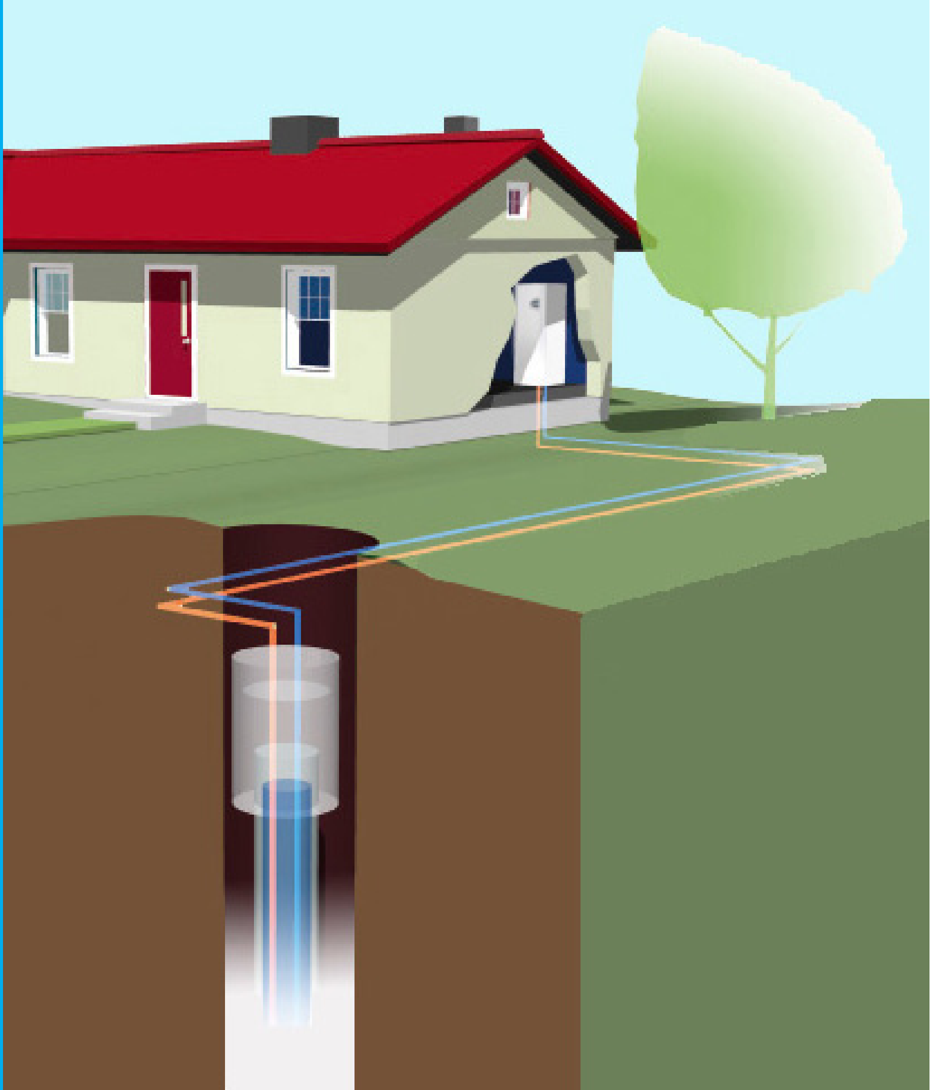

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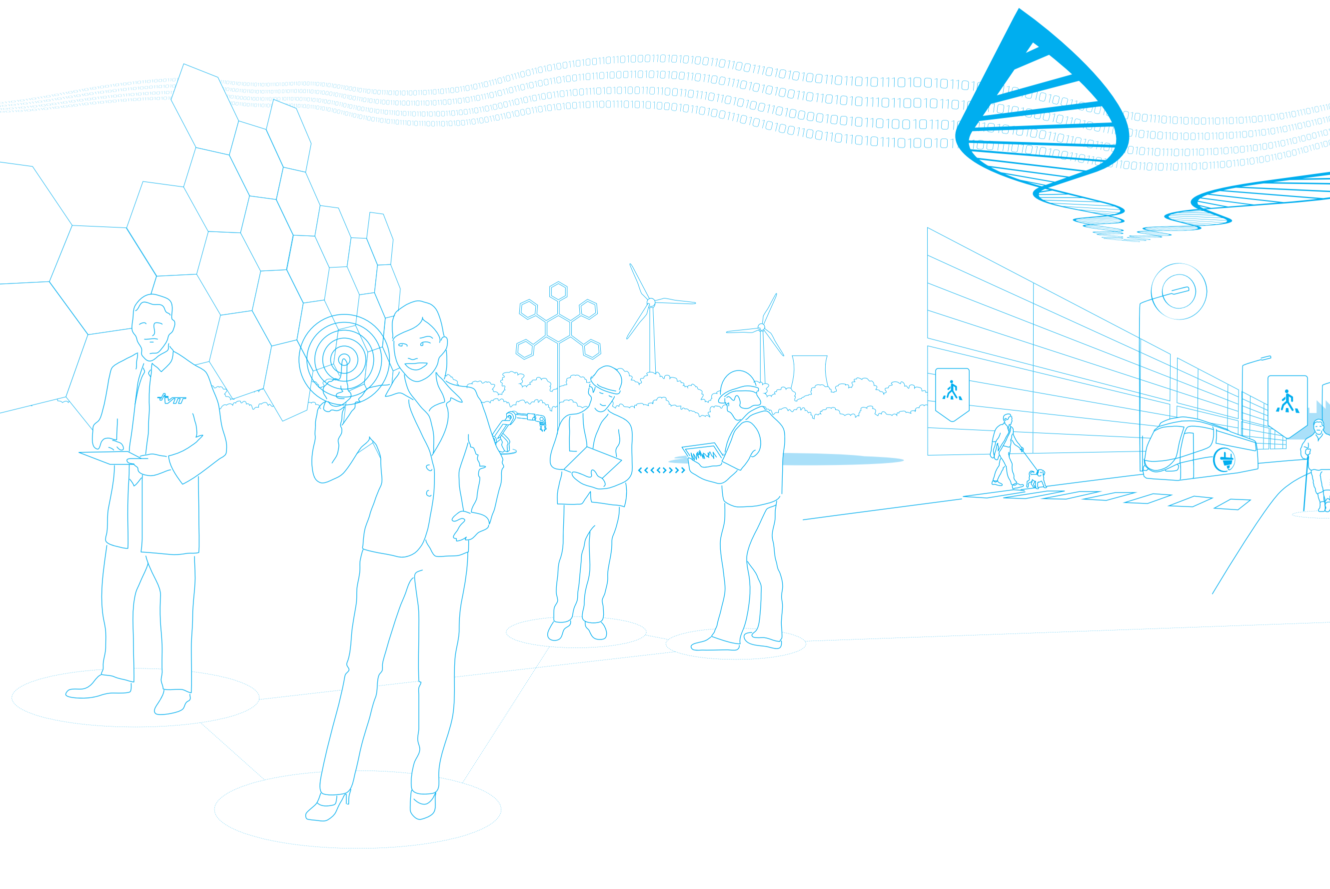

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Espoo 2014. VTT Technology 164. 90 p. + app. 30 p.

Abstract

The SPF project defined a national hourly seasonal performance factor calculation method for air to air heat pumps, air to water heat pumps, ground source heat pumps and exhaust air heat pumps in co-operation with international Annex 39 work.

The energy use of the Finnish building stock was estimated using standard building types further adapted to different decades: a detached house, an apartment building, an office building and a summer cottage. The energy use of these standard building types was calculated with different heat pump types leading to energy saving and renewable energy use of the heat pumps in different buildings.

The current and future cumulative energy consumption of the building stock was modelled using the REMA model developed at VTT. The future effects of heat pumps on the energy use and emissions of the Finnish building stock were modelled comparing with the REMA model a conservative Business as Usual scenario with a Heat Pump scenario.

Keywords seasonal performance factor, heat pump, energy saving, renewable energy

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Tiivistelmä

SPF-hankkeessa määriteltiin kansallinen tunneittainen kausihyötysuhteen laskentamenetelmä ilmalämpöpumpuille, ilma-vesilämpöpumpuille, maalämpöpumpuille sekä poistoilmalämpöpumpuille yhteistyössä kansainvälisen Annex 39 -ohjelman kanssa.

Suomen rakennuskannan energiankulutusta arvioitiin eri vuosikymmenille määriteltyjen tyyppirakennusten avulla, jotka edustivat pientaloa, kerrostaloa, toimistotaloa sekä vapaa-ajan rakennusta. Näille tyyppirakennuksille arvioitiin energiansäästöpotentiaali ja uusiutuvan energian tuotto eri lämpöpumppuvaihtoehdoilla.

Koko rakennuskannan nykyistä ja kumulatiivista energiankulutusta arvioitiin VTT:n kehittämällä REMA-mallilla. Lämpöpumppujen tulevaa vaikutusta suomalaisen rakennuskannan energiankulutukseen ja päästöihin arvioitiin vertaamalla perinteistä Business as Usual -skenaariota lämpöpumppuskenaarioon, joka kuvaa lämpöpumppujen nopeampaa yleistymistä.

Avainsanat seasonal performance factor, heat pump, energy saving, renewable energy

Preface

The object of the SPF project was to define a national seasonal performance factor calculation for heat pumps in co-operation with Annex 39 work. The other goal was to estimate the energy saving and renewable energy potential of heat pumps on the Finnish building stock. The project duration was from 1.3.2011 to 31.12.2013.

The project was financed by the Finnish ministry of employment and the economy, the Finnish ministry of the environment and SITRA, Finnish Innovation Fund. The work was performed by VTT Technical Research Centre of Finland (coordinator), Aalto University and the Finnish heat pump association SULPU.

Contents

Appendices

List of symbols

b	[°C]	constant term of the control curve
$c_{p,air}$	[kJ/kg,K]	specific heat capacity of air
$c_{p,wv}$	[°C]	specific heat capacity of water vapour
$COP_{DSW}(t)$	[-]	hourly heat pump COP for DSW heating
COP_{N}	[-]	measured heat pump COP in test point
$COP_{spaces}(t)$	[-]	hourly heat pump COP for space heating
COP_{T}	[-]	theoretical heat pump COP
$COP_{T}(t)$	[-]	theoretical hourly COP of the heat pump
E_{res}	[kWh/a]	annual renewable energy production
$f_{T}(t)$	[-]	loss factor of the compressor
h	[kJ/kg]	enthalpy
$h_{1}(t)$	[kJ/kg]	outlet air enthalpy before the condenser
$h_{2}(t)$	[kJ/kg]	waste air enthalpy after the condenser
H_{HP}	[h]	equivalent running time at full load
k	[-]	slope of the control curve
L_{w}	[kJ/kg]	evaporation heat for water in 0°C
P_{aux}	[kW]	electricity consumption of the auxiliary devices
P_{rated}	[GW]	installed nominal power of heat pumps
$q_{HP,DSW}(t)$	[kWh]	DSW heating energy production
$q_{HP,spaces}(t)$	[kWh]	space heating energy production
$q_{HP,spaces,max}(t)$	[kWh]	maximum space heating energy production
Q	[m³/s]	nominal flow of air or fluid

$Q_{additional}$	[kWh]	additional heating energy
$Q_{heating,DSW}$	[kWh]	DSW heating energy demand
$Q_{heating,spaces}$	[kWh]	space heating energy demand
$Q_{HP,DSW}$	[kWh]	DSW heating energy production of the heat pump
$Q_{HP,spaces}$	[kWh]	space heating energy production of the heat pump
$Q_{outlet}(t)$	[m³/s]	outlet air flow
Q_{usable}	[kWh/a]	annual heating energy production of a heat pump
S_{Hdd}	[Kh]	heating degree day
t_{DSW}	[h]	DSW heating time of heat pump during one time step
$t_{space,max}(t)$	[h]	space heating time of heat pump during one time step
$t_{time-step}$	[h]	calculation time step
T_{dim}	[°C]	dimensioning outdoor temperature for space heating
T_{DSW}	[°C]	DSW temperature
T_{fluid}	[°C]	fluid temperature leaving the heat collection circuit
T_{Hdd}	[°C]	indoor temperature representing the heating degree day
$T_{HP,max}$	[°C]	maximum water temperature the heat pump can deliver
T_{HSo}	[°C]	heating source temperature
T_{HSy}	[°C]	building heating system temperature
T_{indoor}	[°C]	indoor air temperature
T_{iw}	[°C]	temperature of the inlet water leaving the condenser
$T_{iw,max}$	[°C]	max. inlet water temp. in dimensioning outdoor temp.
$T_{iw,min}$	[°C]	minimum inlet water temperature
$T_{outdoor}(t)$	[°C]	hourly outdoor temperature
$T_{outdoor,iw,min}$	[°C]	outdoor temp. representing minimum inlet water temp.
T_{SW}	[°C]	cold service water temperature
T(t)	[°C]	outlet air or waste air temperature
$w_{HP}(t)$	[kWh	hourly electricity consumption of a heat pump]
W_{aux}	[kWh]	electricity consumption of auxiliary devices of heat pump
W_{HP}	[kWh]	electricity consumption of the heat pump
x(t)	[kg/kg]	absolute humidity of outlet air or waste air

Greek symbols:

$\beta_{HP,DSW}(t)$	[-]	hourly load power ratio for DSW
$\beta_{HP,spaces}(t)$	[-]	hourly load power ratio for space heating
ΔP_e	[Pa]	static ductwork or pipework pressure loss
Δt	[h]	auxiliary device usage time during calculation period
$\phi_{DSW}(t)$	[kW]	hourly DSW heating power demand of the building
$\phi_{HPc}(t)$	[kW]	condenser power of the heat pump
$\phi_{HP,DSW}(t)$	[kW]	hourly DSW heating power of the heat pump
$\phi_{HP,max}(t)$	[kW]	maximum heating power of the heat pump in test point
$\phi_{HP,spaces}(t)$	[kW]	hourly space heating power demand of the heat pump
$\phi_{spaces}(t)$	[kW]	hourly space heating power demand of the building
η	[-]	fan or pump efficiency rate
ρ	[kg/m³]	outlet air density

Abbreviations:

DSW	Domestic Service Water
HP	heat pump

1. Introduction

The effectiveness of a heat pump can be described by means of Coefficient Of Performance (COP) and Seasonal Performance Factor (SPF). COP represents how much heat power a heat pump delivers in relation to the electricity demand of the compressor and electrical devices, and it is calculated by dividing the delivered heat power with the electricity consumption of the heat pump. COP is calculated at single operation conditions and at full capacity, even though these conditions do not always reflect the real performance of heat pumps in practical operation in heating systems. Heat pumps mainly operate intermittently or at reduced capacity (through capacity control) in climatic conditions that differ from the standard rating conditions.

SPF is defined by dividing the energy output of a system by the energy used for the production and therefore it presents better the actual operation and annual savings of the heat pump. The influence of part load or variable capacity on SPF is currently not fully covered by existing methods for calculation of SPF (Annex 39 legal text). According to the European Heat Pump Association, the standard EN14511 does not specify the calculation method for SPF and therefore it is important to clearly define the system boundary.

The first main object of the SPF project was to define a Finnish SPF calculation method for heat pumps in co-operation with international Annex 39 work. The other main object was to estimate the current and future energy saving and renewable energy use potential of heat pumps on the Finnish building stock.

2. Heat pump volume scenarios

2.1 Heat pump stock and capacity prognosis (domestic heat pumps)

The year 2010 numbers of installed heat pumps in this chapter are based on the sales statistics maintained by the Finnish Heat Pump Association (Sulpu).

Air-air heat pumps are dominating the markets in terms of sales numbers. Traditionally, they have been a cost-effective way of retrofitting electrically heated houses. They have also been installed in a large number of summer cottages, where they provide a complement to electric heating. It should be noted that air/air heat pumps are sold through a number of channels: builder's merchants, mail-order firms, and web stores. Since there are no sales statistics for these channels, the sales numbers for air/air heat pumps can only be estimated.

Though the installed number of ground source heat pumps is much lesser than air/air heat pumps they play important role in installed capacity in the use of renewable energy. Ground source heat pumps will also play important role in the future in the new building sector as well as in retrofitting of old oil and electrical heating systems.

Exhaust air heat pumps have a moderate market share, but one which will probably decrease in the future. They have been installed in some new-building construction. However, the standard type of these heat pumps does not comply with the new, more stringent building regulations. They may be used in the most well-insulated new buildings, or may replace old exhaust air heat pumps.

Recently, air/water heat pumps have been introduced on the Finnish retrofit market but their current share of the market is marginal and the development is seen moderate.

The total number of heat pumps is estimated to reach about 950 000 units by 2020. These estimations take into account that part of the heat pump sales are replacements, thus the total heat pump sales will be higher than the numbers shown in Figure 1 and Table 1. The cumulative number of heat pumps is calculated based on the following life time expectations: air/air heat pumps 10 years, ground source heat pumps 20 years, air/water and exhaust heat pumps 15 years. The calculated heat pump heating capacity 2010 and estimations for 2016 and

2020 are presented in Table 2. The scenario of the heating capacity of the heat pumps by Sulpu is presented in Figure 2.

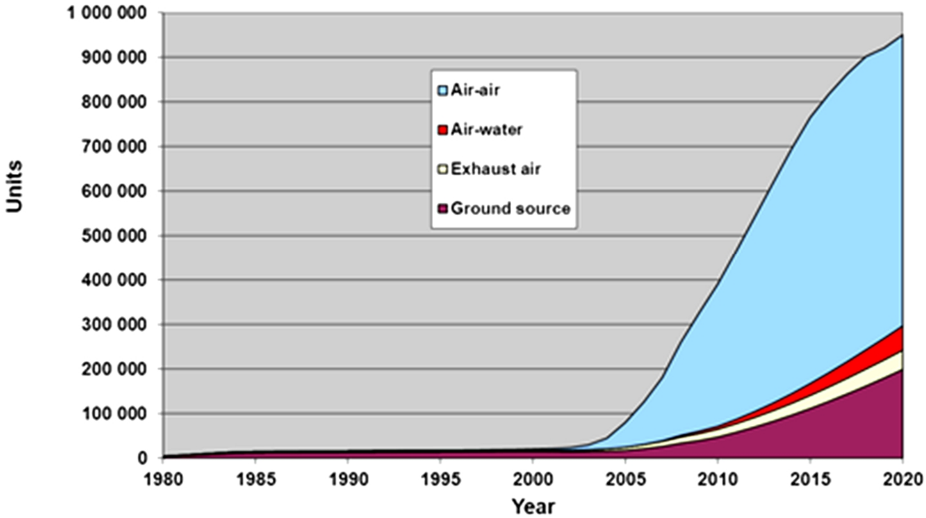

Figure 1. Scenario of the heat pump stock (Sulpu).

Table 1. Number of heat pumps in 2010 and estimated numbers in 2016 and 2020.

Year	Ground source	Air-air	Air-water	Exhaust air	Total
2010	47 390	319 501	6 326	17 533	390 750
2016	127 440	626 098	31 526	32 383	817 447
2020	199 190	653 821	54 326	43 207	950 544

Table 2. Heating capacity of heat pumps in 2010 and estimated capacities in 2016 and 2020.

Year	Ground source, kW	Air-air, kW	Air-water, kW	Exhaust air, kW	Total, MW
2010	564 415	1 520 825	73 255	58 911	2 217
2016	1 517 810	2 980 226	365 071	108 807	4 972
2020	2 372 353	3 112 188	629 095	145 176	6 259

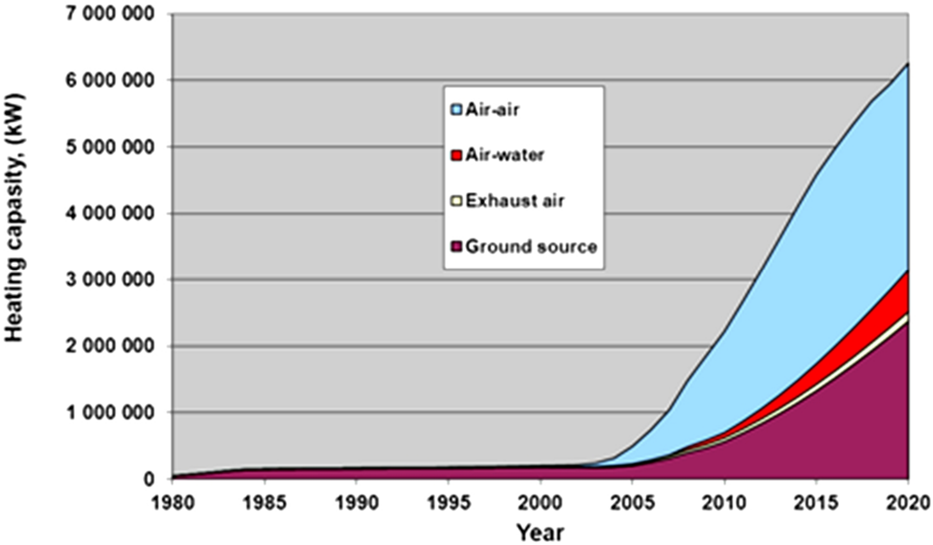

Figure 2. Scenario of the heating capacity of the heat pumps (Sulpu).

2.2 Heat pump stock (non-domestic heat pumps)

The amounts of large heat pumps used for industrial purposes have not been collected before in Finland. Finnish heat pump manufacturers were asked to give data about over 100 kW heat pumps which they have delivered during the last 10 years. Answers were received from four manufacturers. The total number of heat pumps was 95 and the average heating power of the pumps was 464 kW. At least 25 pumps were used for cooling and their average cooling power was 634 kW. The average yearly usage time was 5 525 hours and the average SPF 4.2.

The heat source was given for 25 heat pumps. Six of these 25 pumps utilized renewable energy for heat production: one from water and five from the ground. The total annual renewable heat production of these pumps was calculated with Eq. (1.1) to be around 12 GWh if they are estimated to operate with full power.

2.3 Heat pump distribution by building type

The distribution of heat pumps by building type has been estimated by the statistics of Rakennustutkimus RTS Oy. According to the obtained data based on the statistics of the year 2010 (RTS) the percentage of heat pumps in different building types were calculated (Table 3).

Table 3. Percentage distribution of heat pumps by building type in 2010.

Percentage distribution of heat pumps in 2010					
	Detached houses, %	**Attached houses, %**	**Blocks of flats, %**	**Free time residences, %**	**Total, %**
Ground source	97.90	0.21	0.04	1.85	100
Exhaust air	85.00	10.00	0.00	5.00	100
Air/air	75.76	12.12	4.55	7.58	100
Air/water	100.00	0.00	0.00	0.00	100

These distributions of heat pumps in different building types (Table 3) were used in estimating the number of heat pumps in different building types in 2010 (Table 4), 2016 (Table 5) and 2020 (Table 6). Also the building stock was made to correspond the figures of 2010.

Table 4. Number of heat pumps by building type in 2010.

Number of heat pumps in 2010					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total number**
Building stock, 1000 numbers	1126	380	1221	580	3307
Ground source	46395	101	19	875	47390
Exhaust air	14903	1753	0	877	17533
Air/air	242046	38727	14523	24205	319501
Air/water	6326	0	0	0	6326
Total number of heat pumps	309670	40581	14542	25957	390750

Table 5. Number of heat pumps by building type in 2016.

Number of heat pumps in 2016					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total number**
Building stock, 1000 numbers	1126	380	1221	580	3307
Ground source	124763	271	52	2354	127440
Exhaust air	27526	3238	0	1619	32383
Air/air	474317	75891	28459	47432	626098
Air/water	31526	0	0	0	31526
Total number of heat pumps	658132	79400	28511	51405	817447

Table 6. Number of heat pumps by building type in 2020.

Number of heat pumps in 2020					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total number**
Building stock, 1000 numbers	1126	380	1221	580	3307
Ground source	195007	423	81	3679	199190
Exhaust air	36726	4321	0	2160	43207
Air/air	495319	79251	29719	49532	653821
Air/water	54326	0	0	0	54326
Total number of heat pumps	310	83995	29800	55372	950544

3. Simplified seasonal performance factor calculation method

3.1 Adaptation of the Eurostat method to national conditions

The simplified calculation method was used for the calculation of renewable energy production and energy saving potential of the heat pumps used in Finland for the National Renewable Energy Action Plan (NREEAP) and the National Energy Efficiency Action Plan (NEEAP). NREEAPs are roadmaps of all EU Member States for reaching its legally binding 2020 target for the share of renewable energy in their final energy consumption. NEEAPs include a an indicative energy savings target for the Member States, obligations on national public authorities as regards energy savings and energy efficient procurement, and measures to promote energy efficiency and energy services.

The simplified SPF calculation method is based on the method presented in renewable energy directive (Annex VII) by EUROSTAT, DG ENERGY and Industry. The renewable energy production E_{res} (kWh/a) of a heat pump, the portion of the heat pump energy output which is accepted as renewable, is calculated as

$$E_{res} = Q_{usable}\left(1 - \frac{1}{SPF}\right) \quad (1.1)$$

where Q_{usable} is the annual heating energy production of the heat pump (kWh/a) and SPF is the seasonal performance factor.

Q_{usable} is defined as the installed capacity of a heat pump (kW) multiplied with $Q_{usablefactor}$ (h/a). Table 7 presents the values for SPF and $Q_{usablefactor}$ suggested by EUROSTAT (DG ENERGY). These values were examined in the SPF project by VTT and new values suggested for calculation of the renewable energy production and energy saving potential of the heat pumps in Finland (Table 8).

Table 7. SPF and $Q_{usablefactor}$ values suggested by EUROSTAT.

