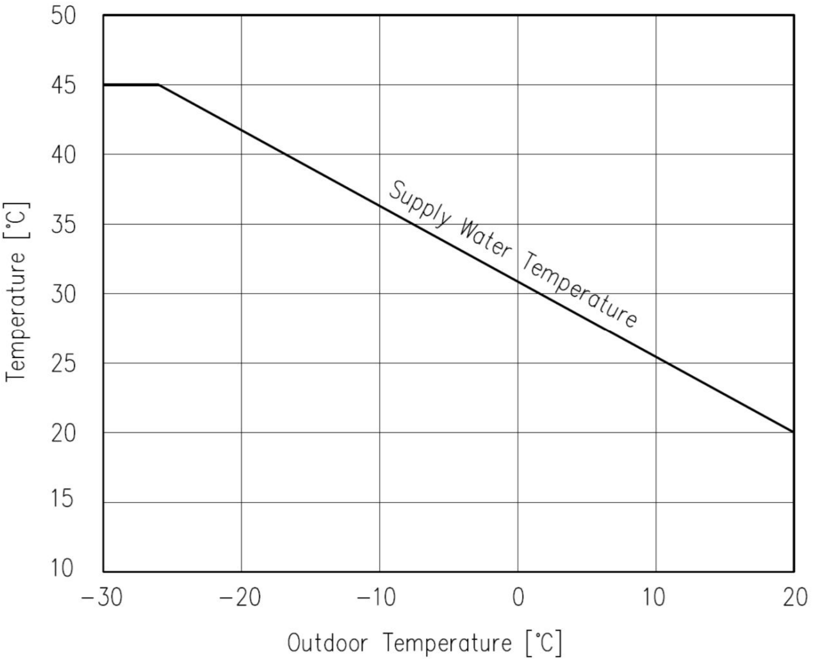


Figure D2. Supply water temperature control with the heat pumps according to the outdoor temperature (low-temperature radiator heating system).

	Description / Value	Notifications
Domestic hot water system		
Domestic hot water consumption	0.500 $m^3/(m^2$, year)	Area-based consumption (based on ongoing FInZEB-project)
Domestic hot water circulation system	Yes	No circulation system
DHW circulation system temperatures	60/55 °C	Designing temperatures
DHW circulation system water flow	0.23 dm^3/s	Designing water flow

The usage profile of the domestic hot water consumption is presented in Appendix A.

Internal heat gains from lighting, persons and household equipment

The usage of the building, including usage profiles and specific internal gain power outputs, is assumed to be according to the Finnish building code part D3. The internal gains from lighting, persons and household equipment are shown in Table D3. The heat gains presented are used in every room of the building.

Table D3. The internal gains from lighting, persons and household equipment in the 1960s apartment building.

Internal heat gain	**Specific power / Notifications**
Persons	3.0 W/m^2, which equals to 1 person per 28 m^2 with activity level of 1.2 met and clothing 0.75 ± 0.25 clo
Lighting	11.0 W/m^2
Household equipment	4.0 W/m^2

Hourly internal heat gains from household equipment and persons are calculated by multiplying the specific powers (W/m^2) shown in Table D3 by the constant usage rate 0.6 and hourly internal heat gain from lighting by the constant usage rate of 0.1, according to the Finnish building code part D3.

Appendix E: LCC Calculation output values

New detached house GSHP		
Investment cost of heating system [1]	13 000 €	
Investment cost of solar electrical energy	4 €	m2
Investment cost of solar heating energy	24 €	m2
Annual maintenance cost (share of investment cost)	1 %	
Maintenance costs of solar electrical energy	2 €	m2
Maintenance costs of solar heating	14 €	m2
Renewing cost and period (€) [3]	4 000 €	15y
Residual value after 25 years % of investment	50 %	
New detached house AWHP		
Investment cost of heating system	10 000 €	
Electrical after-heating radiator (€) [3]	2 500 €	
Ventilation investment (€) [4]	2 500 €	
Annual maintenance cost (share of investment cost)	2 %	
Renewing cost	3 000 €	15y
Residual value	10 %	
New detached house EAHP		
Investment cost of heating system [1]	10 000 €	
Free-cooling (€) [1]	2 500 €	
Annual maintenance cost (share of investment cost) [3]	1,50 %	
Renewing cost	10 000 €	20y
Residual value after 25 years	75 %	
New detached house AAHP		
Investment cost of heating system [1]	10 000 €	
Electrical after-heating radiator (€) [3]	800 €	
Annual maintenance cost (share of investment cost) [3]	1,50 %	
Renewing cost	3 000 €	15 y
Residual value after 25 %	10 %	