Heat source	SPF			$Q_{usablefactor}$		
	warm climate	average climate	**cold climate**	warm climate	average climate	**cold climate**
Air	3.5	3.3	**3.0**	1 000	1 500	**2 500**
Water	3.6	3.5	**3.0**	1 150	1 600	**3 500**
Ground	3.7	3.6	**3.0**	1 150	1 600	**3 500**

Table 8. SPF and $Q_{usablefactor}$ values by VTT suggested to be used as national values in Finland.

Heat pump type	SPF, cold climate	$Q_{usablefactor}$, cold climate
Air-air	3.0	1 500
Air-water	2.0	2 000
Exhaust air	2.0	3 500
Ground	3.0	2 500

Justifications for the values in Table 8 are presented below for different heat pump types.

Ground source heat pumps

According to the statistics of Sulpu the average installed heating capacity of one heat pump is 11.9 kW. This capacity gives the yearly energy consumption of 41.7 MWh per one heat pump using the values of the proposal by EUROSTAT. This energy consumption was considered to be too high because most of the ground source heat pumps are installed in single family houses. The heating energy demand of a single family house ranges widely, but exceeds 30 MWh/year only in old buildings built before 1980.

In the future the multifamily installations (terraced and apartment buildings) will gain popularity but at the same time the energy demand of the building stock will decrease. A $Q_{usablefactor}$ value of 2500 instead of the EUROSTAT value of 3000 was proposed to have more realistic estimates for the renewable energy use of ground source heat pumps. This value is based on the yearly energy demand of 30 MWh per unit. The SPF value 3 proposed by EUROSTAT was considered to be at a right level compared to the literature values.

Air/air heat pumps

According to the statistics of Sulpu the average heating capacity of one air/air heat pump is 4.8 kW. With this heating capacity and the $Q_{usablefactor}$ value of 2500 proposed by EUROSTAT the yearly heating energy production of an air/air hest pump is 11.9 MWh. This annual heating energy production is considerably higher than the empirical (Elvari, VTT) and theoretical studies (Aalto, VTT) made for Finnish air/air heat pumps have shown. For example, the field studies made in Elvari project suggest an average energy production of 2.5 MWh/year per one air/air heat pump and the theoretical studies imply average heating energy productions between 3–7 MWh/year depending on the heating demand of the building.

The suggested national value 1500 for the $Q_{usablefactor}$ is based on the average heating capacity based on the statistics of the Finnish Heat Pump Association Sulpu and the estimated yearly energy production of 5 MWh/year which is a compromise of the experiences from field measurements and theoretical studies stated above. The SPF value 3 proposed by EOROSTAT was considered to be at the same level as the laboratory tests made by VTT and the Finnish magazine Tekniikan Maailma have shown.

Air/water heat pumps

Air/water heat pumps are rather new in the Finnish heat pump markets so there are few experiences from them. In this study the energy production of one air-water heat pump was estimated to be 24 MWh/year which is 80% of the energy production of a ground source heat pump. This assumption was proposed by the Finnish Heat Pump Association Sulpu. An energy production of 24 MWh/year together with the statistical average heating capacity of 11.6 kW, also based on the experiences by Sulpu, the national value for $Q_{usablefactor}$ is 2000. This is substantially lower that the value 3000 proposed by EUROSTAT.

The SPF value of 3 given by EUROSTAT was considered to be too high compared to the laboratory tests made by Tekniikan Maailma and experiences by Sulpu. Therefore a national SPF value of 2 is proposed in this report.

Exhaust air heat pumps

In the case of exhaust air heat pumps it is proposed to use a higher national value 3500 for $Q_{usablefactor}$ instead of the suggested 3000 by EUROSTAT. The higher value is based on experiences from literature and Sulpu which suggest the average heating energy production of one exhaust air heat pump to be around 12 MWh/year per heat pump and the statistical average heating capacity 3.4 kW.

The SPF value of 3 proposed by EUROSTAT was considered to be too high compared to the experiences by Aalto and literature, therefore a lower national value of 2 was proposed in this study.

3.2 Energy saving estimations using a simplified SPF calculation method

So called KETO-calculation was performed by VTT for the Ministry of employment and the economy in autumn 2013. KETO (kansallinen energiatehokkuusohjelma) is national implementation plan of EED directive (Directive 2012/27/EU). KETO-calculation for heat pumps covered the energy saving estimations for years 2010–2020. The number of heat pumps in this calculation were based on updated heat pump scenarios (chapter 2) of SULPU. The average nominal powers were based on SULPU's estimation from year 2010 and expert estimation on the future development until year 2020. Based on the sales statistics (2010 -> 2012) the average power of all heat pump types are increasing and number of big installations, that are not included in the statistics, are increasing. Reasonable estimate for the increasing average power is 20% from year 2010 until 2020.

Energy saving potential was calculated based on the official instructions of the European Union[1]. The use of renewable energy was calculated with Eq. (1.1) based the method presented in the annex VII of the directive 2009/28/EY. The estimated total heat produced by the heat pumps, Q_{usable}, was calculated with multiplying the equivalent running time at full load with the installed nominal power of heat pumps regarding the life time of each heat pump type:

$$Q_{usable} = H_{HP} * P_{rated} \tag{1.2}$$

where

Q_{usable}	is the estimated total heat produced by the heat pumps, GWh
H_{HP}	is the equivalent running time at full load, h
P_{rated}	is the installed nominal power of heat pumps regarding the life time of each heat pump type, GW.

The equivalent running times H_{HP} and seasonal performance factors SPF suitable for the Finnish climate are presented in Table 9. These values are defined in the official instructions[1] and therefore vary from the values presented in Table 8. The life times of the heat pumps in the cumulative calculations were: 20 years for ground source heat pumps, 15 years for air to water heat pumps and 10 years for air to air heat pumps.

[1] The Official Journal of the European Union (6.3.2013): Commission decision, given on March 1 2013, on directions for member states for calculation of the share of renewable energy produced with different heat pump technologies according to the 5th article of the European Parliament and Commission directive 2009/28/EY (information number C(2013) 1082)

Table 9. Equivalent yearly running times (HHP) and average seasonal performance factors (SPF) for Finnish climate.

Heat pump	Equivalent yearly running time H_{HP}, h	Average seasonal performance factor, SPF
Air to air	1970	2.5
Air to water	1710	2.5
Exhaust air	600	2.5
Ground source	2470	3.5

Calculated cumulative energy savings of new heat pump installations for years 2010–2020 are presented in Table 10.

Table 10. Estimated total energy saving potential (E_{RES}) of new heat pump installations.

Heat pump	Cumulative saving between 2010–2013, TWh	Cumulative saving between 2014–2016, TWh	Cumulative saving between 2017–2020, TWh	Cumulative saving between 2014–2020, TWh
Air to air	7.567	3.909	0.322	4.231
Air to water	0.381	0.576	0.417	0.993
Exhaust air	0.066	0.053	0.034	0.087
Ground source	9.464	6.788	5.409	12.197
Total	**17.478**	**11.325**	**6.182**	**17.508**

Besides new installations energy saving can also be achieved when old poorly working heat pumps are replaced by new better technology. The estimated energy saving with these replacement installations is presented in Table 11. These calculations are based on very conservative improvement estimations of the seasonal performance factors: ground source SPF from 2.5 to 3.5, air to air SPF from 2.0 to 2.5, air to water SPF from 2.0 to 2.5 and exhaust air SPF from 2.0 to 2.5.

Table 11. Estimated total energy saving potential (E_{RES}) of replacement installations.

Heat pump	**Cumulative saving between 2010–2013 TWh**	**Cumulative saving between 2014–2016 TWh**	**Cumulative saving between 2017–2020 TWh**	**Cumulative saving between 2014–2020 TWh**
Air to air	0.031	0.286	0.549	0.835
Air to water	0.000	0.000	0.023	0.023
Exhaust air	0.001	0.000	0.000	0.001
Ground source	0.026	0.007	0.015	0.022
Total	**0.063**	**0.294**	**0.587**	**0.881**

4. Detailed seasonal performance factor calculation method

The detailed SPF calculation method was developed by Aalto University. The Finnish version of the detailed calculation method is presented in Appendix 1.

4.1 Calculation principles and boundaries

The hourly calculation method presented here can be used for heating energy calculation of air-air-, air-water-, exhaust air and ground source heat pumps. The calculation method cannot be used for power dimensioning of a heat pump. Calculation can be performed also with other time steps than one hour, even though the time step used in this report is one hour.

Measured performance values for the heat pump are needed for calculation input values at least in one test point. In the calculation an on-off controlled heat pump operates always with its nominal power. Evaporator and condenser powers of on-off controlled heat pumps are assumed to change according to temperatures and COP when the performance values of the heat pump are known in one test point. The calculation is more accurate if performance values are available from several test points. The condenser power of an on-off controlled heat pump is dependent on evaporator power and COP. The true COP is directly proportional to the theoretical COP value. The heating power of all power-controlled heat pumps is defined according to the hourly heating power demand of the building.

The calculation method does not take into account the heat storage ability of the domestic service water accumulator. The calculation method assumes that the heat pump heats up both domestic service water and spaces in turns so that heating up the domestic service water is the primary function.

4.2 Calculation description

4.2.1 Air-air heat pump

The SPF calculation for an air-air heat pump is performed according to following steps:

1. Definition of following input values for the calculation:
    a. Outdoor air temperature throughout the year and the calculation time step (chapter 4.3.1)
    b. Heating power or heating energy demand for space heating (chapter 4.3.3)
    c. Inlet air temperature from the heat pump or indoor air temperature set point if the inlet air temperature is not known (chapter 4.3.4)
    d. Measured COP, heating power and temperatures at least in one test point for the heat pump (chapter 4.3.4)
    e. Lowest outdoor temperature, where the heat pump can be operated (chapter 4.3.4)
2. Calculation of space heating power demand for each time step (if not available as input value) (chapter 4.5.2)
3. Calculation of heat pump COP for each time step (chapter 4.5.4)
4. Calculation of the effect of partial power on COP for each time step if the heat pump is power controlled (chapter 4.5.5)
5. Calculation of the heating power of the heat pump for each time step (chapter 4.5.10)
6. Calculation of the space heating energy demand for each time step (chapter 4.5.13)
7. Calculation of the space heating energy which the heat pump can deliver for each time step and the annual delivered space heating energy (chapter 4.5.13)
8. Calculation of the electricity consumption of the heat pump for each time step and the annual electricity consumption (chapter 4.5.14)
9. Calculation of the heat pump SPF (chapter 4.5.16)
10. Calculation of the additional space heating demand (chapter 4.5.17)

4.2.2 Air-water heat pump

The SPF calculation for an air-water heat pump is performed according to following steps:

1. Definition of following input values for the calculation:
    a. Outdoor air temperature throughout the year and the calculation time step (chapter 4.3.1)
    b. DSW (domestic service water) heating power or heating energy demand and DSW temperature (chapter 4.3.2)
    c. Heating power or heating energy demand for space heating and heating up the ventilation inlet air (chapter 4.3.3)
    d. Maximum and minimum temperatures for inlet water, dimensioning outdoor temperature and the outdoor temperature where the inlet water temperature is equal to the minimum temperature (chapter 4.3.3)
    e. Measured COP, heating power and temperatures at least in one test point for the heat pump (chapter 4.3.4)
    f. Highest DSW heating up temperature with the heat pump without additional heating demand for DSW (chapter 4.3.4)
    g. Lowest outdoor temperature, where the heat pump can be operated (chapter 4.3.4)
2. If the heat pump is used only for DSW heating, following steps are calculated:
    a. Calculation of DSW heating demand for each time step (if not available as input value) (chapter 4.5.1)
    b. Calculation of heat pump COP for DSW heating for each time step (chapter 4.5.4)
    c. Calculation of the DSW heating power of the heat pump for each time step (chapter 4.5.6)
    d. Calculation of the effect of partial power on COP for DSW heating for each time step if the heat pump is power controlled (chapter 4.5.5)
    e. Calculation of the DSW heating time during each time step (chapter 4.5.8)
    f. Calculation of the DSW heating energy which the heat pump can deliver for each time step and the annual delivered DSW heating energy (chapter 4.5.9)

3. If the heat pump is used also for space heating and/or heating up the ventilation inlet air besides DSW heating, following steps are calculated:
    a. Calculation of heating power demand for space heating and heating up the ventilation inlet air for each time step (if not available as input value) (chapter 4.5.2)
    b. Calculation of heat pump COP for space heating and heating up the ventilation inlet air for each time step (chapter 4.5.4)
    c. Calculation of the heating power of the heat pump for space heating and heating up the ventilation inlet air for each time step (chapter 4.5.10)
    d. Calculation of the effect of partial power on COP for space heating and heating up the ventilation inlet air for each time step if the heat pump is power controlled (chapter 4.5.5)
    e. Calculation of the heating time available for space heating and heating up the ventilation inlet air during each time step step (chapter 4.5.12)
    f. Calculation of the heating energy demand of space heating and heating up the ventilation inlet air during each time step (chapter 4.5.13)
    g. Calculation of the heating energy which the heat pump can deliver for space heating and heating up the ventilation inlet air during each time step and the annual delivered heating energy deliver for space heating and heating up the ventilation inlet air (chapter 4.5.13)
4. Calculation of the electricity consumption of the heat pump for DSW heating, space heating and heating up the ventilation inlet air during each time step and the annual electricity consumption (chapter 4.5.14)
5. Calculation of, if needed, the electricity use of auxiliary devices not included in the measured COP value of the heat pump (chapter 4.5.15)
6. Calculation of the heat pump SPF (chapter 4.5.16)
7. Calculation of the additional space heating demand (chapter 4.5.17).

4.2.3 Ground source heat pump

The SPF calculation for a ground source heat pump is performed according to the same steps as for an air-water heat pump with the only difference of needing also the return temperature of the fluid from the heat collection circuit as an input value and using the fluid temperature entering the evaporator in the COP calculation.

4.2.4 Exhaust air heat pump

The SPF calculation for an exhaust air heat pump is performed according to following steps:

1. Definition of following input values for the calculation:
   a. Outdoor air temperature throughout the year if the hourly heating power demand for space heating and heating up the ventilation inlet air is not known and the calculation time step (chapter 4.3.1)
   b. DSW heating power of heating energy demand and DSW temperature (chapter 4.3.2)
   c. Calculation of heating power and heating energy demand for space heating and heating up the ventilation inlet air (chapter 4.3.3)
   d. Maximum and minimum temperatures for inlet water, dimensioning outdoor temperature and the outdoor temperature where the inlet water temperature is equal to the minimum temperature (chapter 4.3.3)
   e. Measured COP, heating power and temperatures at least in one test point for the heat pump (chapter 4.3.4)
   f. Highest DSW heating up temperature with the heat pump without additional heating demand for DSW (chapter 4.3.4)
   g. Temperature and humidity of the outlet air and the lowest temperature of the waste air (chapter 4.3.4)
2. If the heat pump is used for DSW heating, following steps are calculated:
   a. Calculation of DSW heating demand for each time step (if not available as input value) (chapter 4.5.1)
   b. Calculation of heat pump COP for DSW heating for each time step (chapter 4.5.4)
   c. Calculation of the DSW heating power of the heat pump for each time step (chapter 4.5.7)
   d. Calculation of the effect of partial power on COP for DSW heating for each time step if the heat pump is power controlled (chapter 4.5.5)
   e. Calculation of the DSW heating time during each time step (chapter 4.5.8)
   f. Calculation of the DSW heating energy which the heat pump can deliver for each time step and the annual delivered DSW heating energy (chapter 4.5.9)

3. If the heat pump is used also for space heating and/or heating up the ventilation inlet air besides DSW heating, following steps are calculated:
    a. Calculation of heating power demand for space heating and heating up the ventilation inlet air for each time step (if not available as input value) (chapter 4.5.2)
    b. Calculation of heat pump COP for space heating and heating up the ventilation inlet air for each time step (chapter 4.5.4)
    c. Calculation of the heating power of the heat pump for space heating and heating up the ventilation inlet air for each time step (chapter 4.5.11)
    d. Calculation of the effect of partial power on COP for space heating and heating up the ventilation inlet air for each time step if the heat pump is power controlled (chapter 4.5.5)
    e. Calculation of the heating time available for space heating and heating up the ventilation inlet air during each time step (chapter 4.5.12)
    f. Calculation of the heating energy demand of space heating and heating up the ventilation inlet air during each time step (chapter 4.5.13)
    g. Calculation of the heating energy which the heat pump can deliver for space heating and heating up the ventilation inlet air during each time step and the annual delivered heating energy deliver for space heating and heating up the ventilation inlet air (chapter 4.5.13)
4. Calculation of the electricity consumption of the heat pump for DSW heating, space heating and heating up the ventilation inlet air during each time step and the annual electricity consumption (chapter 4.5.14)
5. Calculation of, if needed, the electricity use of auxiliary devices not included in the measured COP value of the heat pump (chapter 4.5.15)
6. Calculation of the heat pump SPF (chapter 4.5.16)
7. Calculation of the additional space heating demand (chapter 4.5.17)

4.3 Calculation input values

4.3.1 Weather data

Following input data is needed for the calculation:

- Hourly outdoor temperature $T_{outdoor}(t)$, °C.
- Time step for calculation and weather data $t_{time\text{-}step}$, h.

As hourly weather data e.g. the annual values of the Finnish Building Code part D3 (2012) can be used. This data is available at the web pages of the Finnish

Meteorological Institute [http://ilmatieteenlaitos.fi/rakennusten-energialaskennan-testivuosi]. The calculation can be performed with also other time steps than one hour, but in this report one hour is used as the time step. The calculation time step $t_{time\text{-}step}$ must be equal to the time step of the weather data. It is worth noticing that with a longer time step the accuracy of the calculation decreases.

4.3.2 DSW heating demand

If the heat pump is used for DSW heating, following data is needed as input values:

- Hourly DSW heating power demand $\phi_{DSW}(t)$, kW.
- Annual DSW heating energy demand $Q_{heating,DSW}$, kWh/a, if the hourly heating power demand $\phi_{DSW}(t)$is not known.
- DSW temperature T_{DSW}, °C.
- Temperature of the cold service water T_{SW}, °C.

The transfer and storage heat losses are included in the DSW heating power $\phi_{DSW}(t)$ and heating energy demand $Q_{heating,DSW}$. The hourly DSW heating power demand $\phi_{DSW}(t)$ can be calculated using a dynamical simulation program or it can be estimated using the method presented in chapter 4.5.1. The annual DSW heating energy demand $Q_{heating,DSW}$ can be calculated using e.g. a method according to Part D5 (2012) of the Finnish Building Code.

If solar heat collectors are utilized in DSW heating besides the heat pump, the annual heating energy produced by the solar heat collectors and the heating power which can be utilized in DSW heating must be substituted from the annual heating energy demand $Q_{heating,DSW}$ and the hourly heating power demand $\phi_{DSW}(t)$. The hourly heating power produced with the solar heat collectors can be calculated using dynamical simulation programs such as IDA-ICE 4.5 and TRNSYS 17 taking into account the hourly DSW consumption in the simulated building.

4.3.3 DSW heating demand

Following input data concerning the heating demand of the building is needed when:

- The heat pump is used for space heating:
  - Hourly space heating power demand $\phi_{spaces}(t)$, kW.
  - Annual space heating energy demand $Q_{heating,spaces}$, kWh/a, if the hourly space heating power demand $\phi_{spaces}(t)$ is not known.
- The heat pump is used for the after-heating of the spaces and ventilation inlet air:

- The sum of the hourly after-heating power demands for space heating and ventilation inlet air heating $\phi_{spaces,ventilation}(t)$, kW.
- The sum of the hourly after-heating energy demands for space heating and ventilation inlet air heating $Q_{heating,spaces,ventilation}$, kWh/a if the hourly after-heating power demand $\phi_{spaces,ventilation}(t)$ is not known.

The heating distribution and storage heat losses are included in the heating power and heating energy demand of space heating and ventilation inlet air heating. The annual heating energy demand for space heating and ventilation inlet air heating can be calculated using e.g. a method according to Part D5 (2012) of the Finnish Building Code. The hourly heating power demand of space heating and ventilation inlet air heating is primarily calculated using a dynamical simulation program or it can be estimated using a method presented in chapter 4.5.2.

For reasons of simplification, in the following text and formulas of this report the space heating includes also the heating of the ventilation inlet air. The calculation method can anyhow be directly utilized also in cases where the heat pump heats up also the ventilation inlet air besides of spaces by using the sum of the heating energy $Q_{heating,spaces,ventilation}$ and heating power $\phi_{spaces,ventilation}$ for space heating and ventilation inlet air instead of the heating energy $Q_{heating,spaces}$ and heating power $\phi_{spaces}(t)$ for space heating.

If solar heat collectors are utilized in space heating besides the heat pump, the annual heating energy and the heating power produced by the solar heat collectors must be substituted from the annual space heating energy demand $Q_{heating,spaces}$ and the hourly space heating power demand $\phi_{spaces}(t)$. The hourly heating power and heating energy produced with the solar heat collectors can be calculated using e.g. methods presented in chapter 4.3.2.

If the heat pump is linked to a water-circulated heating distribution network, following input data are needed according to the heating distribution network:

- Dimensioning outdoor temperature Tdim, °C used for the calculation of the heating power of the building.
- Maximum temperature of the inlet water Tiw,max (°C) with the dimensioning outdoor temperature Tdim, °C.
- Minimum temperature of the inlet water Tiw,min (°C)
- The minimum outdoor temperature Toutdoor,iw,min where the inlet water temperature reaches its minimum value Tiw,min

4.3.4 Heat pump

Product data measured e.g. according to standards SFS-EN 14511-3, SFS-EN 16147 or SFS-EN 14825 are used as input data for the heat pump. Following input data is needed for the calculation:

- The measured COP_N for an on-off controlled heat pump at least in one test point.
- The measured COP_N for a power controlled heat pump with maximum power and at least in one test point representing the partial power operation.
- Maximum heating power $P_{HP,max}$ (kW) produced by an air-air, air-water or ground source heat pump in those test points where the COP_N has been measured.
- Temperatures of those test points where the COP_N has been measured.
- The maximum water heating temperature, $T_{HP, max}$ (°C) of the heat pump without utilization of additional heating.

The maximum water heating temperature, $T_{HP, max}$ (°C) of the heat pump without utilization of additional heating. The temperature levels of the test points have been defined e.g. in standard SFS-EN 14511-2. The input values mentioned before are given depending on the heat pump type at least in one test point, e.g:

- Air-air heat pump: $T_{outdoor}$ /T_{ndoor} = (+7/+20°C)
- Air-water heat pump: $T_{outdoor}$/T_{iw} = (+7/+35°C)
- Ground source heat pump: T_{fluid}/T_{iw} = (0/+35°C)
- Exhaust air heat pump: T_{indoor}/T_{iw} = (+20/35°C).

where

$T_{outdoor}$	outdoor air temperature, °C
T_{indoor}	indoor air temperature, °C
T_{iw}	temperature of the inlet water leaving the condenser and entering the heating distribution network, °C
T_{fluid}	temperature of the fluid leaving the heat collection circuit and entering the evaporator, °C.

If input data in these test points is not available, also other test points mentioned in e.g. standard SFS-EN 14511-2 can be utilized. It is worth underlining that the accuracy of the calculation increases when several test points are utilized. Following heat pump specific input data are also needed:

- Air-air heat pump:
    - o The in-blast air temperature of the heat pump T_{ib} (°C) (the temperature of the air heated flowing through the condenser) or the set point indoor air temperature of the indoor air T_{indoor} (°C), if the in-blast temperature is not known.
    - o The minimum outdoor temperature according to the recommendation of the heat pump manufacturer $T_{outdoor,min}$ (°C), where the heat pump can be operated.

- Air-water heat pump:
    - o The minimum outdoor temperature according to the recommendation of the heat pump manufacturer $T_{outdoor,min}$ (°C), where the heat pump can be operated.
- Ground source heat pump:
    - o The return temperature of the fluid from the heat collection circuit and entering the evaporator T_{fluid} (°C). If more detailed information, e.g. case-specific data calculated with a heat collection circuit dimensioning program, can be utilized, the time-dependency of the fluid temperature can be taken into account in the calculation using the hourly fluid temperature from the heat collection circuit. If more detailed information is not available the average monthly or yearly return temperature can be used.
- Exhaust air heat pump:
    - o Outlet air flow from the building Q_{outlet} (m^3/s) entering the evaporator of the heat pump.
    - o Outlet air temperature $T_{outlet}(t)$, °C. Hourly outlet air temperatures calculated using e.g. a dynamical simulation program can be used as inlet values. In other case the constant indoor air set point temperature T_{indoor} (°C) can be used as the outlet air temperature.
    - o The absolute humidity of the outlet air x_{outlet} (kg/kg). If hourly outlet air temperatures are used as an input values, also hourly values for the absolute humidity x_{outlet} must be used. Hourly absolute humidities can be calculated using e.g. dynamical simulation programs. If the absolute humidity is not known, it can be calculated e.g. using the method presented in Annex 2 (chapter 4.6) with the relative humidity and temperature of the outlet air as input values.
    - o Minimum waste air temperature after the evaporator $T_{waste,min,}$ °C according to the information given by the heat pump manufacturer.

4.4 Calculation results

Following results are given by the SPF calculation method:

- Heating energy produced by the heat pump.
- Electricity consumption of the heat pump.
- SPF of the heat pump.
- Additional heating energy demand if the heat pump cannot produce all of the heating energy demand.

4.5 Calculation

4.5.1 DSW heating power demand

Primarily the hourly DSW heating power demands $\phi_{DSW}(t)$ calculated according to hourly DSW consumptions should be used as the inlet values for the calculation. If the hourly DSW heating power demands $\phi_{DSW}(t)$ are not known, the heating power can be estimated according to the annual DSW heating energy demand $Q_{heating,DSW}$ (D5, 2012) if the heating power demand is assumed to be constant

$$\phi_{DSW} = \frac{Q_{heating,DSW}}{t_{DSW}} \tag{4.1}$$

where

t_{DSW} yearly usage time of DSW, h.