New apartment building GSHP		
Investment cost of heating system [1]	90 000 €	
Free cooling (€) [1]		
Annual maintenance cost (share of investment cost) [3]	1 %	/15y
Renewing cost and period (€) [3]	25 000 €	
Residual value after 25 years (% of investment cost) [3]	50 %	/m2
Investment cost of solar electrical energy	4 €	
New apartment building AWHP		
Investment cost of heating system [1]	70 000 €	
Free cooling (€) [1]	2 500 €	
Annual maintenance cost (share of investment cost) [3]	1,5 %	/15y
Renewing cost (€) and period [3]	25 000 €	
Residual value after 25 years (% of investment cost) [3]	10 %	
New apartment building DH		
Investment cost of heating system [1]	95 000 €	inc. Connection
Free cooling (€) [1]	2 500 €	
Annual maintenance cost (share of investment cost) [3]	0,5 %	/15y
Renewing cost and period (€) [3]	1 000 €	
Residual value after 25 years (% of investment cost) [3])	50 %	/m2
Investment cost of solar electrical energy	4 €	/m2
Investment cost of solar heating energy	20 €	25y
Annual maintenance costs of solar electrical energy (% of investment cost)	2 %	20y
Annual maintenance costs of solar heating (% of investment cost)	2,5 %	

Apartment building (built in the 1960s) EAHP		
Investment cost of heating system [1]	90 000 €	
Renewing of radiators	135 000 €	
Investment cost of solar electrical energy	4 €	m2
Investment cost of solar heating energy	20 €	m2
Annual maintenance cost (share of investment cost) [3]	1,50 %	
Maintenance costs of solar electrical energy	2 €	m2
Maintenance costs of solar heating	14 €	m2
Renewing cost	15 000 €	20y
Residual value after 25 years	50 %	
Apartment building (built in the 1960s) GSHP		
Investment cost of heating system [1]	165 000 €	
Renewing of radiators	135 000 €	
	1 %	
Renewing cost and period (€) [3]	35 000 €	15y
Residual value after 25 years (% of investment cost) [3]	50 %	
Apartment building (built in the 1960s) AWHP		
Investment cost of heating system [1]	103 000 €	
Renewing of radiators	135 000 €	
Annual maintenance cost (share of investment cost) [3]	1,5 %	
Renewing cost (€) and period [3]	30 000 €	15y
Residual value after 25 years (% of investment cost) [3]	10 %	
Apartment building (built in the 1960s) DH		
Investment cost of heating system [1]	55 000 €	
Annual maintenance cost (share of investment cost) [3]	0,5 %	
Renewing cost and period (€) [3]	1 000 €	15y
Residual value after 25 years (% of investment cost) [3])	50 %	

All information includes VAT 24%
All the prices of energy costs are based on Vantaa Energia 1.6.2014.
[1] Souce: KH-kortisto, FinZEB-project, projects of VTT.
[2] District heating as extra heating.
[3] SFS EN 15978. Rakennusten energiajärjestelmien taloudellisuuden arviointimenettelyt.