If the DSW temperature T_{DSW} is higher than the maximum water temperature $T_{HP,max}$ that the heat pump can deliver without additional heating, the portion of the additional heating is substituted from the total heating power demand calculated according to DSW consumption or the annual heating energy demand calculated with Eq. 4.1. In this case the corrected heating power demand $\phi_{DSW}(t)$ calculated with Eq. 4.2 is used as the DSW heating power demand to be produced by the heat pump.

$$\phi_{DSW}(t) = \phi_{DSW}(t)\left(1 - \frac{T_{DSW} - T_{HP,max}}{T_{DSW} - T_{SW}}\right) \tag{4.2}$$

where

T_{DSW} DSW temperature, °C
$T_{HP,max}$ maximum water temperature that the heat pump can deliver, °C
T_{SW} temperature of cold service water, °C.

4.5.2 Space heating power demand

If the hourly space heating power demand of the building $\phi_{spaces}(t)$ is not known, it can be calculated based on the annual space heating energy demand $Q_{heating,spaces}$ using the following equation

$$\phi_{spaces}(t) = \frac{Q_{heating,spaces}}{S_{Hdd}}\left(T_{Hdd} - T_{outdoor}(t)\right)$$, when THdd > Toutdoor (4.3)

$$\phi_{spaces}(t) = 0$$, when THdd ≤ Toutdoor.

where

S_{Hdd}	heating degree day, Kh
T_{Hdd}	indoor temperature representing the heating degree day, °C
$T_{outdoor}(t)$	hourly outdoor temperature, °C.

The space heating power demand or space heating energy demand of the equation (4.3) are based on the heating power or the energy demand of the zones which are located in the sphere of influence of the air-air heat pump.

The heating degree day S_{Hdd} can be calculated with the following equation using e.g. 17°C for the indoor temperature representing the heating degree day. In this temperature is it assumed that the indoor heat loads are enough to heat up the indoor air from 17°C to the set point temperature.

The space heating power demand or space heating energy demand of the equation (4.3) are based on the heating power or the energy demand of the zones which are located in the sphere of influence of the air-air heat pump.

The heating degree day S_{Hdd} can be calculated with the following equation using e.g. 17°C for the indoor temperature representing the heating degree day. In this temperature is it assumed that the indoor heat loads are enough to heat up the indoor air from 17°C to the set point temperature.

$$S_{Hdd} = \sum\left(T_{Hdd} - T_{outdoor}(t)\right)\cdot t_{timestep} \qquad (4.4)$$

where

$T_{outdoor}(t)$	hourly outdoor temperature, °C.
$t_{timestep}$	calculation time step, h.

4.5.3 Heat distribution network temperature and in-blast temperature

The hourly inlet water temperature of the heat distribution network $T_{iw}(t)$ can be calculated with following equations.

$$T_{iw}(t) = T_{iw,max}$$, when $T_{outdoor}(t) \leq T_{dim}$ (4.5)

$$T_{iw}(t) = k \cdot T_{outdoor}(t) + b$$, when $T_{outdoor}$ is between $T_{dim} < T_{outdoor}(t) < T_{outdoor,iw,min}$ (4.6)

$$T_{iw}(t) = T_{iw,min}\text{, when } T_{outdoor}(t) \geq T_{outdoor,iw,min} \tag{4.7}$$

where

$T_{iw,max}$	maximum inlet water temperature in the dimensioning outdoor temperature, °C
k	slope of the control curve, -
$T_{outdoor}(t)$	hourly outdoor temperature, °C
b	constant term of the control curve, °C
$T_{iw,min}$	mimimum inlet water temperature, °C.

The slope of the control curve can be calculated with following equation

$$k = \frac{T_{iwv,max} - T_{iw,min}}{T_{dim} - T_{outdoor,iw,min}} \tag{4.8}$$

where

$T_{iw,max}$	maximum inlet water temperature in the dimensioning outdoor temperature, °C
$T_{iw,min}$	mimimum inlet water temperature, °C
T_{dim}	dimensioning outdoor temperature for the heating of the building, °C
$T_{outdoor,iw,min}$	outdoor temperature representing the minimum inlet water temperature, °C.

The constant term of the control curve b can be calculated with the following equation

$$b = T_{iw,max} - k \cdot T_{dim} \tag{4.9}$$

where

k	slope of the control curve, -.

If the value of the inlet water temperature $T_{iw}(t)$ calculated with the equations (4.5–4.7) is higher than the maximum water temperature $T_{HP,max}$ that the heat pump can deliver without additional heating, the value of the exceeding inlet water temperatures is $T_{HP,max}$. Figure 3 presents an example about inlet water temperatures for different outdoor temperatures.

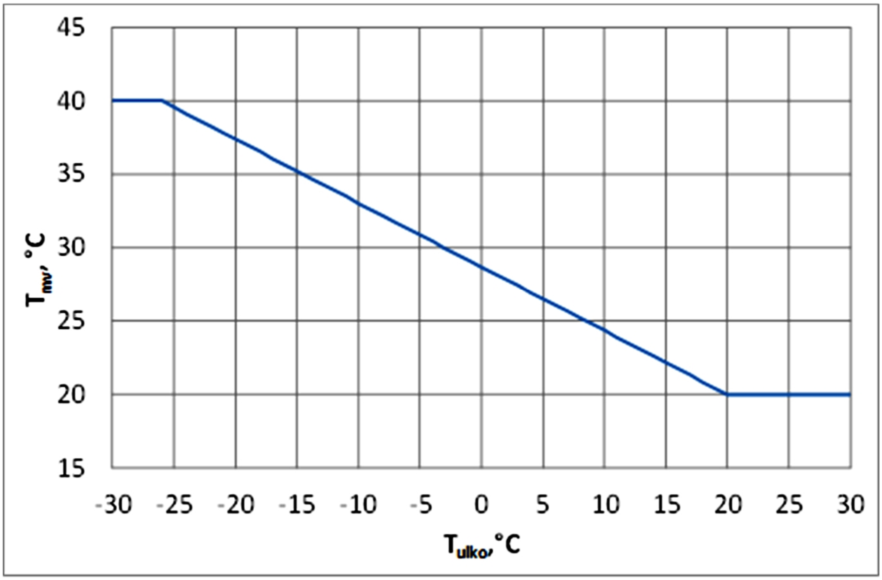

Figure 3. Example about an inlet water temperature control curve (T_{mv} = T_{iw} and T_{ulko} = $T_{outdoor}$).

The in-blast temperature T_{ib} (°C) of the air-air heat pump is the temperature of the heated-up air leaving the condenser. If the in-blast temperature is not known, it can be estimated according to the indoor air set point temperature T_{indoor}. The in-blast temperature can be estimated to be 15°C warmer that the indoor air set point temperature if more detailed knowledge is not available.

4.5.4 Heat pump COP

The hourly COP(t) of the heat pump is calculated with the following equation

$$COP(t) = f_T(t) \cdot COP_T(t) \tag{4.10}$$

where

$f_T(t)$	loss factor of the compressor, -
$COP_T(t)$	theoretical hourly COP of the heat pump, -.

The effect of partial power on the COP of a power-controlled heat pump is taken into account using the method presented in chapter 4.5.5.

The loss factor $f_T(t)$ of Eq. (4.10), which takes into account the heating process losses of the heat pump is calculated with Eq. (4.11):

$$f_T(t) = \frac{COP_N}{COP_T} \tag{4.11}$$

where

COP_N	measured heat pump COP, -
COP_T	theoretical heat pump COP, -.

If the heat pump COP_N has been measured only in one test point the loss factor is assumed to be constant throughout the whole calculation period (e.g. a year). If the COP has been measured in several test points the loss factor can be calculated for each test point with Eq. (4.11). The loss factor values $f_T(t)$ between different test points can be linearly interpolated in sections using the method presented in Annex 1 (chapter 4.6). For lower or higher temperatures than the test point temperatures the nearest measured loss factor value can be used.

The hourly theoretical $COP_T(t)$ in Eq. (4.10) is calculated with Eq. (4.12) using heating source and building heating system temperatures $T_{HSo}(t)$ and $T_{HSy}(t)$ defined for each time step. The theoretical heat pump COP_T is calculated with Eq. (4.12) using constant heating source and building heating system temperatures.

$$COP_T = \frac{T_{HSy}}{T_{HSy} - T_{HSo}} \tag{4.12}$$

where

T_{HSy}	building heating system temperature, K
T_{HSo}	heating source temperature, K.

The DSW temperature T_{DSW} is used as the building heating system temperature T_{HSy} in calculation of the COP for DSW heating. Accordingly the inlet water temperature $T_{iw}(t)$ is used as the building heating system temperature T_{HSy} for a water-circulated network and the in-blast temperature T_{ib} as the building heating system temperature T_{HSy} for an air-air heat pump (see chapter 4.5.3) when calculating the COP for space heating. If the DSW or inlet water temperature is higher than the maximum water temperature that the heat pump can deliver, $T_{HP,max}$, the maximum deliver temperature $T_{HP,max}$ is used in Eq. (4.12) as the building heating system temperature T_{HSy}.

Depending on the heat pump type following temperatures are used as the heating source temperature T_{HSy} in Eq. (4.12):

- Air-air- and air-water heat pump: Outdoor air temperature Toutdoor(t).
- Ground source heat pump: Temperature of the fluid leaving the heat collection circuit and entering the evaporator $T_{fluid}(t)$.
- Exhaust air heat pump: Minimum waste air temperature $T_{waste,min}$.

4.5.5 Heat pump COP with partial power

The effect of a partial power load on the COP of a power-controlled heat pump can be taken into account if the COP has been measured both with a maximum power and at least in one test point representing partial power.

The hourly load power ratios $\beta_{HP,DSW}(t)$ ja $\beta_{HP,spaces}(t)$ are calculated for DSW and space heating with following equations

$$\beta_{HP,lkv}(t) = \frac{\phi_{DSW}(t)}{\phi_{HP,DSW}(t)} \tag{4.13}$$

where

$\phi_{DSW}(t)$	hourly DSW heating power demand, kW (see chapter 4.5.1)
$\phi_{HP,DSW}(t)$	hourly maximum DSW heating power demand of the heat pump, kW (see Eq. 4.15).

$$\beta_{HP,spaces}(t) = \frac{\phi_{spaces}(t)}{\phi_{HP,spaces}(t)} \tag{4.14}$$

where

$\phi_{spaces}(t)$	hourly space heating power demand, kW (see chapter 4.5.2)
$\phi_{HP,spaces}(t)$	hourly maximum space heating power demand of the heat pump, kW (see Eq. 4.22)

Hourly DSW and space heating COP values $COP_{DSW}(t)$ and $COP_{spaces}(t)$ can be interpolated between known power ratios e.g. with the method presented in Annex 1 (chapter 4.6). If the COP values have been measured for e.g. power ratios 1.0 and 0.5, temperature corrections are first calculated for these COP values with Eq. (4.10) and then partial power corrections are performed by interpolating the corrected COP values between power ratios 0.5 and 1.0. If the power ratio is momentarily lower than 0.5 the COP representing the power ratio 0.5 can be used in calculation.

4.5.6 Heating power of air-water- and ground source heat pump in DSW heating

If the maximum heating power $\phi_{HP,max}$ of an on-off- or power controlled air-water- or ground source heat pump has been measured only in one test point, its hourly maximum DSW heating power $\phi_{HP,DSW}(t)$ is calculated with following equation

$$\phi_{HP,DSW}(t) = \phi_{HP,max} \frac{COP_{DSW}(t)}{COP_N} \tag{4.15}$$

where

$\phi_{HP,max}$	maximum heating power of the heat pump in test point, kW
$COP_{DSW}(t)$	hourly heat pump COP in DSW heating, -
COP_N	measured heat pump COP in test point, -.

The $COP_{DSW}(t)$ is calculated with Eq. (4.10) using the defined DSW temperature T_{DSW} as the input value. If the DSW temperature is higher than the maximum water temperature $T_{HP,max}$ that the heat pump can deliver without additional heating, the $COP_{DSW}(t)$ is calculated using the temperature $T_{HP,max}$.

The hourly heating power $\phi_{HP,DSW}(t)$ of a power-controlled heat pump is equal to the hourly DSW heating power demand $\phi_{DSW}(t)$ (see chapter 4.5.1) if $\phi_{DSW}(t)$ is smaller than $\phi_{HP,DSW}(t)$. If the DSW heating power demand $\phi_{DSW}(t)$ is larger than the DSW heating power $\phi_{HP,DSW}(t)$ calculated with Eq. (4.15), the value calculated with Eq. (4.15) is used as the hourly DSW heating power of the heat pump.

If the maximum heating power of an on-off- or power-controlled air-water- or ground source heat pump has been measured in several test points, the maximum heating power values between different test points can be linearly interpolated in sections using the method presented in Annex 1 (chapter 4.6). The interpolated values can be utilized between test points instead of the heating power calculated with Eq. (4.15). The maximum heating power in lower or higher temperatures than the test point temperatures can be calculated with Eq. (4.15) using the heating power of the nearest measured test point as the maximum heating power $\phi_{HP,max}$.

4.5.7 DSW heating power of an exhaust air heat pump

The hourly DSW heating power $\phi_{HP,DSW}(t)$ of an on-off-controlled exhaust air heat pump is calculated with following equation

$$\phi_{HP,DSW}(t) = \phi_{HPc}(t) \frac{COP_{DSW}(t)}{COP_{DSW}(t) - 1} \tag{4.16}$$

where

$\phi_{HPc}(t)$	condenser power of the heat pump, kW
$COP_{DSW}(t)$	hourly heat pump COP for DSW heating, -.

The hourly DSW heating power $\phi_{HP,DSW}(t)$ of a power-controlled exhaust air heat pump is equal to the hourly DSW heating power demand $\phi_{DSW}(t)$ (see chapter 4.5.1) if $\phi_{DSW}(t)$ is smaller than $\phi_{HP,DSW}(t)$. If the DSW heating power demand $\phi_{DSW}(t)$ is larger than the DSW heating power $\phi_{HP,DSW}(t)$ calculated with Eq. (4.16), the value calculated with Eq. (4.16) is used as the hourly DSW heating power of the heat pump.

The condenser power of the exhaust heat pump, used in Eq. (4.16), is calculated with following equation

$$\phi_{HPc}(t) = Q_{outlet}(t) \cdot \rho\left(h_1(t) - h_2(t)\right) \tag{4.17}$$

where

$Q_{outlet}(t)$	outlet air flow, m³/s
ρ	outlet air density, kg/m³
$h_1(t)$	outlet air enthalpy (before the condenser), kJ/kg
$h_2(t)$	waste air enthalpy (after the condenser), kJ/kg.

The outlet and waste air enthalpies can be calculated with following equation

$$h(t) = c_{p,air} \cdot T(t) + x(t) \cdot \left(L_w + c_{p,wv} \cdot T(t)\right) \tag{4.18}$$

where

$c_{p,air}$	specific heat capacity of air, kJ/kg,K
$T(t)$	outlet air or waste air temperature, °C
$x(t)$	absolute humidity of outlet air or waste air, kg/kg
L_w	evaporation heat for water in 0°C, kJ/kg
$c_{p,wv}$	specific heat capacity of water vapour, kJ/kg,K.

In Eq. (4.18) the value 1.006 kJ/kg,K can be used for the specific heat capacity of air, 1.85 kJ/kg,K for the specific heat capacity of water vapour and 2502 kJ/kg for the evaporation heat for water.

For calculation of the outlet air enthalpy the outlet air temperature is used as T(t) and the absolute humidity of outlet air is used as x(t) in Eq. (4.18). If the absolute humidity of outlet air is not known, it can be calculated by means of the relative humidity $RH_{outlet}(t)$ and temperature $T_{outlet}(t)$ of outlet air using the method presented in Annex 2 (chapter 4.6).

For calculation of the waste air enthalpy with Eq. (4.18) the minimum waste air temperature $T_{waste,min}$ according to the information given by the heat pump manufacturer can be used as T(t). The absolute humidity of waste air can be calculated using the method presented in Annex 2 (chapter 4.6) with 100% as the relative humidity RH_{waste} and T_{waste} as the temperature.

4.5.8 DSW heating time

The DSW heating time, t_{DSW}, during one time step is calculated with following equation

$$t_{DSW}(t) = t_{timestep} \frac{\phi_{DSW}(t)}{\phi_{HP,DSW}(t)} \text{, when } \phi_{DSW} < \phi_{HP,DSW} \qquad (4.19)$$

$$t_{DSW}(t) = t_{timestep} \text{, when } \phi_{DSW} \geq \phi_{HP,DSW}$$

where

$t_{timestep}$	calculation time step, h
$\phi_{DSW}(t)$	DSW heating power demand, kW (see chapter 4.5.1)
$\phi_{HP,DSW}(t)$	DSW heating power of the heat pump, kW (see chapters 4.5.6 and 4.5.7).

4.5.9 DSW heating energy

The DSW heating energy production of the heat pump during one calculation time step is calculated with following equation

$$q_{HP,DSW}(t) = \phi_{HP,DSW}(t) \cdot t_{DSW} \qquad (4.20)$$

where

$\phi_{HP,DSW}(t)$	DSW heating power of the heat pump, kW (see chapters 4.5.6 and 4.5.7)
t_{DSW}	DSW heating time by the heat pump during one time step, h (see chapter 4.5.8).

For an air-water heat pump the hourly DSW heating energy production $q_{LP,lkv}(t)$ is calculated only for those time steps where the outdoor air temperature $T_{outdoor}(t)$ is higher than the lowest utilization temperature for the heat pump, $T_{outdoor,min}$, defined as an input value.

The annual DSW heating energy production $Q_{HP,DSW}$ is the sum of hourly DSW heating energies $q_{HP,DSW}(t)$ as presented in the following equation

$$Q_{HP,DSW} = \sum q_{HP,DSW}(t). \qquad (4.21)$$

4.5.10 Space heating power of an air-air, air-water and ground source heat pump

If the maximum space heating power $\phi_{HP,max}$ of an on-off- or power-controlled air-air, air-water or ground source heat pump has been measured only in one test point, the hourly maximum space heating power $\phi_{HP,spaces}(t)$ of these heat pump types is calculated with following equation

$$\phi_{HP,spaces}(t) = \phi_{HP,max} \frac{COP_{spaces}(t)}{COP_N} \tag{4.22}$$

where

$\phi_{HP,max}$	maximum heating power in the test point, kW
$COP_{spaces}(t)$	hourly heat pump COP for space heating, -
COP_N	measured heat pump COP in test point, -.

The heat pump $COP_{spaces}(t)$ is calculated with Eq. (4.10) using the hourly heat source temperature and the inlet water temperature $T_{iw}(t)$ of the heating distribution network or the in-blast temperature T_{ib} (air-air heat pump) as input values. If the value of the inlet water temperature is higher that the maximum water temperature that the heat pump can deliver without additional heating, the $COP_{spaces}(t)$ is calculated by using the temperature $T_{HP,max}$

The hourly space heating power $\phi_{LP,tilat}(t)$ of a power-controlled heat pump is equal to the hourly space heating power demand $\phi_{spaces}(t)$ (see chapter 4.5.2) if $\phi_{spaces}(t)$ is smaller than $\phi_{HP,spaces}(t)$. If the space heating power demand $\phi_{spaces}(t)$ is larger than the space heating power $\phi_{HP,spaces}(t)$ calculated with Eq. (4.22), the value calculated with Eq. (4.22) is used as the hourly space heating power of the heat pump.

If the maximum heating power $\phi_{HP,max}$ of an on-off- or power-controlled air-air-, air-water- or ground source heat pump has been measured in several test points, the maximum heating power values between different test points can be linearly interpolated in sections using the method presented in Annex 1 (chapter 4.6). The interpolated values can be utilized between the test points instead of the heating power calculated with Eq. (4.22). The maximum heating power in lower or higher temperatures than the test point temperatures can be calculated with Eq. (4.22) using the heating power of the nearest measured test point as the maximum heating power $\phi_{HP,max.}$

4.5.11 DSW heating time

The hourly space heating power $\phi_{HP,spaces}(t)$ of an on-off-controlled exhaust air heat pump is calculated with following equation

$$\phi_{HP,spaces}(t) = \phi_{HPc}(t) \frac{COP_{spaces}(t)}{COP_{spaces}(t) - 1} \tag{4.23}$$

where

$\phi_{HPc}(t)$ condenser power of the heat pump, kW
$COP_{spaces}(t)$ hourly heat pump COP for space heating, -.

The exhaust air heat pump condenser power of Eq. (4.23) is equal to the exhaust air heat pump condenser power calculated in chapter (4.5.7).

The hourly space heating power $\phi_{HP,spaces}(t)$ of a power-controlled exhaust air heat pump is equal to the hourly space heating power demand $\phi_{spaces}(t)$ (see chapter 4.5.2) if $\phi_{spaces}(t)$ is smaller than $\phi_{HP,spaces}(t)$. If the space heating power demand $\phi_{spaces}(t)$ is larger than the space heating power $\phi_{HP,spaces}(t)$ calculated with Eq. (4.23), the value calculated with Eq. (4.23) is used as the hourly space heating power of the exhaust air heat pump.

4.5.12 Space heating time

The space heating time, $t_{space,max}(t)$ during one time step is calculated with following equation

$$t_{spaces,max}(t) = t_{timestep} - t_{DSW}(t) \tag{4.24}$$

where

$t_{timestep}$ calculation time step, h
$t_{DSW}(t)$ DSW heating time during one time step, h (see chapter 4.5.8).

Eq. (4.24) can be used for a heat pump, which heats up both DSW and spaces. For a heat pump only heating up the spaces, the total length of the time step can be used for space heating.

4.5.13 Space heating energy

The space heating energy production qspaces(t) of the heat pump during one calculation time step is calculated with following equation

$$q_{spaces}(t) = \phi_{spaces}(t) \cdot t_{timestep} \tag{4.25}$$

where

$\phi_{spaces}(t)$ hourly space heating power demand, kW (see chapter 4.5.2)
$t_{timestep}$ calculation time step, h.

The maximum space heating energy $q_{HP,spaces,max}(t)$ that the heat pump can produce during one time step is calculated with following equation

$$q_{HP,spaces,max}(t) = \phi_{HP,spaces}(t) \cdot t_{spaces,max}(t) \tag{4.26}$$

where

$\phi_{HP,spaces}(t)$ space heating power, kW (see chapters 4.5.10 and 4.5.11)

$t_{spaces,max}(t)$ maximum space heating time during one time step, h (see chapter 4.5.12).

For a heat pump used only for space heating the maximum space heating time $t_{spaces,max}(t)$ is equal to the calculation time step.

The space heating energy production $q_{HP,spaces}(t)$ during one calculation time step is equal to the maximum space heating energy $q_{HP,spaces,max}(t)$ calculated with Eq. (4.26) if the space heating energy demand $q_{spaces}(t)$ (Eq. 4.25) is larger than the $q_{HP,spaces,max}(t)$ according to Eq. (4.27). In other case the space heating energy production is equal to the space heating energy demand (Eq. 4.28).

$$q_{HP,spaces}(t) = q_{HP,spaces,max}(t) \text{, when } q_{spaces} > q_{HP,spaces,max} \tag{4.27}$$

$$q_{HP,spaces}(t) = q_{spaces}(t) \text{, when } q_{spaces} \leq q_{HP,spaces,max} \tag{4.28}$$

where

$q_{HP,spaces,max}(t)$ maximum heating energy production during one calculation time step, kWh

$q_{spaces}(t)$ space heating energy demand during one calculation time step, kWh.

For an exhaust air heat pump the space heating energy production $q_{HP,spaces}(t)$ is calculated only for those time steps where the outdoor air temperature $T_{outdoor}(t)$ is higher than the lowest utilization temperature for the exhaust air heat pump, $T_{outdoor,min}$, defined as an input value.

The annual space heating energy production $Q_{HP,spaces}$ is the sum of the space heating energies produced during each time step $q_{HP,spaces}(t)$:

$$Q_{HP,spaces} = \sum q_{HP,spaces}(t) \tag{4.29}$$

4.5.14 Electricity consumption of the heat pump

The hourly electricity consumption of a heat pump $w_{HP}(t)$ including also the electricity consumption of the compressor and those auxiliary devices included in the electricity consumption of the heat pump in a test situation is calculated with the following equation

$$w_{HP}(t) = \frac{q_{HP,DSW}(t)}{COP_{DSW}(t)} + \frac{q_{HP,spaces}(t)}{COP_{spaces}(t)} \tag{4.30}$$

where

$q_{HP,DSW}(t)$	hourly DSW heating energy production, kWh
$COP_{DSW}(t)$	hourly heat pump COP for DSW heating, -
$q_{HP,spaces}(t)$	hourly space heating energy production, kWh
$COP_{spaces}(t)$	hourly heat pump COP for space heating, -.

The annual electricity consumption of the heat pump W_{HP} is the sum of the as presented in the following equation:

$$W_{HP} = \sum w_{HP.}(t) \tag{4.31}$$

4.5.15 Electricity consumption of the auxiliary devices

According to standards SFS-EN 14511-3 and SFS-EN 14825, the measured electricity consumption of the heat pump and the heat pump COP_N include the compressor electricity consumption, electricity consumption for the melting of the evaporator and a part of the electricity consumption of the auxiliary devices of the heat pump. The measured electricity consumption of the auxiliary devices includes the total electricity consumption of all control and protective devices and the electricity consumption of the fans and pumps transferring air or fluid inside of the heat pump unit. Thus the electricity consumption of the fans and pumps transferring air or fluid in ducts or pipes outside of the heat pump unit is not included in the electricity consumption measured in test conditions.

The electricity consumption of the fans and pumps, not included in the COP values measured according to the above-mentioned standards, is separately taken into account in the electricity consumption of the auxiliary devices, W_{aux}, depending on the heat pump type. The electricity consumption of the fans of the exhaust air heat pump is calculated into the electricity consumption of the auxiliary devices. Accordingly the pumping electricity consumption of the ground source heat pump heat collection circuit is taken into account to the extent of the pipe network outside of the heat pump unit. However, the pumping electricity consumption of the heat distribution network is not taken into account in the electricity consumption of the auxiliary devices of the heat pump, but it is instead taken into account in the electricity consumption calculation of the auxiliary devices of the heating distribution system e.g. according to part D5 (2012) of the Finnish Building Code.

The electricity consumption of the auxiliary devices of the heat pump, W_{aux}, not included in the electricity consumption of the heat pump and the measured COP_N values can be calculated with the following equation

$$W_{aux} = P_{aux}\Delta t \tag{4.32}$$

where

P_{aux}	the electricity consumption of the auxiliary devices of the heat pump not included in the measured heat pump COP value, kW
Δt	usage time of the auxiliary devices during the calculation period, h.

The electricity power P_{aux} of the auxiliary devices of the heat pump is calculated with the following equation

$$P_{aux} = \frac{Q \cdot \Delta P_e}{\eta} \tag{4.33}$$

where

Q	the nominal flow of the air or fluid Q, m³/s
ΔP_e	the static pressure loss of the ductwork or pipework outside the heat pump unit, Pa
η	the fan or pump efficiency rate, -.

4.5.16 Heat pump SPF

The SPF of the heat pump is defined according to following equation

$$SPF = \frac{Q_{HP,DSW} + Q_{HP,spaces}}{W_{HP} + W_{aux}} \tag{4.34}$$

where

$Q_{HP,DSW}$	annual DSW heating energy production of the heat pump, kWh (chapter 4.5.9)
$Q_{HP,spaces}$	annual space heating energy production of the heat pump, kWh (chapter 4.5.13)
W_{HP}	annual electricity consumption of the heat pump, kWh (chapter 4.5.14)
W_{aux}	annual electricity consumption of the auxiliary devices of the heat pump, kWh (chapter 4.5.15).

4.5.17 Additional heating energy

If the heat pump is not able to produce all the space and DSW heating energy demand, additional heating is needed. This additional heating energy can be produced e.g. by means of an electric resistance inside of the hot-water tank or by using another heating system. The additional heating energy demand is calculated with the following equation

$$Q_{additional} = Q_{heating,DSW} + Q_{heating,spaces} - Q_{HP,DSW} - Q_{HP,spaces} \quad (4.35)$$

where

$Q_{heating,\ DSW}$	DSW heating energy demand, kWh (see chapter 4.3.2)
$Q_{heating,\ spaces}$	space heating energy demand, kWh (see chapter 4.3.3)
$Q_{HP,\ DSW}$	DSW heating energy production of the heat pump, kWh (see chapter 4.5.9)
$Q_{HP,\ spaces}$	space heating energy production of the heat pump, kWh (see chapter 4.5.13).

4.6 Annexes for the detailed calculation method

4.6.1 Annex 1

The value of the variable X depending on the function A(X) can be linearly interpolated between two known points X_i and X_{i+1} when the values of the variable a known in the points $A(X_i)$ and $A(X_{i+1})$. The values of the variable A(X) between these two points can be calculated with the following equation (L1):

$$A(X) = A(X_i) + \frac{A(X_{i+1}) - A(X_i)}{X_{i+1} - X_i}(X - X_i) \quad (L1)$$

where

$A(X_i)$	value of function A with the variable X in point i
$A(X_{i+1})$	value of function A with the variable X in point i+1
X_i	value of the variable X in point i
X_{i+1}	value of the variable X in point i+1.

4.6.2 Annex 2

The absolute humidity of air can be calculated by means of the relative humidity of the air and the air temperature with following equations.

The partial water vapour pressure of air ph (t) can be calculated with the following equation

$$p_h(t) = \frac{RH(t) \cdot p_{hs}(t)}{100} \qquad \text{(L2)}$$

where

RH(t)	relative humidity of air, %
$p_{wvs}(t)$	saturation pressure of water vapour, kPa.

The saturation pressure of water vapour $P_{wvs}(t)$ of Eq. (L2) can be estimated e.g. with the following equation

$$p_{wvs}(t) = \frac{\exp\left(77.345 + 0.0057 \cdot T(t) - \frac{7235}{T(t)}\right)}{1000 \cdot T(t)^{8.2}} \qquad \text{(L3)}$$

where

T	air temperature, K.

The absolute humidity of air x(t) can be calculated with the following equation

$$x(t) = 0.622 \frac{p_{wv}(t)}{p - p_{wv}(t)} \qquad \text{(L4)}$$

where

$p_{wv}(t)$	partial pressure of the water vapour, kPa
p	total air pressure, kPa.

The normal pressure 101.3 kPa of air can be used as the total air pressure in Eq. (L4).

4.7 Comparing the detailed calculation method with heat pump manufacturers estimations

The detailed SPF calculation method was validated and further improved by VTT utilizing an excel application. In the future it would be beneficial to further validate the method by comparing the results with real measurement values from relevant case studies.

Heat pump manufacturers operating in Finland were asked to dimension heat pumps for two case studies to compare these dimensioning results to the results obtained with the detailed SPF calculation method:

- standard building type B representing a detached house built between 1960–70
- standard building type D3 representing a passive house level detached house.

More information about these houses is given in chapter 5. Five heat pump manufacturers operating in Finland were asked to dimension heat pumps for the heat pump types belonging to their sortiment for both houses. The weather file to be used was Jyväskylä in middle Finland. The heating demands, air temperatures and temperatures of the heating distribution system were given as background information for the dimensioning. Dimensioning data was received from two heat pump manufacturers. Tables 12–15 show this data compared with values calculated with the detailed SPF calculated method.

Table 12. Results for standard building type B, ground source heat pump.

	Heat pump manufacturer 1	**Heat pump manufacturer 2**	**SPF-calculation method**
Energy production of the heat pump, kWh/a	30 184	26 655	30 100
Additional heating energy demand, kWh	300	845	500
Electricity use of the heat pump, kWh/a	10 780	8 736	7 900
SPF of the heat pump	2.8	3.05	3.8

Table 13. Results for standard building type B, air to water heat pump.

	Heat pump manufacturer 2	**SPF-calculation method**
Energy production of the heat pump, kWh/a	22 985	28 400
Additional heating energy demand, kWh	4 515	2 200
Electricity use of the heat pump, kWh/a	9 256	10 600
SPF of the heat pump	2.48	2.7

Table 14. Results for standard building type D3, ground source heat pump.

	Heat pump manufacturer 1	Heat pump manufacturer 2	SPF-calculation method
Energy production of the heat pump, kWh/a	8 900	5 750	9 000
Additional heating energy demand, kWh	0	150	0
Electricity use of the heat pump, kWh/a	2 781	2 005	2 300
SPF of the heat pump	3.2	2.87	3.9

Table 15. Results for standard building type D3, air to water heat pump.

	Heat pump manufacturer 2	SPF-calculation method
Energy production of the heat pump, kWh/a	5 521	8 800
Additional heating energy demand, kWh	379	100
Electricity use of the heat pump, kWh/a	2 335	2 900
SPF of the heat pump	2.36	3.0

5. Standard building types

5.1 Classification and structures

The energy use of the Finnish building stock was estimated using standard building types further adapted to different decades: a detached house, an apartment building, an office building and a summer cottage. The building types were based on the building types utilized in the “Sustainable Energy” project by Aalto University (Figure 4 – Figure 6).

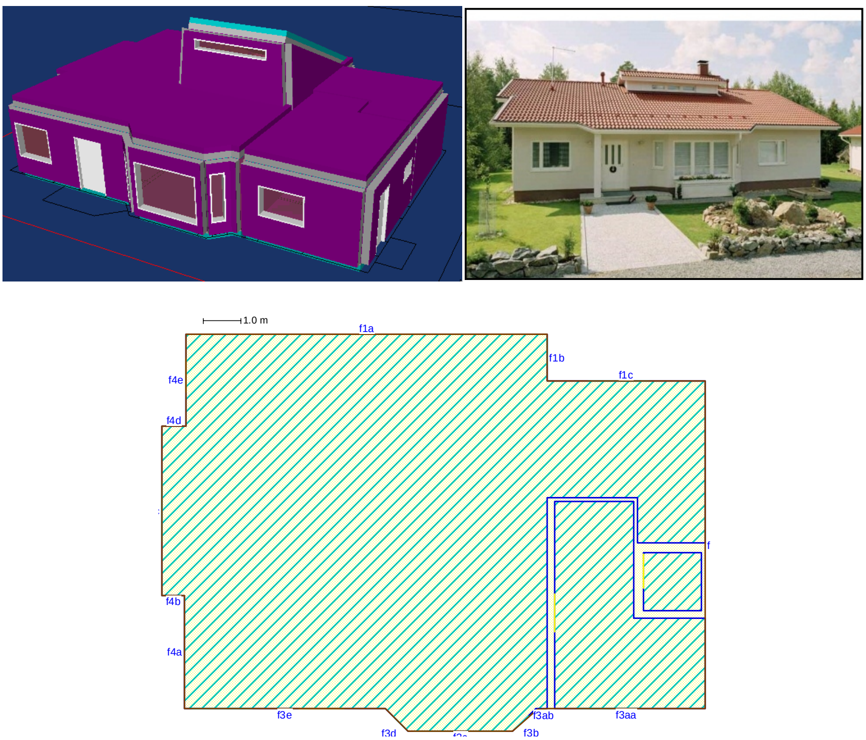

Figure 4. Detached house and recreational cottage building.

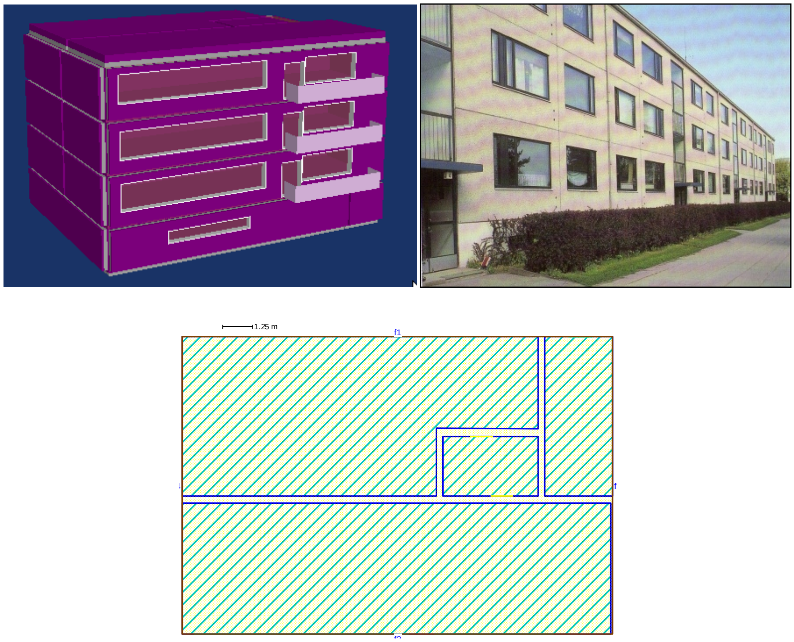

Figure 5. Apartment house.

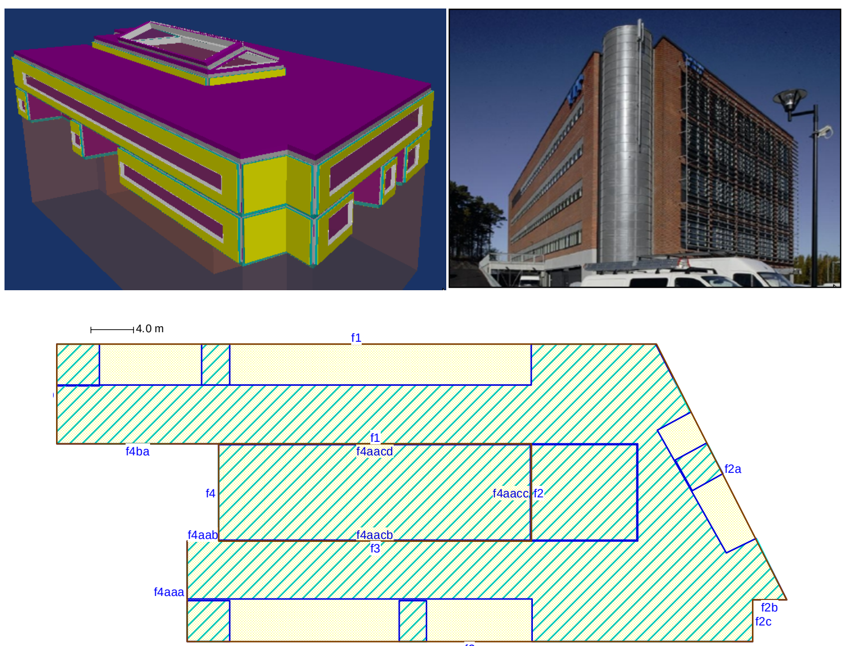

Figure 6. Office building.

The living areas of the standard building types were following: detached house 134 m^2, apartment house 814 m^2 and cottage 134 m^2. The net area of the office building was 2 695 m^2.

The standard building types were further divided to subgroups A, B, C1, C2, D1, D2 and D3 representing the construction styles and building energy use of different decades (Table 16). The specific parameters for different subgroups were selected based on various previous studies. These parameters are presented in following tables.

Table 16. Subgroups of standard building types.

Subgroup	**Building year (and energy demand)**
A	before 1960
B	1960–1979
C1	1980–2000
C2	2001–2010
D1	after 2010 (energy demand fulfilling Finnish building code 2012 Part D5)
D2	after 2010 (low-energy building)
D3	after 2010 (very low-energy building, passive house)

Table 17. Air-tightness of the building envelope n50, 1/h.

Sub-group	**Standard building type**			
	Detached house	Apartment house	Office building	Cottage
A	*	*	*	*
B	*	2.3 [a]	2.3 [a]	*
C1	4.0 [d]	1.0	1.5	7.9 [b]
C2	3.5 [d]	0.9 [e]	0.9 [f]	5.8 [c]
D1	2.0	0.7	0.5	5.8 [c]
D2	0.8	0.6	0.5	0.8
D3	0.6	0.6	0.5	0.6

* For houses with natural ventilation the air-leakage through the envelope is included in the air-change rate. Sources: [a] Polvinen et al., 1983, [b] Dyhr, 1993, [c] Vinha et al., 2009, [d] Vinha et al., 2009 and Polvinen et al., 1983, [e] Vinha et al., 2009, [f] Suomela, 2010 and Eskola et al., 2009.

Table 18. Heat loss values (U-values) of the building structures, W/m2K. OW = outer wall, UF = upper floor, BF = base floor, W = window.

Sub-group	Standard building type			
	Detached house	Apartment house	Office building	Cottage
A	OW = 0.69 [a] UF = 0.41[a] BF = 0.48 W = 2.2[a]	OW = 0.83[a] UF = 0.42[a] BF = 0.48 W = 2.2[a]	OW = 0.83[a] UF = 0.42[a] BF = 0.48 W = 2.2[a]	as detached house of A
B	OW = 0.42[a] UF = 0.24[a] BF = 0.48 W = 2.2[a]	OW = 0.47[a] UF = 0.29[a] BF = 0.48 W = 2.2[a]	OW = 0.47[a] UF = 0.29[a] BF = 0.48 W = 2.2[a]	as detached house of A
C1	OW = 0.28[b] UF = 0.22[b] BF = 0.36[b] W = 1.6[a]	OW = 0.28[b] UF = 0.22[b] BF = 0.36[b] W = 1.6[a]	OW = 0.28[b] UF = 0.22[b] BF = 0.36[b] W = 1.6[a]	as detached house of B
C2	OW = 0.25[c] UF = 0.16[c] BF = 0.25[c] W = 1.4[c]	OW = 0.25[c] UF = 0.16[c] BF = 0.25[c] W = 1.4[c]	OW = 0.25[c] UF = 0.16[c] BF = 0.25[c] W = 1.4[c]	as detached house of C1
D1	OW = 0.17[d] UF = 0.09[d] BF = 0.16[d] W = 1.0[d]	OW = 0.17[d] UF = 0.09[d] BF = 0.16[d] W = 1.0[d]	OW = 0.17[d] UF = 0.09[d] BF = 0.16[d] W = 1.0[d]	according to Finnish building code, part C3 (2010), log wall U-value 0.4
D2	OW = 0.14, UF = 0.08, BF = 0.12, W = 0.9[e]			as detached house of D2
D3	OW = 0.08 UF = 0.07 BF = 0.09, W = 0.7[f]			as detached house of D3

Sources: [a] Nykänen & Heljo, 1985, [b] C3, 1985, [c] C3, 2003, [d] C3, 2010, [e] Peuhkuri & Pedersen, 2010, [f] Nieminen et al., 2007.

Table 19. Set indoor temperatures, °C.

Sub-group	**Standard building type**			
	Detached house [a]	Apartment house	Office building	Cottage
A	21.0	22.0 [b]	21.5	21.0
B	21.0	22.0 [b]	21.5	21.0
C1	21.0	22.0 [b]	21.5	21.0
C2	21.0	21.5 [b]	21.5	21.0
D1, D2, D3	21.0	21.0 [c]	21.5	21.0

[a] bathroom and sauna set temperatures 21 °C, [b] cellar and staircase set temperatures 19.0 °C, WC and bathroom set temperatures 23 °C, [c] cellar and staircase set temperatures 17.0 °C, WC and bathroom set temperatures 23 °C.

Table 20. Ventilation systems. NV = natural ventilation, ME = mechanical exhaust ventilation, MSE = mechanical suppy and exhaust ventilation, HR = heat recovery (yearly efficiency rate).

Sub-group	**Standard building type**			
	Detached house	Apartment house	Office building	Cottage
A	NV	NV	NV	NV
B	NV	ME	ME	NV
C1	ME	ME	MSE + HR (50%)	ME
C2	MSE + HR (60%)	MSE + HR (60%)	MSE + HR (80%)	ME
D1	MSE + HR (60%)	MSE + HR (60%)	MSE + HR (80%)	MSE + HR (60%)
D2	MSE + HR (80%)	MSE + HR (80%)	MSE + HR (80%)	MSE + HR (80%)
D3	MSE + HR (85%)	MSE + HR (85%)	MSE + HR (85%)	MSE + HR (80%)

Table 21. Air-change rate, 1/h.

Sub-group	Standard building type			
	Detached house	Apartment house	Office building	Cottage
A	0.41 [a]	0.62 [a]	0.62 [a]	0.41*
B	0.41 [a]	0.43 [b]	0.43 [b]	0.41*
C1	0.46 [a]	0.5 [d]	0.5 [d]	0.46*
C2	0.40 [c]	0.56 [c]	0.5 [e]	0.40*
D1	0.5 [f]	0.5 [f]	0.5 [f]	0.5*
D2	0.5 [f]	0.5[f]	0.5 [f]	0.5*
D3	0.5[f]	0.5[f]	0.5 [f]	0.5*

* During usage time, in other times only air-leakage through the envelope. Sources: [a] Ruotsalainen, 1992, [b] Dyhr, 1993, [c] Vinha et al., 2005 and Vinha et al., 2009, [d] Finnish building code: part D2, 1987, [e] Finnish building code: part D2, 2003, [f] Finnish building code: part D2, 2010.

Table 22. Warm service water consumption.

Sub-group	Standard building type			
	Detached house	Apartment house	Office building	Cottage
A	42 dm^3/ pers,day [a]	64 dm^3/ pers,day [b]	100 dm^3/rm^2, a [c]	According to the usage profile
B	42 dm^3/ pers,day [a]	62 dm^3/ pers,day [b]	– II –	– II –
C1	42 dm^3/ pers,day [a]	59.2 dm^3/ pers,day [b]	– II –	– II –
C2	42 dm^3/ pers,day [a]	57.6 dm^3/ pers,day [b]	– II –	– II –
D1, D2, D3	42 dm^3/ pers,day [a]	56 dm^3/ pers,day [b]	– II –	– II –

Sources: [a] Motiva, 2009, [b] Virta & Pylsy, 2011, [c] Finnish Building Code, Part D5, 2007.

The lighting and device electricity use of the different standard building types was estimated according to the Finnish Building Code, part D3 (2012).

The electricity use of the following systems are based on the the Finnish Building Code, part D5 (2012). The electricity use of courtyard lighting was 2 kWh/m^2 for detached houses, apartment houses and office buildings. The parking place heating was 150 kWh/parking place for detached houses, apartment houses and office buildings. The annual electricity use of the elevator was 23 kWh/resident for the apartment house and 2 000 kWh/elevator for the office building with 4 elevators. The electricity use for sauna heating is presented in Table 23. The apartment house had 8 flats with 3 residents per a flat. Saunas were heated once a week.

Table 23. Electricity use for sauna heating.

Sub group	**Standard building type**			
	Detached house	Apartment house	Office building	Cottage
A	Apartment sauna 8 kWh/ one heating	Building sauna 410 kWh/flat,a	-	-
B	Apartment sauna 8 kWh/ one heating	Building sauna 410 kWh/flat,a	-	-
C1	Apartment sauna 8 kWh/ one heating	Apartment sauna 8 kWh/ one heating	-	-
C2	Apartment sauna 8 kWh/ one heating	Apartment sauna 8 kWh/ one heating	-	-
D1, D2, D3	Apartment sauna 8 kWh/ one heating	Apartment sauna 8 kWh/ one heating	-	-

Source: Finnish Building Code, Part D5 (2007).

5.2 Energy demands of standard building types

The energy demands of the different standard building types and subgroups were simulated using IDA ICE dynamical simulation program with the test weather data 2012 of Jyväskylä, Central Finland (Kalamees et al., 2012). The heating and cooling energy use of the detached house is presented in Table 24 and the electricity use in Table 25. For the apartment house the heating and cooling energy use is presented in Table 26 and the electricity use in Table 27. The heating and cooling energy use of the office building is presented in Table 28 and the electricity use in Table 29. For the cottage the heating and cooling energy use is presented in Table 30 and the electricity use in Table 31.

Table 24. Detached house: heating and cooling demand.

Sub-group	Dimensioning power, W/m²		Heating and cooling energy net demand, kWh/m²			
	Space heating	Inlet air heating	Space heating	Space cooling	Inlet air heating	Warm service water heating
A	96	0	242	0	0	21
B	78	0	189	0	0	21
C1	66	0	157	0	0	21
C2	45	8	98	0	10	21
D1	34	11	68	2	9	21
D2	30	8	53	3	2	21
D3	24	8	38	4	2	21

Table 25. Detached house: specific electricity demand, kWh/m^2.

Sub-group	Device electricity	Lighting	Courtyard lighting	Fan electricity	Parking place electricity	Sauna
A	23	7	2	0	2	3
B	23	7	2	0	2	3
C1	23	7	2	2	2	3
C2	23	7	2	5	2	3
D1	23	7	2	6	2	3
D2	23	7	2	6	2	3
D3	23	7	2	6	2	3

Table 26. Apartment house: heating and cooling demand.

Sub-group	Dimensioning power, W/m²		Heating/cooling energy net demand, kWh/m²			
	Space heating	Inlet air heating	Space heating	Space cooling	Inlet air heating	Warm service water heating
A	87	0	200	0	0	49
B	60	0	125	0	0	47
C1	39	0	51	0	0	45
C2	24	16	22	0	17	44
D1	18	15	11	0	15	43
D2	17	12	8	0	4	43
D3	14	12	4	0	3	43

Table 27. Apartment house: specific electricity demand, kWh/m^2.

Sub-group	Devices	Lighting	Courtyard lighting	Fans	Parking places	Elevator	Saunas
A	30	10	2	0	2	2	0.1
B	30	10	2	1	2	2	0.1
C1	30	10	2	1	2	2	0.1
C2	30	10	2	7	2	2	0.5
D1	30	10	2	7	2	2	0.5
D2	30	10	2	7	2	2	0.5
D3	30	10	2	7	2	2	0.5

Table 28. Office building: heating and cooling demand.

Sub-group	Dimensioning power, W/m^2		Heating/cooling energy net demand, kWh/m^2			
	Space heating	Inlet air heating	Space heating	Space cooling	Inlet air heating	Warm service water heating
A	96	0	232	0	0	6
B	67	0	135	0	0	6
C1	47	54	105	12	27	6
C2	44	45	52	20	5	6
D1	36	47	41	16	6	6
D2	32	47	33	23	6	6
D3	29	47	25	27	5	6

Table 29. Office building: specific electricity demand, kWh/m^2.

Sub-group	Devices	Lighting	Courtyard lighting	Fans	Parking places	Elevators
A	30	22	2	0	9	3
B	30	22	2	2	9	3
C1	30	22	2	12	9	3
C2	30	22	2	12	9	3
D1	30	22	2	13	9	3
D2	30	22	2	14	9	3
D3	30	22	2	13	9	3

Table 30. Cottage: heating and cooling demand.

Sub-group	Dimensioning power, W/m^2		Heating/cooling energy net demand, kWh/m^2			
	Space heating	Inlet air heating	Space heating	Space cooling	Inlet air heating	Warm service water heating
A	108	0	94	0	0	11
B	108	0	91	0	0	11
C1	88	0	63	0	0	11
C2	88	0	61	0	0	11
D1	51	13	39	0	1	11
D2	33	10	22	0	0	11
D3	27	10	17	0	0	11

Table 31. Cottage: specific electricity demand, kWh/m^2.