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VTT Technology 235

Title	**Heat pumps in energy and cost efficient nearly zero energy buildings in Finland**
Author(s)	Suvi Häkämies (edit.), Jussi Hirvonen, Juha Jokisalo, Antti Knuuti, Risto Kosonen, Tuomo Niemelä, Satu Paiho & Sakari Pulakka
Abstract	This report is the final report of development project "HP4NZEB – Heat Pump Concepts for Nearly Zero Energy Buildings", where the main objective was to outline the role of heat pumps in energy- and cost-efficient nearly zero energy building solutions. The project outlined that Finnish nearly zero energy level for buildings can be achieved more cost-efficiently with concepts utilizing heat pumps than district heating. The building types and the studied heat pump concepts were: Building type 1: New detached house, 180 m^2: • Concept 1: Ground source heat pump • Concept 2: Air-to-water heat pump • Concept 3: Exhaust air heat pump • Concept 4: Air-to-air heat pump Building type 2: New apartment building: • Concept 1: Ground source heat pump • Concept 2: Air-to-water heat pump • Concept 3: District heating (for reference) Building type 3: Renovation concept of 1960s apartment building: • Concept 1: District heating (for reference) • Concept 2: Exhaust air heat pump • Concept 3: Ground source heat pump • Concept 4: Air-to-water heat pump When comparing the E-value and life cycle costs of concepts utilizing heat pumps with district heating, all studied heat pump concepts were more cost efficient in both larger apartment buildings and in smaller detached houses and all studied concepts achieved the Finnish "nearly zero" level. In addition to lower life cycle costs heat pumps can also cool the building and no extra investment for cooling is needed. HP4NZEB project – coordinated by Green Net Finland and with project partners Aalto University, VTT Technical Research Centre of Finland Ltd and Finnish Heat Pump Association SULPU – was the Finnish national project participating IEA Heat Pump Programme's Annex 40.
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Nimeke	**Lämpöpumppuratkaisuihin perustuvat energiatehokkaat ja kustannusoptimaaliset lähes nollaenergiarakennuskonseptit**
Tekijä(t)	Suvi Häkämies (toim.), Jussi Hirvonen, Juha Jokisalo, Antti Knuuti, Risto Kosonen, Tuomo Niemelä, Satu Paiho & Sakari Pulakka
Tiivistelmä	Tämä raportti on kehityshankkeen "HP4NZEB – Lämpöpumppuratkaisuihin perustuvat energiatehokkaat ja kustannusoptimaaliset lähes nollaenergiarakennuskonseptit " loppuraportti. Hankkeen päätavoitteena oli selvittää asuintaloihin liittyviä lähes nollaenergiarakentamisen ratkaisuja Suomessa. Hankkeessa tarkasteltiin erityisesti sitä, millainen rooli lämpöpumpuilla on näissä ratkaisuissa. Projektissa optimoitiin järjestelmäkirjosta asuintaloihin ja niiden korjausrakentamiseen liittyviä lämpöpumppuja hyödyntäviä lähes nollaenergiarakentamisen ratkaisuja, jotka ovat Suomen olosuhteisiin sopivia. Hankkeessa tutkittiin eri lämpöpumpputyyppien energiatehokkuutta sekä ratkaisujen kustannusvaikutuksia kolmentyyppisissä tarkastelukohteissa: tyypillisessä suomalaisessa uudispientalossa, uudiskerrostalossa sekä 1960-luvulla rakennetun tyyppikerrostalon korjaustarkentamisessa. Saavutettuja uudistalojen E-lukutasoja verrattiin FInZEB-hankkeen tekemiin ehdotuksiin Suomen lähes nollaenergiarakennusten E-lukutasoista. Molemmissa uudistalotyypeissä – pientalossa ja kerrostalossa – FInZEB-hankkeen suosittelema lähes nollaenergiataso saavutettiin kaikissa tarkastelutapauksissa. Korjausrakennuskohteessa kaikki tarkastellut lämpöpumppukonseptit saavuttivat alhaisemman E-lukutason kuin vertailukohtana käytetty kaukolämpö. Kustannustehokas energiatehokkuuden optimitaso asettui uusilta kerrostaloilta vaadittuun vähimmäistasoon. HP4NZEB-hanke toteutettiin vuosina 2013–2015 Green Net Finlandin (koordinaattori), Aalto-yliopiston, VTT:n ja Suomen lämpöpumppuyhdistyksen yhteistyönä. Hankkeella osallistuttiin myös Kansainvälisen energiajärjestö IEA:n Lämpöpumppuohjelman annex-yhteistyöhön (Annex 40).
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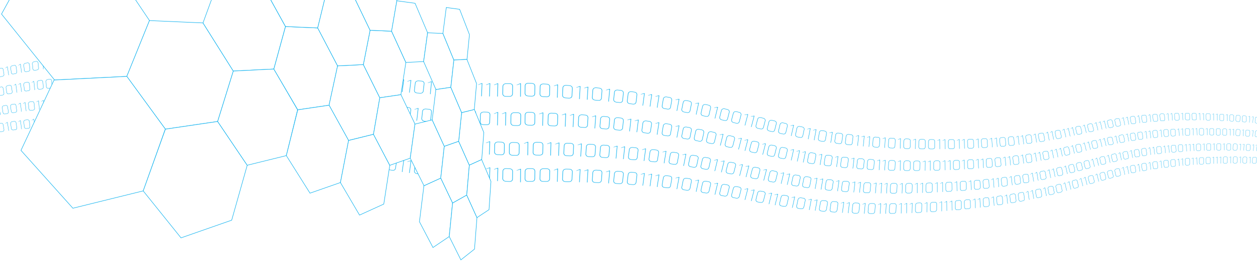

Heat pumps in energy and cost efficient nearly zero energy buildings in Finland

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