Subgroup	Devices	Lighting	Pumps and fans
A	30	22	0
B	30	22	2
C1	30	22	12
C2	30	22	12
D1	30	22	13
D2	30	22	14
D3	30	22	13

5.3 Energy use in the Finnish building stock with standard building types

The cumulative energy consumption of the standard building types was calculated based on the modelled development of the building stock using the REMA model developed at VTT. The model is described here briefly, a more detailed description of the model is available in Tuominen et al. (2014). The simulated energy demand results of each standard building type and subgroup were used as an input for the REMA model to calculate the total energy consumption of the building stock in each year, taking into consideration the estimated changes in the future development of the building stock. The building stock for year 2010 is presented in Table 32.

Table 32. Modelled size of building stock in 2010 according to the REMA model, in millions of m^2. Inconsistences in totals are due to rounding.

Construction year	Detached homes	Apartment buildings	Office buildings	Cottages
1980–2010	57	49	47	5
1960–1979	40	51	30	6
–1960	50	19	24	10
Total	147	119	100	21

The model uses the built area of each building type to multiply the specific energy demands presented in section 5.2 to achieve an estimate of annual cumulative consumption, for each year, producing a time series. This calculation allows the estimation of the consumption of delivered energy throughout the building stock. However, the REMA model also contains a simplified model of energy production, which allows the estimation of primary energy consumption and CO_2-emissions for various scenarios.

Besides national building statistics, the forecast development of the building stock is also based on previous VTT predictions of future development of the stock, which are further based on the theory of Rank Bo about the effects of economic and social factors on the building stock. For new construction, the estimates are largely based on long term observations and, for residential construction, also on statistical population projections. The projected figures for new construction, as well as the removal of old buildings from the stock, vary depending on the type of building and the time period in question. The beginning of the modelling was set in the year 2010 to allow comparing the modelled results to statistics and previous studies. Figure 7 shows the results of the REMA modelling compared with statistics and selected previous studies. The modelled results fit reasonably well within the variation present in the literature.

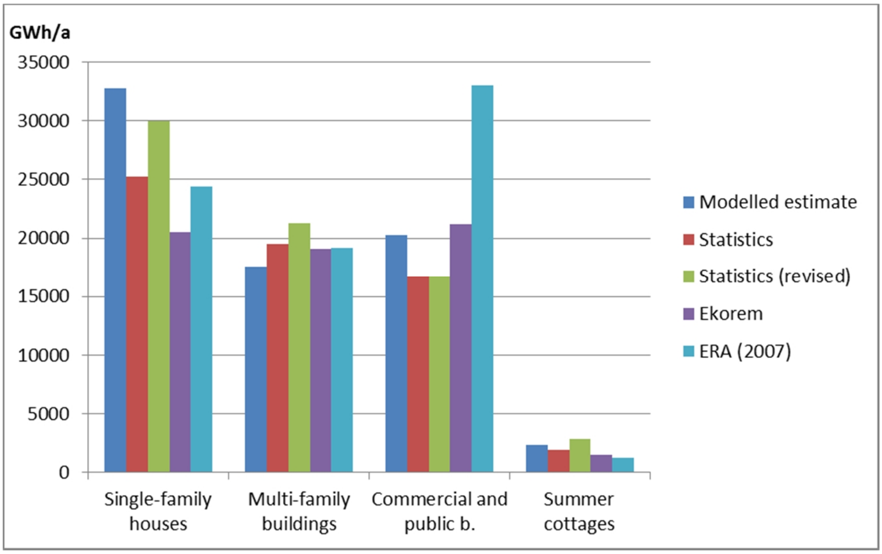

Figure 7. Calculated heating energy consumption of the standard building types compared to previous estimations from Statistics, Ekorem model and ERA (2007).

6. Energy saving potential and renewable energy use of the heat pumps in Finland

The method used to estimate the energy saving and renewable energy use potentials of the heat pumps on the Finnish building stock was based on the description of the building stock as standard building types and on the calculation of the thermal characteristics of each heat pump type on these typical buildings. The descriptions and energy consumption calculations of the type buildings are presented in chapter 4.

In this chapter the heat pump characteristics, calculated energy savings and use of renewable energy are presented for the standard building types of detached house, apartment house and cottage. Finally, the energy saving potential and reduction of emissions of heat pumps on the Finnish building stock is estimated.

6.1 Energy use of the standard type buildings with heat pumps

To estimate the energy saving and renewable energy potential of heat pumps on the Finnish building stock the behaviour of different heat pumps on the type buildings, described in chapter 5, were modelled. Seasonal performance factors for different heat pump types were calculated with the detailed SPF calculation method developed in this project (chapter 4). The calculated heat pump types were:

1. ground source heat pump
2. air to water heat pump
3. air to air heat pump
4. exhaust air heat pump.

Following assumptions were made in the calculations:

- individual characteristics of different heat pumps represents the best available technology of today
- dimensioning of the heat pumps was chosen to be both realistic and yet to deliver a close to maximal heat production
- temperature of the heating system was chosen to represent the prevailing system and thermal dimensioning values of each type building.

Energy consumption simulations and heat pump calculations were carried out with Jyväskylä[2] weather data. Heat pump calculations were performed for three standard building types: detached house, apartment house and cottage.

6.1.1 Detached houses

Ground source heat pump

The ground source heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology.

Table 33. Ground source heat pump in detached house: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	0 ºC	35 ºC	5.0
hot water production	0 ºC	52 ºC	2.7

The temperature of the ground source was modelled as a cosine function with yearly average value of 0 ºC and peak-to-peak amplitude of 2 ºC (Figure 8). The warmest month was presupposed to be August.

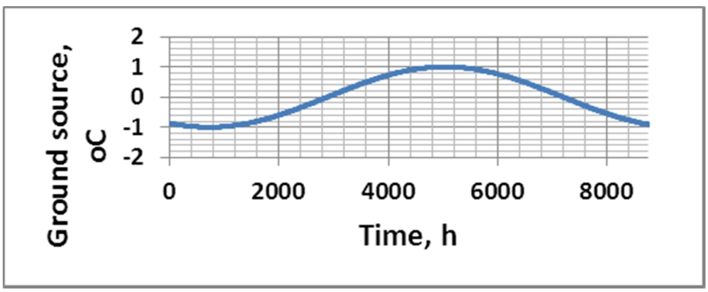

Figure 8. Ground source temperature over one year period.

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC.

[2] http://www.ym.fi/fi-FI/Maankaytto_ja_rakentaminen/Lainsaadanto_ja_ohjeet/Rakentamismaarayskokoelma

The heating power varied from 14 kW (building type A) to 7 kW (building type D3) at declared operation temperatures of 0 ºC / +35 ºC. The results of the yearly calculation are presented in Table 34.

Table 34. Ground source heat pump in detached house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A(1	37.5	9.7	28.1	3.9	0.8
B(1	30.1	7.9	22.4	3.8	0.5
C1(1	25.9	5.6	20.5	4.6	0.0
C2(2	18.9	4.1	14.9	4.6	0.0
D1(3	14.6	3.4	11.3	4.3	0.0
D2(4	11.1	2.6	8.6	4.2	0.0
D3(5	9.0	2.3	6.8	3.9	0.0

(1Old house, radiators, (2Old house, floor heating, (3New building, floor heating,(4Low energy building, floor heating, (7Passive house, floor heating

Air to water heat pump

Air to water heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology. The outdoor temperature used was based on the weather data for Jyväskylä.

Table 35. Air to water heat pump in detached house: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	7 ºC	35 ºC	4.2
hot water production	7 ºC	47 ºC	3.3

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power varied from 12 kW (building type A) to 6 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. The results of the yearly calculation are presented in Table 36.

Table 36. Air to water heat pump in detached house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A(1	33.7	12.2	21.5	2.8	4.6
B(1	28.4	10.6	17.9	2.7	2.2
C1(1	24.0	9.0	15.1	2.7	1.9
C2(2	18.2	5.6	12.7	3.3	0.7
D1(3	14.0	5.1	9.1	2.8	0.5
D2(4	10.9	3.5	7.5	3.1	0.3
D3(5	8.8	2.9	6.0	3.0	0.1

(1Old house, radiators, (2Old house, floor heating, (3New building, floor heating, (4Low energy building, floor heating , (5Passive house, floor heating

Air to air heat pump

Air to air heat pumps were modelled with three performance points with different loads. The performance factors were chosen to represent the best practice of the available technology.

Table 37. Air to air heat pump in detached house: performance points.

Load	Temperature of heat source	Temperature of heating	COP
100%	7 ºC	35 ºC	3.6
75%	7 ºC	35 ºC	4.1
50%	7 ºC	35 ºC	5.4

The outdoor temperature was based on the weather data for Jyväskylä[3]. The heating power varied from 8 kW (building type A) to 3 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. It was presumed that the effective floor area of the heat pump is 50% of the total floor area and that the air heat pump raises the indoor air temperature by 2 ºC of the working area. The results of the yearly calculation are presented in Table 38.

[3] http://www.ym.fi/fi-FI/Maankaytto_ja_rakentaminen/Lainsaadanto_ja_ohjeet/Rakentamismaarayskokoelma

Table 38. Air to air heat pump in detached house: results.

Building type	Heat produced by heat pump for space heating, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use[1], MWh/a	SPF	Back-up heat required, MWh/a
A	18.6	5.6	11.5	3.3	19.7
B	14.4	4.4	8.8	3.3	16.2
C1	12.2	3.7	7.6	3.3	13.8
C2	7.7	2.3	4.9	3.3	11.2
D1	5.2	1.6	3.3	3.3	9.3
D2	4.1	1.3	2.6	3.2	7.0
D3	3.0	1.0	1.9	3.1	6.0

[1] The renewable energy is the virtual value i.e. the increased energy consumption of higher room air temperature has been taken into account.

Exhaust air heat pump

Exhaust air heat pumps were modelled with three performance points: 1) heating at full power, 2) heating at 46% power and 3) hot water production. The performance factors were chosen to represent the best practice of the available technology.

Table 39. Exhaust air heat pump in detached house: operation modes.

Operation mode	Temperature of exhaust air	Temperature of heating	COP
heating, 100% load	-9 ºC	35 ºC	3.15
heating, 46% load	-9 ºC	35 ºC	4.7
hot water production	-9 ºC	50 ºC	2.5

The humidity of the indoor air was presumed to be the same as the outdoor air humidity. Weather data of Jyväskylä was used as the climate data. The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power of the exhaust air heat pump is determined by the exhaust air flow rate and it was 2,8 kW for each case at declared operation temperatures of -9 ºC / +35 ºC. The exhaust air flow rate was 42 l/s. The results of the yearly calculation are presented in Table 40.

Table 40. Exhaust air heat pump in detached house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Energy saving / Renewable energy(1 MWh/a	SPF	Back-up heat required, MWh/a
A	17.5	6.4	11.4 / 4.2	2.8	20.7
B	16.7	6.1	10.8 / 3.7	2.7	13.9
C1	15.1	4.8	10.5 / 3.3	3.1	10.9
C2	14.4	4.4	10.2 / 3.1	3.2	8.2
D1	13.5	4.2	9.5 / 2.3	3.3	4.9
D2	12.3	3.7	8.8 / 2.0	3.3	3.0
D3	11.2	3.4	8.0 / 1.6	3.3	1.9

[1] Energy saving means the total energy from exhaust air (=evaporator energy) and renewable energy means energy saving deducted by the ventilation heat demand.

6.1.2 Apartment houses

Ground source heat pump

Ground source heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology. The temperature of the ground source was modelled as a cosine function with yearly average value of 0 ºC and peak-to-peak amplitude of 2 ºC (Figure 8). The warmest month was taken to be August.

Table 41. Ground source heat pump in apartment house: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	0 ºC	35 ºC	4,8
hot water production	0 ºC	52 ºC	2,7

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power varied from 80 kW (building type A) to 30 kW (building type D3) at declared operation temperatures of 0 ºC / +35 ºC. The results of the yearly calculation are presented in Table 42.

Table 42. Ground source heat pump in apartment house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A[(1]	232.4	64.5	169.0	3.6	6.6
B[(1]	160.2	46.7	114.3	3.4	3.7
C1[(1]	97.2	30.9	66.8	3.1	0.1
C2[(2]	82.5	26.2	56.8	3.2	0.1
D1[(3]	65.6	20.8	45.2	3.2	0.0
D2[(4]	52.8	18.2	34.9	2.9	0.0
D3[(5]	47.8	17.3	30.8	2.8	0.0

[(1]Old house, radiators, [(2]Old house, floor heating, [(3]New building, floor heating, [(4]Low energy building, floor heating, [(5]Passive house, floor heating

Air to water heat pump

Air to water heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology. The outdoor temperature was based on the weather data for Jyväskylä.

Table 43. Air to water heat pump in apartment house: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	7 ºC	35 ºC	4.2
hot water production	7 ºC	50 ºC	3.3

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power varied from 70 kW (building type A) to 25 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. The results of the yearly calculation are presented in Table 44.

Table 44. Air to water heat pump in apartment house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A(1	222.2	68.1	154.4	3.3	16.8
B(1	159.1	51.2	108.2	3.1	4.7
C1(1	93.6	31.5	62.4	3.0	3.6
C2(2	80.8	26.8	54.2	3.0	1.8
D1(3	64.6	20.7	44.1	3.1	1.0
D2(4	52.4	17.7	34.9	3.0	0.4
D3(5	47.4	16.5	31.1	2.9	0.4

(1Old house, radiators, (2Old house, floor heating, (3New building, floor heating, (4Low energy building, floor heating, (5Passive house, floor heating

Air to air heat pump

Air to air heat pumps were modelled with three performance points with different loads. The performance factors were chosen to represent the best practice of the available technology. The outdoor temperature was based in the weather data for Jyväskylä[4].

Table 45. Air to air heat pump in apartment house: performance points.

Load	Temperature of heat source	Temperature of heating	COP
100%	7 ºC	35 ºC	3.6
75%	7 ºC	35 ºC	4.1
50%	7 ºC	35 ºC	5.4

The heating power of one heat pump varied from 4 kW (building type A) to 3 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. It was presumed that the effective floor area of the heat pump is 75% of the total floor area and that the air heat pump raises the indoor air temperature by 2 ºC of the working area. The results of the yearly calculation are presented in Table 46.

[4] http://www.ym.fi/fi-FI/Maankaytto_ja_rakentaminen/Lainsaadanto_ja_ohjeet/Rakentamismaarayskokoelma

Table 46. Air to air heat pump in apartment house in one dwelling: results.

Building type	Heat produced by heat pump for space heating, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A	12.4	4.0	7.3	3.1	7.5
B	8.1	2.5	5.0	3.3	5.5
C1	3.8	1.1	2.4	3.3	4.3
C2	1.8	0.5	1.2	3.3	5.1
D1	0.7	0.3	0.5	2.6	4.7
D2	0.5	0.2	0.4	2.4	3.9
D3	0.3	0.2	0.2	1.8	3.7

Exhaust air heat pump

Exhaust air heat pumps were modelled with two performance point: 1) heating and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology.

Table 47. Exhaust air heat pump in apartment building: operation modes.

Operation mode	Temperature of exhaust air	Temperature of heating	COP
heating	-9 ºC	35 ºC	3.5
hot water production	-9 ºC	50 ºC	2.5

The humidity of the indoor air was presumed to be the same as the outdoor air humidity. Weather data of Jyväskylä[5] was used as the climate data. The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power of the exhaust air heat pump is determined by the exhaust air flow rate and it was 19,5 kW for each case at declared operation temperatures of -9 ºC / +35 ºC. The exhaust ai flow rate was 300 l/s. The results of the yearly calculation are pre-

[5] http://www.ym.fi/fi-FI/Maankaytto_ja_rakentaminen/Lainsaadanto_ja_ohjeet/Rakentamismaarayskokoelma

sented in Table 48. Exhaust air heat pumps were supposed to be installed only to building types with no exhaust air heat recovery devices.

Table 48. Exhaust air to water heat pump in apartment house: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Energy saving / Renewable energy[1] MWh/a	SPF	Back-up heat required, MWh/a
A	126.9	44.4	82.8 / 30.8	2.9	112.2
B	114.1	41.0	73.5 / 21.9	2.8	49.7
C1	87.9	33.3	55.0 / 9.6	2.6	9.4

[1] Energy saving means the total energy from exhaust air (=evaporator energy) and renewable energy means energy saving deducted by the ventilation heat demand.

6.1.3 Cottages

<u>Ground source heat pump</u>

Ground source heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology. The temperature of the ground source was modelled as cosine function with yearly average value of 0 ºC and peak-to-peak amplitude of 2 ºC (Figure 8). The warmest month was taken to be August.

Table 49. Ground source heat pump in cottage: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	0 ºC	35 ºC	5.0
hot water production	0 ºC	52 ºC	2.7

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power varied from 8 kW (building type A) to 4 kW (building type D3) at declared operation temperatures of 0 ºC / +35 ºC. The results of the yearly calculation are presented in Table 50.

Table 50. Ground source heat pump in cottage: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A[(1]	13.8	3.8	10.1	3.7	1.5
B[(1]	13.4	3.7	9.8	3.6	1.8
C1[(1]	10.1	2.8	7.4	3.6	0.6
C2[(2]	10.0	2.6	7.5	3.8	0.5
D1[(3]	7.0	1.7	5.4	4.2	0.2
D2[(4]	4.5	1.2	3.4	3.7	0.0
D3[(5]	3.7	1.1	2.8	3.5	0.0

[(1]Old house, radiators, [(2]Old house, floor heating, [(3]New building, floor heating, [(4]Low energy building, floor heating, [(5]Passive house, floor heating

Air to water heat pump

Air to water heat pumps were modelled with two performance points: 1) heating at full power and 2) hot water production. The performance factors were chosen to represent the best practice of the available technology. The outdoor temperature was based on the weather data for Jyväskylä.

Table 51. Air to water heat pump in detached house: operation modes.

Operation mode	Temperature of heat source	Temperature of heating	COP
heating	7 ºC	35 ºC	4,2
hot water production	7 ºC	47 ºC	3,3

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power varied from 8 kW (building type A) to 4 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. The results of the yearly calculation are presented in Table 53.

Table 52. Air to water heat pump in cottage: results.

Building type	Heat produced by heat pump for space heating and domestic hot water MWh/a	Electricity use of heat pump MWh/a	Renewable energy use MWh/a	SPF	Back-up heat required MWh/a
A(1	12.4	4.9	7.6	2.5	2.9
B(1	12.0	4.7	7.3	2.5	3.2
C1(1	9.3	3.7	5.7	2.5	1.4
C2(2	8.6	3.2	5.5	2.7	1.9
D1(3	6.6	2.2	4.5	3.0	0.6
D2(4	4.2	1.5	2.8	2.9	0.3
D3(5	3.6	1.3	2.4	2.8	0.2

(1Old house, radiators, (2Old house, floor heating, (3New building, floor heating, (4Low energy building, floor heating, (5Passive house, floor heating

Air to air heat pump

Air to air heat pumps were modelled with three performance points with different loads. The performance factors were chosen to represent the best practice of the available technology. The outdoor temperature was based on the weather data for Jyväskylä.

Table 53. Air to air heat pump in cottage: performance points.

Load	Temperature of heat source	Temperature of heating	COP
100%	7 ºC	35 ºC	3.6
75%	7 ºC	35 ºC	4.1
50%	7 ºC	35 ºC	5.4

The heating power varied from 6 kW (building type A) to 4 kW (building type D3) at declared operation temperatures of +7 ºC / +35 ºC. It was presumed that the effective floor area of the heat pump is 50% of the total floor area and that the air heat pump raises the indoor air temperature by 2 ºC of the working area. The results of the yearly calculation are presented in Table 54.

Table 54. Air to air heat pump in cottage: results.

Building type	Heat produced by heat pump for space heating, MWh/a	Electricity use of heat pump, MWh/a	Renewable energy use, MWh/a	SPF	Back-up heat required, MWh/a
A	6.9	2.3	4.1	3.0	8.4
B	6.7	2.3	4.0	2.9	8.5
C1	4.7	1.6	2.9	3.0	6.0
C2	4.6	1.5	2.8	3.0	5.9
D1	2.7	1.0	1.7	2.8	4.4
D2	1.5	0.6	1.0	2.5	3.0
D3	1.1	0.5	0.7	2.3	2.6

Exhaust air heat pump

Exhaust air heat pumps were modelled with three performance points: 1) heating at full power, 2) heating at 46% power and 3) hot water production. The performance factors were chosen to represent the best practice of the available technology. The humidity of the indoor air was presumed to be the same as the outdoor air humidity. Weather data of Jyväskylä was used as the climate data.

Table 55. Exhaust air heat pump in cottage: operation modes.

Operation mode	Temperature of exhaust air	Temperature of heating	COP
heating, 100% load	-9 ºC	35 ºC	3.15
heating, 46% load	-9 ºC	35 ºC	4.7
hot water production	-9 ºC	50 ºC	2.5

The dimensioning supply temperature of the heating network varied between the building types from +70 ºC (building type A with radiators) to +35 ºC (building type D3 with floor heating). Linear weather compensation of the supply temperature was used in each case. The temperature of the hot water demand was +55 ºC. The heating power of the exhaust air heat pump is determined by the exhaust air flow rate and it was 2,8 kW for each case at declared operation temperatures of -9 ºC / +35 ºC. The exhaust air flow rate was 42 l/s. The results of the yearly calculation are presented in Table 56.

Table 56. Exhaust air to water heat pump in cottage: results.

Building type	Heat produced by heat pump for space heating and domestic hot water, MWh/a	Electricity use of heat pump, MWh/a	Energy saving /Renewable energy[1] MWh/a	SPF	Back-up heat required, MWh/a
A	9.6	3.6	6.2 / 1.5	2.7	5.6
B	9.4	3.5	6.1 / 1.4	2.7	5.7
C1	7.6	2.8	5.0 / 1.1	2.7	3.0
C2	7.4	2.6	5.0 / 1.0	2.8	3.1

[1]Energy saving means the total energy from exhaust air (=evaporator energy) and renewable energy means energy saving deducted by the the ventilation heat demand.

6.2 Energy saving and renewable energy use by building type

Tables 57–59 present energy saving and renewable energy use by building type for years 2010, 2016 and 2020 in accordance with the heat pump (HP) scenario presented in section 6.3.

Table 57. Renewable energy use and energy savings by building type in 2010.

Energy savings and renewable energy produced[6] in 2010, GWh				
	Detached houses	Apartment buildings	Free time residences	Total
Ground source	936	2	3	941
Air/water	107	10	0	117
Air/air	1803	184	29	2016
Exhaust air	155	0	2	157
Total	3001	196	34	3231

6 Renewable energy for other than exhaust air heat pumps. With exhaust air heat pumps only part of the savings can be considered renewable energy, see section 6.1.

Table 58. Renewable energy use and energy savings by building type in 2016.

Energy savings and renewable energy produced[6] in 2016, GWh				
	Detached houses	**Apartment buildings**	**Free time residences**	**Total**
Ground source	2434	5	6	2445
Exhaust air	579	11	0	590
Air/air	2960	670	42	3672
Air/water	306	77	3	386
Total	6279	763	51	7093

Table 59. Renewable energy use and energy savings by building type in 2020.

Energy savings and renewable energy produced[6] in 2020, GWh				
	Detached houses	**Attached houses**	**Free time residences**	**Total**
Ground source	3360	7	8	3375
Exhaust air	890	18	0	908
Air/air	3726	842	49	4617
Air/water	374	109	4	487
Total	8350	976	61	9387

6.3 Effects of heat pumps on the energy use and emissions of the Finnish building stock

The effects of heat pumps on the energy use in the building stock were modelled using the REMA model. REMA, described in section 5.3, was used to model the future energy use in the Finnish building stock. As a starting point, the model has a conservative Business as Usual or BAU scenario, where the present trends in the development of the building stock, including heat pumps, are assumed to continue in the future but taking into account known changes in building regulation. For the purposes of this project, another scenario called Heat Pump or HP scenario was calculated based on the results of the calculations concerning heat pump use in the type buildings, presented in section 6.1, and the calculation concerning the increase of heat pump use in the future, presented in section 6.2. The HP scenario and the calculations used to produce it are intented to present a possible development path where heat pumps are used in a rather large scale and they are installed and operated at close to optimum settings. This scenario is seen as technically possible but dependent on future decisions.

REMA model comprises the whole building stock, allowing the inclusion of factors such as the different energetic properties of different types and ages of buildings, the replacement of various alternative heat sources with heat pumps and differentiating heat pumps retrofitted in old buildings from the ones installed in new buildings. REMA model also includes a simplified model of the energy production infrastructure that allows the assessment of the effects on CO_2 emissions.

The calculation of the scenario starts from year 2010 and ends on year 2020 based on the data available in Table 4 and Table 6. This means that some of the results will differ from the baseline scenario already in past years, namely 2010–2013. As the fast increase in the number of heat pumps in the recent years has brought uncertainty in their effects on energy use in the building stock, the results for 2013 are presented in Table 60 together with the forecast for the year 2020 in Table 61. It should be noted that the difference shown in these tables shows the difference between BAU and HP scenarios. As BAU scenario also includes a modest amount of heat pumps, the figures should not be interpreted to show the total effect of all heat pumps. For such figures, the reader is directed to section 6.4. The differences between the scenarios presented here represent the difference of an accelerated adoption of heat pumps as opposed to a continuation of a business as usual scenario.

Table 60. Modelled energy use for heating in 2013 (GWh).

	District heat	Oil	Wood	Electricity	Total
BAU scenario	28960	16196	17062	10553	72771
HP scenario	28957	14788	16539	9364	69648
Difference	-3	-1408	-523	-1189	-3123

Table 61. Modelled energy use for heating in 2020 (GWh).

	District heat	Oil	Wood	Electricity	Total
BAU scenario	28608	14785	16006	11086	70485
HP scenario	28598	11510	15086	10022	65216
Difference	-10	-3275	-920	-1064	-5269

The results indicate that in 2013 total modelled use of heating energy in the HP scenario would be 72 800 GWh, of which electricity accounts for 10 600 GWh. This is 3100 GWh less in total and 1200 GWh less in electricity than was projected in the

BAU scenario, the difference being due to a faster than anticipated increase in the number of heat pumps. By 2020 the numbers are forecast to be 70 500 GWh of total heating energy in the HP scenario, of which 11 100 GWh is electricity, and which is 5300 GWh lower in total and 1100 GWh lower in electricity than the BAU.

Table 62 and Table 63 show the results for modelled CO_2 emissions. The said differences in energy consumption cause the emissions to be 800 kilotonnes lower in 2013 and 1300 kilotonnes lower in 2020 in the HP scenario compared to BAU.

Table 62. Modelled CO_2 emissions from the building stock in 2013 (KT). DHW stands for domestic hot water.

	Space heating	**DHW**	**Electricity (non-heating)**	**Total**
BAU scenario	12573	2023	4916	19511
HP scenario	11806	2023	4916	18745
Difference	-767	0	0	-767

Table 63. Modelled CO_2 emissions from the building stock in 2020 (KT). DHW stands for domestic hot water.

	Space heating	**DHW**	**Electricity (non-heating)**	**Total**
BAU scenario	11792	2084	4811	18688
HP scenario	10554	2013	4811	17379
Difference	-1238	-71	0	-1309

A time series of the development of energy consumed and CO_2 emissions caused in the building stock can be seen in Figure 9. It should be noted that the modelling after 2020 is not accurate but can be used as an indicator of the rought direction of the development. It can be seen in the figure that both the energy use and CO_2 emissions are on a likely path of reductions in any case because new regulations require much lower energy consumption from buildings. Over time new buildings and buildings renovated to new standards replace older, more energy consuming buildings causing the downward trend. The effect of heat pumps in the HP scenario is to slightly increase the reductions and also quicken their pace in the near future. This is a desirable development as reductions in CO_2 emissions taking place soon are preferable to later reductions due to the urgency in the mitigation of the climatic effects.

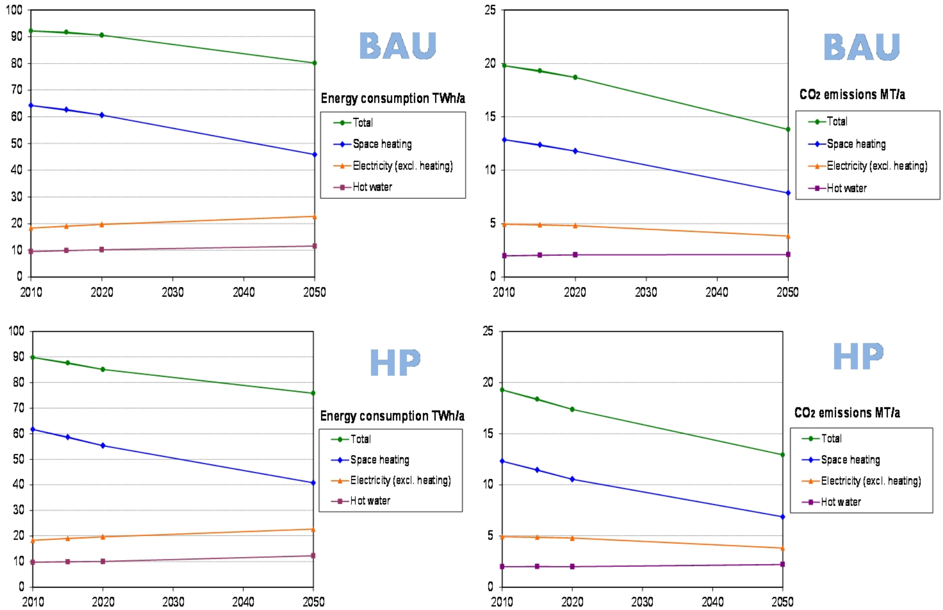

Figure 9. The development of energy use and CO_2 emissions in the two scenarios.

6.4 Renewable energy use and energy savings by heat pumps

Figure 10 presents energy savings for the different heat pump type in accordance with the heat pump (HP) scenario presented in section 6.3. This is approximate also for renewable energy use, except for exhaust air pumps where only part of the savings can be considered renewable energy, for more discussion see section 6.1. Table 64 summarizes the estimated use of renewable energy and energy savings of the heat pumps.

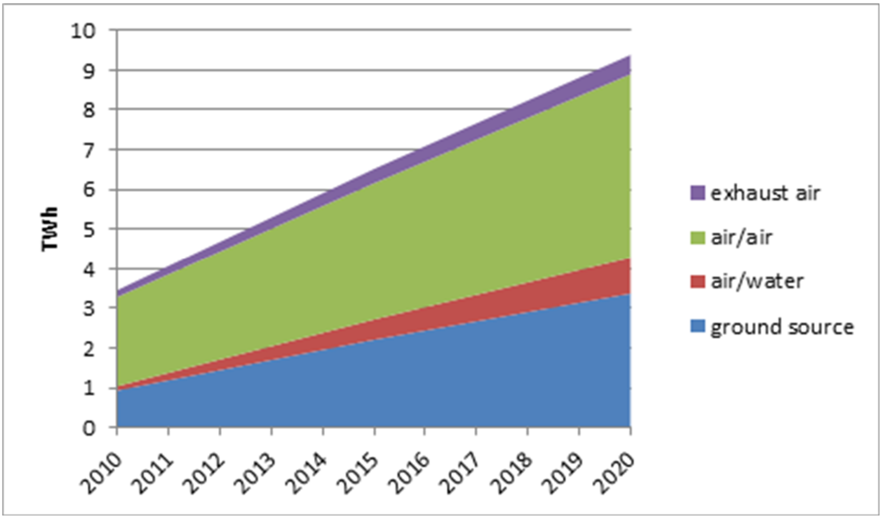

Figure 10. Estimate of energy saved by heat pumps in 2010–2020. For heat pumps other than exhaust air, it represents also renewable energy production.

Table 64. Summary of the estimated use of renewable energy and energy savings of the heat pumps.

Year	Renewable energy, GWh	Energy savings, GWh
2010	3128	3231
2016	6903	7093
2020	9133	9387

7. Annex co-operation

One task of the project was participating in IEA Annex 39 “A common method for testing and rating of residential HP and AC annual/seasonal performance”.

The background for Annex 39 was the demand for a common SPF calculation method for fair comparison between different types of heat pump systems as well as fair comparison with other competing technologies using fossil fuels. A common SPF method could also later be incorporated in different labelling, rating and certification schemes. The common method should be a transparent and harmonised method for calculation of heat pump system SPF and based on repeatability and reliable test data from laboratory measurements.

Heat pumps using aerothermal, geothermal or hydrothermal energy as a source are defined as renewable in the European RES Directive if the SPF is above a specific value. The renewable energy production E_{res} (kWh/a) of a heat pump is calculated as a function of SPF and the annual heating energy production of the heat pump (Q_{usable}), see Chapter 3. The Annex Commission has established in 2013 guidelines on how Member States shall estimate the values of Qusable and SPF for the different heat pump technologies and applications, taking into consideration differences in climatic conditions, especially very cold climates. From a European point of view, it was therefore very important and urgent to define a common standard for SPF calculation at the time when the Annex 39 was prepared.

The legal text for Annex 39 also states that “The development of heat pump standards differs between Asia, North America and Europe and there is a large number of national standards for both testing and calculation of SPF. The heat pump manufacturers would need common testing methods and common SPF methods to simplify the export of heat pumps to different countries. The end users need reliable information in the selection procedure both between different heat pumps as well as in comparing heat pumps with other competing technologies.”

A common SPF calculation method is not easy to define because of different building standards and heat distribution systems. A real value of the SPF should be calculated for each specific installation, from field measured data. A simplified general approach would be making the calculations for one specific building in one specific climate, or to define a limited number of regions with typical climate and buildings.

Annex 39 was coordinated by SP Technical Research Institute of Sweden. Other participants besides VTT Technical Research Centre of Finland and Aalto University were Oak Ridge National Laboratory (ORNL) and Air-Conditioning, Heating, and Refrigeration Institute (AHRI) from USA, Kungliga Tekniska Högskolan (KTH) from Sweden, Austrian Institute of Technology (AIT), EDF from France, Fraunhofer ISE from Germany, HPTCJ from Japan, Korea Institute of Energy Research (KIER) from South Korea and FHNW from Swizerland.

The objects of Annex 39 were to

1. Establish common calculation methods for SPF using a generalised and transparent approach, fair comparison between different heat pump types and comparison between different competing technologies, such as pellet boilers and gas boilers.
2. Establish comprehensive test methods based on further development of existing test standards. The test standards should include test conditions needed for the future SPF calculations.

The Annex work consisted of following tasks

1. Survey and evaluation of existing testing methods and calculation methods for SPF
2. Matrix definition of needs for testing and calculation methods
3. New calculation method for SPF/ Commonly accepted definitions on how SPF is calculated
4. Identify improvements to existing test procedures
5. Validation of SPF method
6. Development of an alternative method to evaluate heat pump performance
7. Communication to stakeholders.

The outcome from the project was meant to be a proposal for a common transparent SPF calculation method for domestic heat pumps including heating, cooling and domestic hot water production. However, a common approach was not found in the Annex 39, instead of this the Annex ended up into listing possible ways of SPF calculation.

8. Summary and conclusions

The main objects of the SPF project were to define a Finnish SPF calculation method for heat pumps in co-operation with international Annex 39 work and to estimate the current and future energy saving and renewable energy use potential of heat pumps on the Finnish building stock.

The developed hourly SPF calculation method can be used for heating energy calculation of air-air-, air-water-, outlet air and ground source heat pumps but not for power dimensioning of a heat pump. Calculation can be performed also with other time steps than one hour. Measured performance values for the heat pump are needed for calculation input values at least in one test point but the calculation is more accurate if performance values are available from several test points. The calculation method does not take into account the heat storage ability of the domestic service water accumulator. The calculation method assumes that the heat pump heats up both domestic service water and spaces in turns so that heating up the domestic service water is the primary function.

The energy use of the Finnish building stock was estimated using standard building types further adapted to different decades: a detached house, an apartment building, an office building and a summer cottage. The energy use of these standard building types was calculated with different heat pump types leading to energy saving and renewable energy use of the heat pumps.

The cumulative energy consumption of the standard building types was calculated based on the modelled development of the building stock using the REMA model developed at VTT. The simulated energy demand results of each standard building type and subgroup were used as an input for the REMA model to calculate the total energy consumption of the building stock in each year, taking into consideration the estimated changes in the future development of the building stock.

The future effects of heat pumps on the energy use in the Finnish building stock were modelled comparing with the REMA model a conservative Business as Usual or BAU scenario with a Heat Pump or HP scenario. In the BAU scenario the present trends in the development of the building stock were assumed to continue in the future but the known changes in building regulation were taken into account. HP scenario was calculated based on the results of the calculations concerning heat pump use in the type buildings and the calculation concerning the increase of heat pump use in the future. The HP scenario presented a possible development path where heat pumps are used in a rather large scale and they are installed and operated at close to optimum settings. This scenario is seen as technically possible but dependent on future decisions.

The HP scenario would have 3100 GWh less total heating energy use and 1200 GWh less electricity use than the BAU scenario in 2013. In 2020 the differences would be 5300 GWh lower total heating energy use and 1100 GWh lower electricity use in HP scenario compared to the BAU scenario. The CO_2 emissions of the HP scenario would be 800 kilotonnes lower in 2013 and 1300 kilotonnes lower in 2020 compared to the BAU scenario.

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Appendix A: Detailed calculation method in Finnish

Lämpöpumppujen energialaskentamenetelmä

1. Määritelmiä

Aika-askel	Laskentahetkien välinen vakioaika, joka on tässä laskentamenetelmässä vapaasti valittavissa Tässä julkaisussa aika-askel on oletusarvoisesti yksi tunti. Laskentamenetelmän yhtälöt ratkaistaan kullakin aika-askeleella.
Lisälämmitys	Lämpöpumpun tuottaman lämpöenergian ja rakennuksen lämmitysenergian välinen erotus, jos lämpöpumppu ei pysty tuottamaan tarvittavaa lämpötehoa. Lisälämmitystarve aiheutuu joko lämpöpumpun toimintaan liittyvistä lämpötilarajoituksista (vrt. toimintarajalämpötila ja ylärajalämpötila) tai lämpöpumpun osatehomitoituksesta, jolloin lämpöpumppu ei tuota rakennuksen lämmitystehon tarvetta mitoitustilanteessa.
Mitoitusulkolämpötila	Rakennusten lämmitysjärjestelmän lämmitystehon mitoituksessa käytettävä ulkoilman vakiolämpötila, joka määritellään Suomessa säävyöhykekohtaisesti Suomen rakentamismääräyskokoelmassa D3 (2012).
On-off-säätöinen lämpöpumppu	On-off-säätöisissä lämpöpumpuissa kompressori kytkeytyy päälle ja toimii nimellisteholla, kunnes lämpöpumpun säätöjärjestelmä havaitsee, että haluttu lämpötila on saavutettu, jolloin kompressori pysähtyy.
SPF-luku	Lämpöpumpun vuoden keskimääräinen lämpökerroin, joka on lämpöpumpulla tuotetun vuotuisen energian suhde lämpöpumpun sekä lämpöpumpun apulaitteiden vuotuiseen sähkönkulutukseen.
Tehosäätöinen lämpöpumppu	Tehosäätöinen (invertteri- tai kapasiteettisäätöinen) lämpöpumppu voi toimia osateholla lämmöntarpeen ollessa pienempi kuin lämpöpumpun tuottama suurin mahdollinen lämmöntuotto toimintalämpötilassa.

Teoreettinen lämpökerroin

Lämpöpumpun hetkellinen lämpökerroin, joka määräytyy pelkästään rakennuksen lämmitysjärjestelmän lämpötilan ja lämmönlähteen lämpötilan perusteella. Teoreettisessa lämpökertoimessa ei ole otettu huomioon kompressorin häviöitä.

2. Laskentamenetelmä

2.1 Laskentaperiaatteet ja rajaukset

Tässä julkaisussa esitettävää tunneittaista laskentamenetelmää voidaan käyttää lämmityskäytössä olevien ilma-ilma-, ilma-vesi-, poistoilma- ja maalämpöpumppujen energialaskentaan. Laskentamenetelmällä ei voida tehdä lämpöpumppujen tehomitoitusta. Laskenta voidaan suorittaa haluttaessa myös muulla kuin tunnin aika-askeleella, mutta tässä julkaisussa aika-askeleen pituutena käytetään yhtä tuntia.

Laskennan lähtötiedoiksi tarvitaan lämpöpumpun mitattuja tuotetietoja vähintään yhdessä testauspisteessä. Laskennassa on-off-säätöinen ilma-ilma-, ilma-vesi- ja maalämpöpumppu toimivat aina nimellistehollaan. On-off-säätöisten lämpöpumppujen höyrystimen ja lauhduttimen tehojen oletetaan muuttuvan lämpötilojen ja niiden myötä lämpökertoimen mukaan, kun lämpöpumpun tuotetiedot tunnetaan yhdessä testauspisteessä. Laskentaa voidaan tarkentaa, mikäli lämpöpumppujen tuotetietoja on käytettävissä useasta testauspisteestä. On-off-säätöisen poistoilmalämpöpumpun lauhduttimen teho riippuu höyrystimen tehosta ja lämpökertoimesta. Lämpöpumppujen todellinen lämpökerroin on suoraan verrannollinen teoreettisen lämpökertoimen arvoon. Kaikkien tehosäätöisten lämpöpumppujen lämmitysteho määräytyy rakennuksen tunneittaisen lämmitystehontarpeen mukaan.

Laskentamenetelmä ei ota huomioon lämminvesivaraajan lämmönvarastointikyvyn vaikutusta lämpöpumpun toimintaan. Laskennassa oletetaan, että käyttövettä ja tiloja lämmittävä lämpöpumppu lämmittää käyttövettä ja tiloja vuorotellen niin, että käyttövettä lämmitetään ensisijaisesti.

2.2 Laskennan kuvaus

2.2.1 Ilma-ilmalämpöpumppu

1. Määritetään seuraavat laskennan lähtötiedot:
    a. Vuoden ulkolämpötila sekä laskennan aika-askeleen pituus (luku 2.3.1).
    b. Tilojen lämmitystehon tai energian tarve (luku 2.3.3).
    c. Lämpöpumpun sisäänpuhalluslämpötila tai tilojen lämmityksen asetusarvo, mikäli sisäänpuhalluslämpötilaa ei tunneta (luku 2.3.4).

   d. Lämpöpumpun mitattu lämpökerroin, lämmitysteho sekä lämpötilat vähintään yhdessä testauspisteessä (luku 2.3.4).
   e. Matalin ulkolämpötila, jossa lämpöpumppua voidaan käyttää (luku 2.3.4).
2. Lasketaan tilojen lämmitystehon tarve kullakin aika-askeleella, mikäli sitä ei ole saatavilla lähtötietona (luku 2.5.2).
3. Lasketaan lämpöpumpun lämpökerroin kullakin aika-askeleella (luku 2.5.4).
4. Lasketaan osatehon vaikutus lämpökertoimen arvoon kullakin aika-askeleella, mikäli lämpöpumppu on tehosäätöinen (luku 2.5.5).
5. Lasketaan lämpöpumpun lämmitysteho kullakin aika-askeleella (luku 2.5.10).
6. Lasketaan tilojen lämmitysenergian tarve kullakin aika-askeleella (luku 2.5.13).
7. Lasketaan tilojen lämmitysenergia, jonka lämpöpumppu pystyy tuottamaa kullakin aika-askeleella ja koko vuoden aikana (luku 2.5.13).
8. Lasketaan lämpöpumpun sähköenergia kullakin aika-askeleella sekä vuotuinen sähköenergian kulutus (luku 2.5.14).
9. Lasketaan lämpöpumpun SPF-luku (luku 2.5.16).
10. Lasketaan tarvittava tilojen vuotuinen lisälämmitysenergia (luku 2.5.17).

2.2.2. Ilma-vesilämpöpumppu

Ilma-vesilämpöpumpun laskenta tehdään seuraavien vaiheiden mukaisesti:

1. Määritetään seuraavat laskennan lähtötiedot:
   a. Vuoden ulkolämpötila sekä laskennan aika-askeleen pituus (luku 2.3.1).
   b. Käyttöveden lämmitystehon tai lämmitysenergian tarve sekä lämpötila (luku 2.3.2).
   c. Tilojen ja ilmanvaihdon lämmitysenergian ja tehon tarve (luku 2.3.3).
   d. Menoveden maksimi- ja minimilämpötila, mitoitusulkolämpötila ja ulkolämpötila, jolla menoveden lämpötila vastaa minimilämpötilaa (luku 2.3.3).
   e. Lämpöpumpun mitattu lämpökerroin, lämmitysteho sekä lämpötilat vähintään yhdessä testauspisteessä (luku 2.3.4).
   f. Korkein lämpötila, johon lämpöpumppu pystyy lämmittämään käyttövettä ilman lisälämmityksen tarvetta (luku 2.3.4).
   g. Matalin ulkolämpötila, jossa lämpöpumppua voidaan käyttää (luku 2.3.4).
2. Mikäli lämpöpumppu lämmittää käyttövettä, lasketaan seuraavat vaiheet:
   a. Lasketaan käyttöveden lämmitystehon tarve kullakin aika-askeleella, mikäli sitä ei ole saatavilla lähtötietona (luku 2.5.1).

b. Lasketaan lämpöpumpun lämpökerroin käyttöveden lämmityksessä kullakin aika-askeleella (luku 2.5.4).

c. Lasketaan lämpöpumpun lämmitysteho käyttöveden lämmityksessä kullakin aika-askeleella (luku 2.5.6).

d. Lasketaan osatehon vaikutus käyttöveden lämmityksen lämpökertoimen arvoon kullakin aika-askeleella, mikäli lämpöpumppu on tehosäätöinen (luku 2.5.5).

e. Lasketaan käyttöveden lämmitysaika kunkin aika-askeleen aikana (luku 2.5.8).

f. Lasketaan käyttöveden lämmitysenergia, jonka lämpöpumppu pystyy tuottamaa kullakin aika-askeleella ja koko vuoden aikana (luku 2.5.9).

3. Mikäli lämpöpumppu lämmittää käyttöveden lisäksi myös tiloja ja/tai ilmanvaihtoa, lasketaan seuraavat vaiheet:

a. Lasketaan tilojen ja ilmanvaihdon lämmitystehon tarve kullakin aika-askeleella, mikäli sitä ei ole saatavilla lähtötietona (luku 2.5.2).

b. Lasketaan lämpöpumpun lämpökerroin tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella (luku 2.5.4).

c. Lasketaan lämpöpumpun lämmitysteho tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella (luku 2.5.10).

d. Lasketaan osatehon vaikutus tilojen ja ilmanvaihdon lämmityksen lämpökertoimen arvoon kullakin aika-askeleella, mikäli lämpöpumppu on tehosäätöinen (luku 2.5.5).

e. Lasketaan aika, joka on käytettävissä tilojen ja ilmanvaihdon lämmitykseen kullakin aika-askeleella (luku 2.5.12).

f. Lasketaan tilojen ja ilmanvaihdon lämmitysenergian tarve kullakin aika-askeleella (luku 2.5.13).

g. Lasketaan tilojen ja ilmanvaihdon lämmitysenergia, jonka lämpöpumppu pystyy tuottamaa kullakin aika-askeleella ja koko vuoden aikana (luku 2.5.13).

4. Lasketaan lämpöpumpun sähköenergia käyttöveden, tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella sekä vuotuinen sähköenergian kulutus (luku 2.5.14).

5. Lasketaan tarvittaessa niiden apulaitteiden sähkönkulutuksen osuus, joka ei sisälly lämpökertoimen mitattuun arvoon (luku 2.5.15).

6. Lasketaan lämpöpumpun SPF-luku (luku 2.5.16).

7. Lasketaan tarvittava tilojen vuotuinen lisälämmitysenergia (luku 2.5.17).

2.2.3 Maalämpöpumppu

Maalämpöpumpun laskenta tehdään samojen vaiheiden mukaisesti kuin ilma-vesilämpöpumpun (ks. luku 2.2.2) sillä erotuksella, että lähtötietona tarvitaan lisäksi lämmönkeruupiiristä tulevan nesteen lämpötila (luku 2.3.4) ja lämpökertoimen laskennassa käytetään keruupiiriltä höyrystimelle virtaavan nesteen lämpötilaa.

2.2.4 Poistoilmalämpöpumppu

Poistoilmalämpöpumpun laskenta tehdään seuraavien vaiheiden mukaisesti:

1. Määritetään seuraavat laskennan lähtötiedot:
    a. Vuoden ulkolämpötila, mikäli tilojen ja ilmanvaihdon tunneittaista lämmitystehontarvetta ei tunneta, sekä laskennan aika-askeleen pituus (luku 2.3.1).
    b. Käyttöveden lämmitystehon tai lämmitysenergian tarve sekä lämpötila (luku 2.3.2).
    c. Tilojen ja ilmanvaihdon lämmitysenergian ja tehon tarve (luku 2.3.3).
    d. Menoveden maksimi- ja minimilämpötila, mitoitusulkolämpötila ja ulkolämpötila, jolla menoveden lämpötila vastaa minimilämpötilaa (luku 2.3.3).
    e. Lämpöpumpun mitattu lämpökerroin sekä lämpötilat vähintään yhdessä testauspisteessä (luku 2.3.4).
    f. Korkein lämpötila, johon lämpöpumppu pystyy lämmittämään käyttövettä ilman lisälämmityksen tarvetta (luku 2.3.4).
    g. Poistoilman lämpötila, kosteus sekä jäteilman matalin lämpötila (luku 2.3.4).
2. Mikäli lämpöpumppu lämmittää käyttövettä, lasketaan seuraavat vaiheet:
    a. Lasketaan käyttöveden lämmitystehon tarve kullakin aika-askeleella, mikäli sitä ei ole saatavilla lähtötietona (luku 2.5.1).
    b. Lasketaan lämpöpumpun lämpökerroin käyttöveden lämmityksessä kullakin aika-askeleella (luku 2.5.4).
    c. Lasketaan poistoilmalämpöpumpun lämmitysteho käyttöveden lämmityksessä kullakin aika-askeleella (luku 2.5.7).
    d. Lasketaan osatehon vaikutus käyttöveden lämmityksen lämpökertoimen arvoon kullakin aika-askeleella, mikäli lämpöpumppu on tehosäätöinen (luku 2.5.5).
    e. Lasketaan käyttöveden lämmitysaika kunkin aika-askeleen aikana (luku 2.5.8).

   f. Lasketaan käyttöveden lämmitysenergia, jonka lämpöpumppu pystyy tuottamaa kullakin aika-askeleella ja koko vuoden aikana (luku 2.5.9).

3. Mikäli lämpöpumppu lämmittää käyttöveden lisäksi myös tiloja ja/tai ilmanvaihtoa, lasketaan seuraavat vaiheet:
   a. Lasketaan tilojen ja ilmanvaihdon lämmitystehon tarve kullakin aika-askeleella, mikäli sitä ei ole saatavilla lähtötietona (luku 2.5.2).
   b. Lasketaan lämpöpumpun lämpökerroin tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella (luku 2.5.4).
   c. Lasketaan poistoilmalämpöpumpun lämmitysteho tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella (luku 2.5.11).
   d. Lasketaan osatehon vaikutus tilojen ja ilmanvaihdon lämmityksen lämpökertoimen arvoon kullakin aika-askeleella, mikäli lämpöpumppu on tehosäätöinen (luku 2.5.5).
   e. Lasketaan aika, joka on käytettävissä tilojen ja ilmanvaihdon lämmitykseen kullakin aika-askeleella (luku 2.5.12).
   f. Lasketaan tilojen ja ilmanvaihdon lämmitysenergian tarve kullakin aika-askeleella (luku 2.5.13).
   g. Lasketaan tilojen ja ilmanvaihdon lämmitysenergia, jonka lämpöpumppu pystyy tuottamaa kullakin aika-askeleella ja koko vuoden aikana (luku 2.5.13).
4. Lasketaan lämpöpumpun sähköenergia käyttöveden, tilojen ja ilmanvaihdon lämmityksessä kullakin aika-askeleella sekä vuotuinen sähköenergian kulutus (luku 2.5.14).
5. Lasketaan tarvittaessa niiden apulaitteiden sähkönkulutuksen osuus, joka ei sisälly lämpökertoimen mitattuun arvoon (luku 2.5.15).
6. Lasketaan lämpöpumpun SPF-luku (luku 2.5.16).
7. Lasketaan tarvittava tilojen vuotuinen lisälämmitysenergia (luku 2.5.17).

2.3 Laskennan lähtötiedot

2.3.1 Säätiedot

Laskennan lähtötiedoksi tarvitaan seuraavia tietoja:

- Vuoden tunneittainen ulkoilman lämpötila $T_{ulko}(t)$, °C.
- Laskennan sekä säätietojen aika-askeleen pituus $t_{aika\text{-}askel}$, h.

Säätietoina voidaan käyttää esimerkiksi Suomen RakMk D3:n (2012) mukaisia tunneittaisia energialaskennan säätietoja, jotka ovat saatavilla esimerkiksi Ilmatieteenlaitoksen www-sivuilla [http://ilmatieteenlaitos.fi/rakennusten-energialaskennan-testivuosi]. Laskenta voidaan tehdä haluttaessa myös muulla kuin tunnin aika-askeleella, mutta tässä julkaisussa aika-askeleen pituudeksi oletetaan yksi tunti. Laskennan aika-askeleen pituuden $T_{aika\text{-}askel}$ tulee vastata säätietojen aika-askeleen pituutta, jolloin tunneittaisia säätietoja käytettäessä aika-askeleen pituus on 1 h. On syytä huomata, että aika-askeleen pituuden kasvattaminen lisää laskennan epätarkkuutta.

2.3.2 Käyttöveden lämmitystarve

Mikäli lämpöpumppua käytetään käyttöveden lämmitykseen, laskennan lähtötiedoksi tarvitaan seuraavia lähtötietoja:

- Käyttöveden tunneittainen lämmitystehon tarve $\phi_{lkv}(t)$, kW.
- Käyttöveden lämmityksen vuotuinen lämpöenergian tarve $Q_{lämmitys,lkv}$, kWh/v, mikäli tunneittaista lämmitystehon tarvetta $\phi_{lkv}(t)$ ei tunneta.
- Käyttöveden lämpötila T_{lkv}, °C.
- Kylmän käyttöveden lämpötila T_{kv}, °C.

Käyttöveden lämmitysteho $\phi_{lkv}(t)$ ja lämmitysenergian tarve $Q_{lämmitys,lkv}$ sisältävät siirron ja varastoinnin lämpöhäviöt. Käyttöveden tunneittainen lämmitystehon tarve $\phi_{lkv}(t)$ voidaan laskea esimerkiksi dynaamisella simulointiohjelmalla tai se voidaan arvioida luvussa 2.5.1 esitettävän menetelmän avulla. Vuotuinen käyttöveden lämmitysenergiantarve $Q_{lämmitys,lkv}$ voidaan laskea esimerkiksi Suomen RakMk D5:n (2012) mukaisella laskentamenetelmällä.

Mikäli käyttöveden lämmityksessä käytetään lämpöpumpun lisäksi myös aurinkokeräimiä, tulee vuotuisesta lämpöenergian tarpeesta $Q_{lämmitys,lkv}$ sekä tunneittaisesta lämmitystehon tarpeesta $\phi_{lkv}(t)$ vähentää aurinkokeräimien tuottama lämmitysenergia sekä lämmitysteho, joka pystytään hyödyntämään käyttöveden lämmityksessä. Aurinkokeräinten tuottama tunneittainen lämmitysteho voidaan laskea dynaamisella simulointiohjelmalla, esimerkiksi (IDA-ICE 4.5, TRNSYS 17) ottaen huomioon käyttöveden tunneittainen kulutus simuloitavassa rakennuksessa.

2.3.3 Tilojen ja ilmanvaihdon lämmitystarve

Rakennuksen lämmitystarpeen osalta tarvitaan seuraavia lähtötietoja, kun:

- Lämpöpumppua käytetään tilojen lämmitykseen:
  - Tilojen lämmityksen tunneittainen lämmitystehon tarve $\phi_{tilat}(t)$, kW.
  - Tilojen lämmityksen vuotuinen lämpöenergian tarve $Q_{lämmitys,tilat}$, kWh/v, mikäli tunneittaista lämmitystehon tarvetta $\phi_{tilat}(t)$ ei tunneta.

- Lämpöpumppua käytetään tilojen ja ilmanvaihdon jälkilämmitykseen:
  - Tilojen ja ilmanvaihdon lämmityksen yhteenlaskettu tunneittainen lämmitystehon tarve $\phi_{tilat,iv}(t)$, kW.
  - Tilojen ja ilmanvaihdon jälkilämmityksen yhteenlaskettu vuotuinen lämpöenergian tarve $Q_{lämmitys,tilat,iv}$, kWh/v, mikäli tunneittaista lämmitystehon tarvetta $\phi_{tilat,iv}(t)$ ei tunneta.

Tilojen ja ilmanvaihdon lämmitysenergian sekä tehon tarve sisältää lämmön luovutuksen, jakelun ja varastoinnin häviöt. Vuotuinen tilojen ja ilmanvaihdon lämmitysenergian tarve voidaan laskea esimerkiksi Suomen RakMk D5:n (2012) mukaisella laskentamenetelmällä. Tilojen ja ilmanvaihdon tunneittainen lämmitystehon tarve lasketaan ensisijaisesti dynaamisella simulointiohjelmalla tai se voidaan arvioida luvussa 2.5.2 esitettävän menetelmän avulla.

Jatkossa ilmanvaihdon lämmitystä ei yksinkertaisuuden vuoksi mainita erikseen, vaikka lämpöpumppua käytettäisiin sekä tilojen että ilmanvaihdon lämmitykseen, vaan julkaisun tekstissä ja kaavoissa mainitaan vain tilojen lämmitys. Laskentamenetelmää voidaan kuitenkin täyttää suoraan myös tapauksiin, joissa lämpöpumppu lämmittää tilojen ohella myös ilmanvaihdon tuloilmaa käyttämällä tilojen lämmitysenergian $Q_{lämmitys,tilat}$ ja tehon $\phi_{tila}(t)$ sijaan tilojen ja ilmanvaihdon yhteenlaskettua lämmitysenergiaa $Q_{lämmitys,tilat,iv}$ ja tehoa $\phi_{tila,iv}(t)$.

Mikäli aurinkokeräimiä käytetään lämpöpumpun ohella tilojen lämmitykseen, tulee vuotuisesta lämpöenergian tarpeesta $Q_{lämmitys,tilat}$ sekä tunneittaisesta lämmitystehon tarpeesta $\phi_{tila}(t)$ vähentää aurinkokeräimien tuottama lämmitysenergia sekä lämmitysteho, jotka lasketaan esim. kohdassa 2.3.2 mainituilla menetelmillä.

Mikäli lämpöpumppu on kytketty vesikiertoiseen lämmönjakoverkostoon, tarvitaan lämmönjakoverkoston osalta seuraavia lähtötietoja:

- Menoveden maksimilämpötila $T_{mv,max}$ (°C) mitoitusulkolämpötilalla $T_{mit,}$ °C.
- Rakennuksen lämmityksen mitoitusulkolämpötila $T_{mit,}$ °C.
- Menoveden minimilämpötila $T_{mv,min}$, °C.
- Ulkolämpötila $T_{ulko,mv,min}$, jolla ja jota korkeammilla ulkolämpötiloilla menoveden lämpötila saa arvon $T_{mv,min.}$

2.3.4 Lämpöpumppu

Lähtötietoina käytetään lämpöpumpun tuotetietoja, jotka on mitattu esimerkiksi standardien SFS-EN 14511-3, SFS-EN 16147 tai SFS-EN 14825 mukaisesti.

Laskennassa tarvitaan seuraavia lähtötietoja:

- On-off-tyyppisen lämpöpumpun mitattu lämpökerroin COP_N vähintään yhdessä testauspisteessä.
- Tehosäätöisen lämpöpumpun mitattu lämpökerroin COP_N maksimiteholla sekä vähintään yhdessä osatehoa vastaavassa testauspisteessä.

- Ilma-ilma-, ilma-vesi- ja maalämpöpumpun tuottama maksimilämmitysteho $P_{LP,max}$ (kW) niissä testauspisteissä, joissa COP_N on mitattu.
- Niiden testauspisteiden lämpötilat, joissa COP_N on mitattu.
- Korkein lämpötila, $T_{LP, max}$ (°C), johon lämpöpumppu pystyy lämmittämään vettä ilman lisälämmityksen käyttöä.

Testauspisteiden lämpötilatasot on määritetty esim. standardissa SFS-EN 14511-2. Em. lähtötiedot annetaan lämpöpumpputyypistä riippuen vähintään yhdessä testauspisteessä, joita ovat esimerkiksi

- ilma-ilmalämpöpumppu: T_{ulko} /$T_{sisä}$ = (+7/+20 °C)
- ilma-vesilämpöpumppu: T_{ulko}/T_{mv} = (+7/+35 °C)
- maalämpöpumppu: T_{liuos}/T_{mv} = (0/+35 °C)
- poistoilmalämpöpumppu: $T_{sisä}$/T_{mv} = (+20/35 °C),

missä

T_{ulko}	ulkoilman lämpötila, °C
$T_{sisä}$	sisäilman lämpötila, °C
T_{mv}	lauhduttimelta lämmönjakoverkostoon virtaavan menoveden lämpötila, °C
T_{liuos}	lämmönkeruupiiristä höyrystimelle virtaavan liuoksen lämpötila, °C.

Mikäli lähtötietoja ei ole saatavissa em. testauspisteissä, voidaan käyttää myös muita esim. standardissa SFS-EN 14511-2 mainittuja testauspisteitä. On syytä korostaa, että laskentatulos on sitä luotettavampi, mitä useammassa testauspisteessä mitattuja lähtötietoja laskennassa käytetään.

Lisäksi tarvitaan seuraavia lämpöpumppukohtaisia lähtötietoja:

- Ilma-ilmalämpöpumppu:
    - Lämpöpumpun sisäänpuhalluslämpötila T_{sp} (°C) (ilman lämpötila, johon lämpöpumppu lämmittää lauhduttimen läpi virtaavan ilman) tai tilojen lämmityksen asetusarvo $T_{sisä}$ (°C), mikäli sisäänpuhalluslämpötilaa ei tunneta.
    - Valmistajan suosituksen mukainen matalin ulkolämpötila $T_{ulko,min}$ (°C), jossa lämpöpumppua voidaan käyttää.
- Ilma-vesilämpöpumppu:
    - Valmistajan suosituksen mukainen matalin ulkolämpötila $T_{ulko,min}$ (°C), jossa lämpöpumppua voidaan käyttää.

- Maalämpöpumppu:
  - Lämmönkeruupiiristä höyrystimelle tulevan liuoksen lämpötila T_{liuos} (°C). Mikäli liuoksen lämpötilasta on käytettävissä tarkempaa esim. lämmönkeruupiirin mitoitusohjelmistolla laskettua tapauskohtaista tietoa, voidaan liuoksen lämpötilan aikariippuvuus ottaa laskennassa huomioon käyttäen keruupiiristä tulevan liuoksen tunneittaista lämpötilaa. Mikäli tarkempaa tietoa ei ole käytettävissä, voidaan laskennassa käyttää kuukauden tai vuoden keskimääräistä keruupiiristä tulevan liuoksen lämpötilaa.
- Poistoilmalämpöpumppu:
  - Lämpöpumpun höyrystimelle tuleva rakennuksen poistoilmavirta Q_{poisto}, m³/s.
  - Poistoilman lämpötila $T_{poisto}(t)$, °C. Lähtötietona voidaan käyttää esimerkiksi dynaamisella simulointiohjelmalla laskettua tunneittaista poistoilman lämpötilaa. Muussa tapauksessa poistoilman lämpötilana voidaan käyttää tilojen lämmityksen asetusarvon mukaista vakiolämpötilaa $T_{sisä}$, °C.
  - Poistoilman absoluuttinen kosteus x_{poisto} (kg/kg). Mikäli laskennassa käytetään tunneittaista poistoilman lämpötilaa, tulee poistoilman absoluuttinen kosteus x_{poisto} määritellä myös tunneittain. Tunneittainen absoluuttinen kosteus voidaan laskea esimerkiksi dynaamisilla simulointiohjelmilla. Mikäli absoluuttista kosteutta ei tunneta, se voidaan laskea esimerkiksi liitteessä 2 esitetyllä menetelmällä käyttäen lähtötietona poistoilman suhteellista kosteutta sekä lämpötilaa.
  - Lämpöpumppuvalmistajan ilmoittama jäteilman minimilämpötila höyrystimen jälkeen $T_{jäte,min,}$ °C.

2.4 Laskentatulokset

- Laskentamenetelmä antaa seuraavat tulokset:
- Lämpöpumpun tuottama lämmitysenergia.
- Lämpöpumpun sähköenergian kulutus.
- Lämpöpumpun SPF-luku.
- Lisälämmitysenergia, mikäli lämpöpumppu ei pysty tuottamaan kaikkea tarvittavaa lämmitysenergia.

2.5 Laskenta

2.5.1 Käyttöveden lämmitystehon tarve

Laskennassa tulee käyttää ensisijaisesti tunneittaisen käyttöveden kulutuksen avulla laskettua tunneittaista lämmitystehon tarvetta $\phi_{lkv}(t)$.

Mikäli rakennuksen käyttöveden tunneittaista lämmitystehon tarvetta $\phi_{lkv}(t)$ ei tunneta, se voidaan arvioida esimerkiksi laskennan lähtötiedoissa määritetyn vuotuisen käyttöveden lämmitysenergian tarpeen $Q_{lämmitys,lkv}$ (Suomen RakMk D5, 2012) avulla, mikäli lämmitystehon tarve oletetaan vakioksi

$$\phi_{lkv} = \frac{Q_{lämmitys,lkv}}{t_{lkv}} \tag{1}$$

missä

t_{lkv} käyttöveden käyttöaika vuodessa, h.

Mikäli käyttöveden lämpötila T_{lkv} on suurempi kuin lämpötila $T_{LP,max}$, johon lämpöpumppu pystyy lämmittämään käyttövettä ilman lisälämmitystä, vähennetään lämpötilarajoituksesta johtuva lisälämmitystarpeen osuus käyttöveden kulutuksen tai kaavan (1) avulla lasketusta lämmitystehontarpeesta kaavan (2) avulla. Tällöin käyttöveden lämmitystehontarpeena, joka pyritään kattamaan lämpöpumpun avulla, käytetään kaavalla (2) korjattua tehontarvetta $\phi_{lkv}(t)$.

$$\phi_{lkv}(t) = \phi_{lkv}(t)\left(1 - \frac{T_{lkv} - T_{LP,max}}{T_{lkv} - T_{kv}}\right) \tag{2}$$

missä

T_{lkv} käyttöveden lämpötila, °C
$T_{LP,max}$ lämpötila, johon lämpöpumppu pystyy lämmittämään vettä, °C
T_{kv} kylmän käyttöveden lämpötila, °C.

2.5.2 Tilojen lämmityksen tehontarve

Mikäli rakennuksen tilojen tunneittaista lämmitystehon tarvetta $\phi_{tilat}(t)$ ei tunneta, se voidaan laskea laskennan lähtötiedoissa määritetyn vuotuisen tilojen lämmitysenergian tarpeen $Q_{lämmitys,tilat}$ avulla käyttäen seuraavaa kaavaa:

$$\phi_{tilat}(t) = \frac{Q_{lämmitys,tilat}}{S_{Ts}}\left(T_{Ts} - T_{ulko}(t)\right), \text{ kun } T_{Ts} > T_{ulko}. \quad (3)$$

$$\phi_{tilat}(t) = 0, \text{ kun } T_{Ts} \leq T_{ulko}.$$

missä

S_{Ts}	astetuntiluku, Kh
T_{Ts}	astetuntilukua vastaava sisälämpötila, °C
$T_{ulko}(t)$	tunnittainen ulkoilman lämpötila, °C.

Tässä laskentamenetelmässä tilojen lämmitystehon tarpeena tai kaavassa (3) käytettävänä tilojen lämmitysenergian tarpeena käytetään vain niiden tilojen lämmitystehontarvetta tai lämmitysenergiaa, jotka ovat ilma-ilmalämpöpumpun vaikutuspiirissä.

Astetuntiluku S_{Ts} voidaan laskea seuraavan kaavan avulla käyttäen sisälämpötilan T_{Ts} arvona esimerkiksi 17 °C, jolloin sisäisten lämpökuormien oletetaan lämmittävän tiloja lämmityksen asetusarvoon asti:

$$S_{Ts} = \sum\left(T_{Ts} - T_{ulko}(t)\right) \cdot t_{aika-askel} \quad (4)$$

missä

$T_{ulko}(t)$	tunneittainen ulkoilman lämpötila,°C
$t_{aika-askel}$	laskennan aika-askel, h.

2.5.3 Lämmönjakoverkoston lämpötila ja sisäänpuhalluslämpötila

Menoveden tunneittainen lämpötila $T_{mv}(t)$ voidaan laskea seuraavien kaavojen avulla:

$$T_{mv}(t) = T_{mv,max}, \text{ kun } T_{ulko}(t) \leq T_{mit} \quad (5)$$

$$T_{mv}(t) = k \cdot T_{ulko}(t) + b, \text{ kun } T_{ulko} \text{ on välillä } T_{mit} < T_{ulko}(t) < T_{ulko,mv,min} \quad (6)$$

$$T_{mv}(t) = T_{mv,min}, \text{ kun } T_{ulko}(t) \geq T_{ulko,mv,min} \quad (7)$$

joissa

$T_{mv,max}$	menoveden maksimilämpötila mitoitusulkolämpötilalla, °C
k	säätökäyrän kulmakerroin, -

$T_{ulko}(t)$ tunnittainen ulkoilman lämpötila, °C
b säätökäyrän vakiotermi, °C
$T_{mv,min}$ menoveden minimilämpötila, °C.

Kulmakerroin k voidaan laskea seuraavan kaavan avulla:

$$k = \frac{T_{mv,\max} - T_{mv,\min}}{T_{mit} - T_{ulko,mv,\min}} \tag{8}$$

missä

$T_{mv,max}$ menoveden maksimilämpötila mitoitusulkolämpötilalla, °C
$T_{mv,min}$ menoveden minimilämpötila, °C
T_{mit} rakennuksen lämmityksen mitoitusulkolämpötila, °C
$T_{ulko,mv,min}$ menoveden min. lämpötilaa vastaava ulkolämpötila, °C.

Säätökäyrän vakiotermi b voidaan laskea seuraavan kaavan avulla:

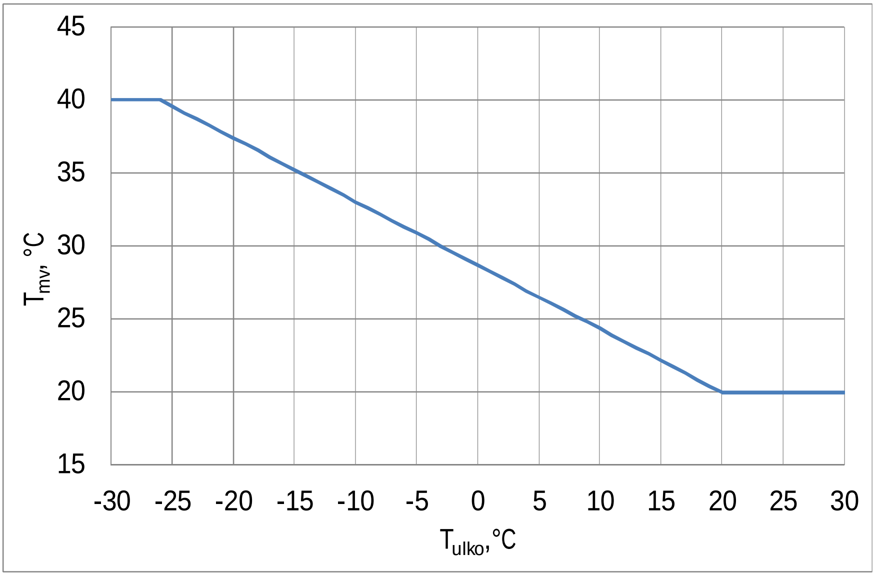
$$b = T_{mv,\max} - k \cdot T_{mit} \tag{9}$$

missä

k säätökäyrän kulmakerroin, -.

Mikäli kaavoilla (5–7) laskettu menoveden lämpötilan $T_{mv}(t)$ arvo on suurempi kuin lämpötila $T_{LP,max}$, johon lämpöpumppu pystyy lämmittämään vettä ilman lisälämmitystä, käytetään laskennassa tämän lämpötilarajan ylittävien menoveden lämpötilojen arvoina lämpötilaa $T_{LP,max}$.

Kuvassa A1 on esimerkki menoveden lämpötilasta eri ulkolämpötilan arvoilla.



Kuva A1. Esimerkki menoveden lämpötilan säätökäyrästä.

Mikäli ilma-ilmalämpöpumpun sisäänpuhalluslämpötilaa T_{sp} (°C) (ilman lämpötila, johon lämpöpumpppu lämmittää lauhduttimen läpi virtaavan ilman) ei tunneta, se voidaan arvioida tilojen lämmityksen asetusarvon $T_{sisä}$ perusteella. Sisäänpuhalluslämpötilan voidaan olettaa olevan 15 °C lämpimämpi kuin tilojen lämmityksen asetusarvon, ellei tarkempaa tietoa ole käytettävissä.

2.5.4 Lämpöpumpun lämpökerroin

Lämpöpumpun tunneittainen lämpökerroin COP(t) lasketaan seuraavan kaavan avulla:

$$COP(t) = f_T(t) \cdot COP_T(t) \qquad (10)$$

missä

$f_T(t)$	kompressorin häviökerroin, -
$COP_T(t)$	lämpöpumpun tunnittainen teoreettinen lämpökerroin, -.

Osatehon vaikutus tehosäätöisen lämpöpumpun lämpökertoimeen otetaan huomioon luvussa 2.5.5 esitettävän menetelmän mukaan.

Kaavassa (10) käytettävä, lämpöpumpun lämmitysprosessin häviöt huomioon ottava häviökerroin $f_T(t)$ lasketaan kaavan (11) avulla:

$$f_T(t) = \frac{COP_N}{COP_T} \tag{11}$$

missä

COP_N	lämpöpumpun mitattu lämpökerroin, -
COP_T	lämpöpumpun teoreettinen lämpökerroin, -.

Mikäli lämpöpumpun mitattu lämpökerroin COP_N tunnetaan vain yhdessä testauspisteessä, oletetaan, että häviökerroin on vakio koko laskentajakson (esim. vuosi) aikana. Mikäli mitattu lämpökerroin tunnetaan useammassa testauspisteessä, voidaan häviökerroin laskea kullekin testauspisteelle kaavan (11) avulla. Testauspisteiden lämpötilojen väliset häviökertoimen arvot $f_T(t)$ voidaan interpoloida lineaarisesti paloittain liitteessä 1 esitetyn menetelmän avulla. Tunnettuja testauspisteitä matalammilla tai korkeammilla lämpötiloilla häviökertoimen arvona voidaan käyttää lähimmän tunnetun häviökertoimen arvoa.

Kaavassa (10) käytettävä tunneittainen teoreettinen lämpökerroin $COP_T(t)$ lasketaan kaavan (12) avulla käyttäen jokaisella aika-askeleella määritettäviä lämmönlähteen $T_{LL}(t)$ ja rakennuksen lämmitysjärjestelmän lämpötiloja $T_{LJ}(t)$. Kaavassa (11) käytettävä lämpöpumpun teoreettinen lämpökerroin COP_T lasketaan testauspistettä vastaavilla lämmönlähteen ja rakennuksen lämmitysjärjestelmän vakiolämpötiloilla kaavan (12) avulla:

$$COP_T = \frac{T_{LJ}}{T_{LJ} - T_{LL}} \tag{12}$$

missä

T_{LJ}	rakennuksen lämmitysjärjestelmän lämpötila, K
T_{LL}	lämmönlähteen lämpötila, K.

Käyttöveden lämmityksen lämpökertoimen laskennassa käytetään lämmitysjärjestelmän lämpötilan arvona $T_{LJ}(t)$ käyttöveden lämpötilaa T_{lkv}. Vastaavasti tilojen lämmityksen lämpökertoimen laskennassa käytetään menoveden lämpötilaa $T_{mv}(t)$ vesikiertoisen lämmönjakojärjestelmän tapauksessa ja sisäänpuhalluslämpötilaa T_{sp} ilma-ilmalämpöpumpun tapauksessa (ks. luku 2.5.3). Mikäli käyttöveden tai menoveden lämpötilan arvo on suurempi kuin korkein lämpötila $T_{LP,max}$, johon lämpöpumppu pystyy lämmittämään vettä ilman lisälämmitystä, käytetään kaavassa (12) lämpötilaa $T_{LP,max}$.

Kaavassa (12) lämmönlähteen lämpötilana $T_{LL}(t)$ käytetään lämpöpumpputyypistä riippuen seuraavia lämpötiloja:

- Ilma-ilma- ja ilma-vesilämpöpumppu: ulkoilman lämpötila $T_{ulko}(t)$.

- Maalämpöpumppu: höyrystimelle virtaavan lämmönkeruunesteen lämpötila $T_{liuos}(t)$.
- Poistoilmalämpöpumppu: jäteilman minimilämpötila $T_{jäte,min}$.

2.5.5 Lämpöpumpun lämpökerroin osateholla

Osatehokuormituksen vaikutus tehosäätöisen lämpöpumpun lämpökertoimeen voidaan ottaa huomioon, mikäli mitattu lämpökertoimen arvo on tiedossa sekä maksimiteholla että vähintään yhdessä osatehoa vastaavassa testauspisteessä.

Tehosäätöisen lämpöpumpun kuormituksen tunneittaiset tehosuhteet $\beta_{LP,lkv}(t)$ ja $\beta_{LP,tilat}(t)$ lasketaan käyttöveden ja ilojen lämmitykselle seuraavien kaavojen avulla:

$$\beta_{LP,lkv}(t) = \frac{\phi_{lkv}(t)}{\phi_{LP,lkv}(t)} \tag{13}$$

missä

$\phi_{lkv}(t)$	käyttöveden tunneittainen lämmitystehon tarve, kW (ks. luku 2.5.1)
$\phi_{LP,lkv}(t)$	lämpöpumpun käyttöveden tunneittainen maksimilämmitysteho, kW (ks. kaava 15)

$$\beta_{LP,tilat}(t) = \frac{\phi_{tilat}(t)}{\phi_{LP,tilat}(t)} \tag{14}$$

missä

$\phi_{tilat}(t)$	tilojen tunneittainen lämmitystehon tarve, kW (ks. luku 2.5.2)
$\phi_{LP,tilat}(t)$	lämpöpumpun tilojen tunneittainen maksimilämmitysteho, kW (ks. kaava 22).

Tunneittaiset lämpökertoimen arvot käyttöveden ja tilojen lämmityksessä ($COP_{lkv}(t)$ ja $COP_{tilat}(t)$) voidaan interpoloida tunnettujen tehosuhteiden välillä esimerkiksi liitteessä 1 esitetyn menetelmän avulla. Jos mitatut lämpökertoimen arvot tunnetaan esimerkiksi tehosuhteen arvoilla 1,0 ja 0,5, lasketaan lämpökertoimille ensin lämpötilakorjaus kaavan (10) avulla, minkä jälkeen tehdään osatehokorjaus interpoloimalla tulokseksi saadut lämpökertoimen arvot tehosuhteen arvojen 0,5 ja 1,0 välillä. Mikäli tehosuhde on hetkellisesti pienempi kuin 0,5, voidaan laskennassa käyttää tällöin tehosuhdetta 0,5 vastaavaa lämpökertoimen arvoa.

2.5.6 Ilma-vesi- ja maalämpöpumpun lämmitysteho käyttöveden lämmityksessä

Mikäli on-off-säätöisen tai tehosäätöisen ilma-vesi- tai maalämpöpumpun maksimilämmitysteho $\phi_{LP,max}$ tunnetaan vain yhdessä testauspisteessä, lasketaan näiden lämpöpumpputyyppien tunneittainen käyttöveden lämmityksen maksimilämmitysteho $\phi_{LP,lkv}(t)$ seuraavan kaavan avulla:

$$\phi_{LP,lkv}(t) = \phi_{LP,max} \frac{COP_{lkv}(t)}{COP_N} \tag{15}$$

missä

$\phi_{LP,max}$	lämpöpumpun maksimilämmitysteho testauspisteessä, kW
$COP_{lkv}(t)$	lämpöpumpun tunneittainen lämpökerroin käyttöveden lämmityksessä, -
COP_N	lämpöpumpun mitattu lämpökerroin testauspisteessä, -.

Lämpökerroin $COP_{lkv}(t)$ lasketaan kaavalla (10) käyttäen lähtötietona määritettyä käyttöveden lämpötilaa T_{lkv}. Mikäli käyttöveden lämpötila on suurempi kuin lämpötila $T_{LP,max}$, johon lämpöpumppu pystyy lämmittämään käyttövettä ilman lisälämmitystä, lasketaan lämpökerroin $COP_{lkv}(t)$ käyttäen lämpötilaa $T_{LP,max}$.

Tehosäätöisen lämpöpumpun tunneittainen lämmitysteho $\phi_{LP,lkv}(t)$ on yhtä suuri kuin käyttöveden tunneittainen lämmitystehon tarve $\phi_{lkv}(t)$ (ks. luku 2.5.1), jos $\phi_{lkv}(t)$ on pienempi kuin $\phi_{LP,lkv}(t)$. Jos käyttöveden lämmitystehontarve $\phi_{lkv}(t)$ on suurempi kuin kaavalla (15) laskettu lämmitysteho $\phi_{LP,lkv}(t)$, käytetään tehosäätöisen lämpöpumpun tunneittaisena käyttöveden lämmitystehona $\phi_{LP,lkv}(t)$ kaavalla (15) laskettua arvoa.

Mikäli on-off-säätöisen tai tehosäätöisen ilma-vesi- tai maalämpöpumpun mitattu maksimilämmitysteho $\phi_{LP,max}$ tunnetaan useassa testauspisteessä, voidaan testauspisteiden väliset maksimitehon arvot interpoloida lineaarisesti paloittain liitteessä 1 esitetyn menetelmän avulla. Interpoloituja arvoja voidaan käyttää testauspisteiden välillä kaavalla (15) lasketun tehon sijaan. Lämpöpumpun maksimilämmitysteho tunnettujen testauspisteiden lämpötiloja matalammilla tai korkeammilla arvoilla voidaan laskea kaavan (15) avulla käyttäen lämmitystehon $\phi_{LP,max}$ arvona lähimmässä tunnetussa testauspisteessä mitattua lämmitystehoa.

2.5.7 Poistoilmapumpun lämmitysteho käyttöveden lämmityksessä

On-off-säätöisen poistoilmalämpöpumpun tunneittainen lämmitysteho $\phi_{LP,lkv}(t)$, joka käytetään käyttöveden lämmitykseen, lasketaan seuraavan kaavan avulla:

$$\phi_{LP,lkv}(t) = \phi_{LPh}(t)\frac{COP_{lkv}(t)}{COP_{lkv}(t)-1} \qquad (16)$$

missä

$\phi_{LPh}(t)$	lämpöpumpun höyrystinteho, kW
$COP_{lkv}(t)$	lämpöpumpun tunneittainen lämpökerroin käyttöveden lämmityksessä, -.

Tehosäätöisen poistoilmalämpöpumpun tunneittainen lämmitysteho $\phi_{LP,lkv}(t)$ on yhtä suuri kuin käyttöveden tunneittainen lämmitystehon tarve $\phi_{lkv}(t)$ (ks. luku 2.5.1), jos $\phi_{lkv}(t)$ on pienempi kuin $\phi_{LP,lkv}(t)$. Jos käyttöveden lämmitystehontarve $\phi_{lkv}(t)$ on suurempi kuin kaavalla (16) laskettu lämmitysteho $\phi_{LP,lkv}(t)$, käytetään tehosäätöisen lämpöpumpun tunneittaisena käyttöveden lämmitystehona $\phi_{LP,lkv}(t)$ kaavalla (16) laskettua arvoa.

Kaavassa (16) käytettävä poistoilmalämpöpumpun höyrystinteho lasketaan seuraavalla kaavalla:

$$\phi_{LPh}(t) = Q_{poisto}(t)\cdot\rho\left(h_1(t) - h_2(t)\right) \qquad (17)$$

missä

$Q_{poisto}(t)$	poistoilmavirta, m³/s
ρ	poistoilman tiheys, kg/m³
$h_1(t)$	poistoilman entalpia (ennen höyrystintä), kJ/kg
$h_2(t)$	jäteilman entalpia (höyrystimen jälkeen), kJ/kg.

Poistoilman ja jäteilman entalpia voidaan laskea seuraavan kaavan avulla:

$$h(t) = c_{pi}\cdot T(t) + x(t)\cdot\left(L_{ho} + c_{ph}\cdot T(t)\right) \qquad (18)$$

missä

c_{pi}	ilman ominaislämpökapasiteetti, kJ/kg,K
$T(t)$	poistoilman tai jäteilman lämpötila, °C
$x(t)$	poistoilman tai jäteilman absoluuttinen kosteus, kg/kg
L_{ho}	veden höyrystymislämpö 0 °C lämpötilassa, kJ/kg
c_{ph}	vesihöyryn ominaislämpökapasiteetti kJ/kg,K.

Kaavassa (18) ilman ominaislämpökapasiteetin c_{pi} arvona voidaan käyttää 1,006 kJ/kg,K, vesihöyryn ominaislämpökapasiteetin c_{ph} arvona 1,85 kJ/kg,K ja veden höyrystymislämmön L_{hg} arvona 2502 kJ/kg.

Laskettaessa poistoilman entalpia kaavan (18) avulla, ilman lämpötilan T(t) ja absoluuttisen kosteuden x(t) arvoina käytetään poistoilman arvoja. Mikäli poistoilman absoluuttista kosteutta ei tunneta, se voidaan laskea poistoilman suhteellisen kosteuden $RH_{poisto}(t)$ ja lämpötilan $T_{poisto}(t)$ avulla käyttäen liitteessä 2 esitettyä menetelmää.

Laskettaessa jäteilman entalpia kaavan (18) avulla ilman lämpötilan T(t) arvona voidaan käyttää lämpöpumppuvalmistajan ilmoittaman jäteilman lämpötilan minimiarvoa $T_{jäte}$. Jäteilman absoluuttinen kosteus voidaan laskea liitteessä 2 esitetyllä menetelmällä käyttäen jäteilman suhteellisen kosteuden $RH_{jäte}$ arvona 100 %:a ja jäteilman lämpötilaa $T_{jäte}$.

2.5.8 Käyttöveden lämmitysaika

Aika t_{lkv}, jonka lämpöpumppu lämmittää käyttövettä yhden laskennan aika-askeleen aikana, lasketaan seuraavan kaavan avulla:

$$t_{lkv}(t) = t_{aika-askel} \frac{\phi_{lkv}(t)}{\phi_{LP,lkv}(t)}, \text{ kun } \square_{lkv} < \square_{LP,lkv} \qquad (19)$$

$$t_{lkv}(t) = t_{aika-askel}, \text{ kun } \square_{lkv} \geq \square_{LP,lkv}$$

missä

$_{aika-askel}$	laskennan aika-askeleen pituus, h
$\phi_{lkv}(t)$	käyttöveden lämmitystehon tarve, kW (ks. luku 2.5.1)
$\phi_{LP,lkv}(t)$	lämpöpumpun lämmitysteho, joka käytetään käyttöveden lämmitykseen, kW (ks. luvut 2.5.6 ja 2.5.7).

2.5.9 Käyttöveden lämmitysenergia

Lämpöpumpun tuottama lämmitysenergia käyttöveden lämmitykseen yhden laskennan aika-askeleen aikana lasketaan seuraavan kaavan avulla:

$$q_{LP,lkv}(t) = \phi_{LP,lkv}(t) \cdot t_{lkv} \qquad (20)$$

missä

$\phi_{LP,lkv}(t)$	lämpöpumpun lämmitysteho käyttöveden lämmityksessä, Kw (ks. luvut 2.5.6 ja 2.5.7)
t_{lkv}	aika, jonka lämpöpumppu lämmittää käyttövettä aika-askeleen aikana, h (ks. luku 2.5.8).

Ilma-vesilämpöpumpun osalta lämpöpumpulla tuotettu tunneittainen lämmitysenergia $q_{LP,lkv}(t)$ lasketaan vain niiden aika-askeleiden osalta, joiden aikana ulkolämpötila $T_{ulko}(t)$ on suurempi kuin lähtötiedoissa määritetty lämpöpumpun matalin käyttölämpötila $T_{ulko,min}$.

Lämpöpumpun tuottama vuotuinen lämmitysenergia käyttöveden lämmitykseen $Q_{LP,lkv}$ on tunneittaisen käyttöveden lämmitysenergian $q_{LP,lkv}(t)$ summa seuraavan kaavan mukaisesti:

$$Q_{LP,lkv} = \sum q_{LP,lkv}(t). \quad (21)$$

2.5.10 Ilma-ilma-, ilma-vesi- ja maalämpöpumpun lämmitysteho tilojen lämmityksessä

Mikäli on-off-säätöisen tai tehosäätöisen ilma-ilma-, ilma-vesi- tai maalämpöpumpun maksimilämmitysteho $\phi_{LP,max}$ tunnetaan vain yhdessä testauspisteessä, lasketaan näiden lämpöpumpputyyppien tunneittainen tilojen lämmityksen maksimilämmitysteho $\phi_{LP,tilat}(t)$ seuraavan kaavan avulla:

$$\phi_{LP,tilat}(t) = \phi_{LP,max} \frac{COP_{tilat}(t)}{COP_N} \quad (22)$$

missä

$\phi_{LP,max}$	lämpöpumpun maksimilämmitysteho testauspisteessä, kW
$COP_{tilat}(t)$	lämpöpumpun tunneittainen lämpökerroin tilojen lämmityksessä, -
COP_N	lämpöpumpun mitattu lämpökerroin testauspisteessä, -.

Lämpökerroin $COP_{tilat}(t)$ lasketaan kaavalla (10) käyttäen lähtötietona tunneittaista lämmönlähteen lämpötilaa sekä lämmönjakoverkoston menoveden lämpötilaa $T_{vm}(t)$ tai ilma-ilmalämpöpumpun tapauksessa sisäänpuhalluslämpötilaa T_{sp}. Mikäli menoveden lämpötila on suurempi kuin lämpötila $T_{LP,max}$, johon lämpöpumppu pystyy lämmittämään vettä ilman lisälämmitystä, lasketaan lämpökerroin $COP_{tilat}(t)$ käyttäen lämpötilaa $T_{LP,max}$.

Tehosäätöisen lämpöpumpun tunneittainen lämmitysteho $\phi_{LP,tilat}(t)$ on yhtä suuri kuin tilojen lämmitystehon tarve $\phi_{tilat}(t)$ (ks. luku 2.5.2), jos $\phi_{tilat}(t)$ on pienempi kuin $\phi_{LP,tilat}(t)$. Jos tilojen lämmitystehontarve $\phi_{tilat}(t)$ on suurempi kuin kaavalla (22) laskettu lämmitysteho $\phi_{LP,tilat}(t)$, käytetään tehosäätöisen lämpöpumpun tunneittaisena tilojen lämmitystehon arvona kaavalla (22) laskettua lämmitystehoa.

Mikäli on-off-säätöisen tai tehosäätöisen ilma-ilma-, ilma-vesi- tai maalämpöpumpun mitattu maksimilämmitysteho $\phi_{LP,max}$ tunnetaan useassa testauspisteessä, voidaan testauspisteiden väliset maksimitehon arvot interpoloida lineaarisesti paloittain liitteessä 1 esitetyn menetelmän avulla. Interpoloituja arvoja voidaan käyttää testauspisteiden välillä kaavalla (22) lasketun tehon sijaan. Lämpöpumpun maksimilämmitysteho tunnettujen testauspisteiden lämpötiloja matalammilla tai korkeammilla arvoilla voidaan laskea kaavan (22) avulla käyttäen lämmitystehon $\phi_{LP,max}$ arvona lähimmässä tunnetussa testauspisteessä mitattua lämmitystehoa.

2.5.11 Poistoilmalämpöpumpun lämmitysteho tilojen lämmityksessä

On-off-säätoisen poistoilmalämpöpumpun tunneittainen lämmitysteho $\phi_{LP,tilat}(t)$, joka käytetään tilojen lämmitykseen, lasketaan seuraavan kaavan avulla:

$$\phi_{LP,tilat}(t) = \phi_{LPh}(t)\frac{COP_{tilat}(t)}{COP_{tilat}(t)-1} \qquad (23)$$

missä

$\phi_{LPh}(t)$	lämpöpumpun höyrystinteho, kW
$COP_{tilat}(t)$	lämpöpumpun tunneittainen lämpökerroin tilojen lämmityksessä, -.

Kaavassa (23) käytettävä poistoilmalämpöpumpun höyrystinteho on yhtä suuri kuin luvussa (2.5.7) laskettu poistoilmalämpöpumpun höyrystinteho.

Tehosäätöisen poistoilmalämpöpumpun tunneittainen lämmitysteho $\phi_{LP,tilat}(t)$ on yhtä suuri kuin tilojen lämmitystehon tarve $\phi_{tilat}(t)$ (ks. luku 2.5.2), jos $\phi_{tilat}(t)$ on pienempi kuin $\phi_{LP,tilat}(t)$. Jos tilojen lämmitystehontarve $\phi_{tilat}(t)$ on suurempi kuin kaavalla (23) laskettu lämmitysteho $\phi_{LP,tilat}(t)$ käytetään tehosäätöisen lämpöpumpun tunneittaisena tilojen lämmitystehon arvona kaavalla (23) laskettua lämmitystehoa.

2.5.12 Tilojen lämmitysaika

Aika, joka on käytettävissä tilojen lämmitykseen yhden aika-askeleen aikana $t_{tilat,max}(t)$, lasketaan seuraavan kaavan avulla:

$$t_{tilat,max}(t) = t_{aika-askel} - t_{lkv}(t) \qquad (24)$$

missä

$t_{aika-askel}$	laskennan aika-askeleen pituus, h
$t_{lkv}(t)$	aika, jonka lämpöpumpppu lämmittää käyttövettä aika-askeleen aikana, h (ks. luku 2.5.8).

Kaavaa (24) voidaan käyttää käyttövettä ja tiloja lämmittävän lämpöpumpun tapauksessa. Pelkästään tiloja lämmittävän lämpöpumpun tapauksessa tilojen lämmitykseen voidaan käyttää koko aika-askeleen pituus.

2.5.13 Tilojen lämmitysenergia

Tilojen lämmitykseen tarvittava lämmitysenergia $q_{tilat}(t)$ aika-askeleen aikana lasketaan seuraavan kaavan avulla:

$$q_{tilat}(t) = \phi_{tilat}(t) \cdot t_{aika-askel} \quad (25)$$

missä

$\phi tilat(t)$	tilojen lämmityksen tunneittainen tehontarve, kW (ks. luku 2.5.2)
taika-askel	laskennan aika-askeleen pituus, h.

Maksimienergiamäärä qLP,tilat,max(t), jonka lämpöpumppu pystyy enimmillään tuottamaan aika-askeleen aikana tilojen lämmitykseen, lasketaan seuraavan kaavan avulla:

$$q_{LP,tilat,max}(t) = \phi_{LP,tilat}(t) \cdot t_{tilat,max}(t) \quad (26)$$

missä

$\phi_{LP,tilat}(t)$	lämpöpumpun lämmitysteho tilojen lämmityksessä, kW (ks. luvut 2.5.10 ja 2.5.11)
$t_{tilat,max}(t)$	aika, jonka lämpöpumppu voi enimmillään lämmittää tiloja aika-askeleen aikana, h (ks. luku 2.5.12).

Pelkästään tiloja lämmittävän lämpöpumpun tapauksessa $t_{tilat,max}(t)$ on yhtä suuri kuin aika-askeleen pituus.

Lämpöpumpun tuottama tilojen lämmitysenergia $q_{LP,tilat}(t)$ yhden laskennan aika-askeleen aikana on yhtä suuri kuin kaavalla (26) laskettu maksimilämmitysenergia $q_{LP,tilat,max}(t)$, jos tilojen lämmitysenergian tarve $q_{tilat}(t)$ (kaava 25) on suurempi kuin $q_{LP,tilat,max}(t)$ kaavan (27) mukaisesti. Muussa tapauksessa lämpöpumpun tilojen lämmitykseen tuottama energia on yhtä suuri kuin tilojen lämmitysenergian tarve kaavan (28) mukaisesti:

$$q_{LP,tilat}(t) = q_{LP,tilat,max}(t) \text{, kun } q_{tilat} > q_{LP,tilat,max} \quad (27)$$

$$q_{LP,tilat}(t) = q_{tilat}(t) \text{, kun } q_{tilat} \leq q_{LP,tilat,max} \quad (28)$$

joissa

$q_{LP,tilat,max}(t)$	maksimilämmitysenergia, jonka lämpöpumppu voi tuottaa aika-askeleen aikana, kWh
$q_{tilat}(t)$	tilojen lämmitysenergian tarve aika-askeleen aikana, kWh.

Ulkoilmalämpöpumppujen osalta lämpöpumpulla tuotettu lämmitysenergia $q_{LP,tilat}(t)$ lasketaan vain niiden aika-askeleiden osalta, joiden aikana ulkolämpötila $T_{ulko}(t)$ on suurempi kuin lähtötiedoissa määritetty lämpöpumpun matalin käyttölämpötila $T_{ulko,min}$.

Lämpöpumpun tuottama lämmitysenergia tilojen lämmitykseen koko vuoden aikana $Q_{LP,tilat}$ lasketaan laskemalla yhteen jokaisen aika-askeleen aikana tuotettu tilojen lämmitysenergia $q_{LP,tilat}(t)$:

$$Q_{LP,tilat} = \sum q_{LP,tilat}(t) \tag{29}$$

2.5.14 Lämpöpumpun sähköenergia

Seuraavan kaavan avulla lasketaan lämpöpumpun tunneittainen sähköenergia $w_{LP}(t)$, joka sisältää kompressorin sekä niiden lämpöpumpun apulaitteiden kuluttaman sähköenergian, jotka sisältyvät testaustilanteessa lämpöpumpun sähkönkulutukseen:

$$w_{LP}(t) = \frac{q_{LP,lkv}(t)}{COP_{lkv}(t)} + \frac{q_{LP,tilat}(t)}{COP_{tilat}(t)} \tag{30}$$

missä

$q_{LP,lkv}(t)$	lämpöpumpun tuottama tunneittainen käyttöveden lämmitysenergia, kWh
$COP_{lkv}(t)$	lämpöpumpun tunneittainen lämpökerroin käyttöveden lämmityksessä, -
$q_{LP,tilat}(t)$	lämpöpumpun tuottama tunneittainen tilojen lämmitysenergia, kWh
$COP_{tilat}(t)$	lämpöpumpun tunneittainen lämpökerroin tilojen lämmityksessä, -.

Lämpöpumpun sähköenergia W_{LP} vuoden aikana on lämpöpumpun tunneittaisen sähköenergian $w_{LP}(t)$ summa seuraavan kaavan mukaisesti:

$$W_{LP} = \sum w_{LP}(t)\,. \tag{31}$$

2.5.15 Lämpöpumpun apulaitteiden sähköenergia

Standardien SFS-EN 14511-3 ja SFS-EN 14825 mukaisesti mitattuun lämpöpumpun sähkönenergiankulutukseen ja lämpökertoimen COP_N arvoon sisältyvät kompressorin kuluttama sähköenergia, höyrystimen sulatukseen kuluva sähköenergia sekä osa lämpöpumppujen apulaitteiden kuluttamasta sähköenergiasta. Mitattuun apulaitteiden sähköenergiankulutukseen sisältyvät lämpöpumpun kaikkien säätö- ja suojalaitteiden kulutus sekä puhaltimien ja pumppujen kulutus lämpöpumppuyksikön sisällä tapahtuvan ilman tai nesteen siirron osalta. Tällöin lämpöpumpun puhaltimien tai pumppujen sähkönkulutus, joka käytetään ilman tai nesteen siirtoon lämpöpumppuyksikön ulkopuolisessa kanavistossa tai putkistossa, ei sisälly testausolosuhteissa mitattuun sähkönkulutukseen.

Lämpöpumpun puhaltimien ja pumppujen sähköenergiankulutus, joka ei ole mukana em. standardien mukaisesti mitatuissa lämpökertoimien arvoissa, otetaan erikseen huomioon apulaitteiden sähkönkulutuksen W_{apu} avulla lämpöpumpputyypistä riippuen. Poistoilmalämpöpumpun puhaltimien sähköenergiankulutus lämpöpumppuyksikön ulkopuolisen kanaviston osalta lasketaan mukaan apulaitteiden sähköenergian kulutukseen. Vastaavasti lasketaan mukaan maalämpöpumpun lämmönkeruupiirin pumppauksen sähköenergiankulutus lämpöpumppuyksikön ulkopuolisen putkiston osalta. Sen sijaan lämpöpumppuyksikön ulkopuolisen rakennuksen lämmönjakopiirin pumppaukseen käytettävää sähköenergiaa ei lasketa mukaan lämpöpumpun apulaitteiden sähköenergiaan, vaan se otetaan huomioon, kun lasketaan rakennuksen lämmönjakojärjestelmän apulaitteiden sähköenergiankulutusta esimerkiksi laskentamenetelmän Suomen RakMk D5 (2012) mukaisesti.

Lämpöpumpun apulaitteiden kuluttama sähköenergia W_{apu}, joka ei sisälly lämpöpumpun sähkönkulutuksen ja lämpökertoimen COP_N mitattuihin arvoihin, voidaan laskea kaavan (32) avulla:

$$W_{apu} = P_{apu} \Delta t \tag{32}$$

missä

P_{apu}	lämpöpumpun apulaitteiden sähköteho, joka ei sisälly mitattuun lämpökertoimen arvoon, kW
Δt	apulaitteiden käyttöaika laskentajaksolla, h.

Lämpöpumpun apulaitteiden sähköteho P_{apu} voidaan laskea seuraavan kaavan avulla:

$$P_{apu} = \frac{Q \cdot \Delta P_e}{\eta} \quad (33)$$

missä

Q	ilman tai nesteen nimellisvirtaama Q, m³/s
ΔP_e	lämpöpumppuyksikön ulkopuolisen kanaviston tai putkiston staattinen painehäviö, Pa
η	puhaltimien tai pumppujen hyötysuhde,-.

2.5.16 Lämpöpumpun SPF-luku

Lämpöpumpun SPF-luku määritellään seuraavan kaavan avulla:

$$SPF = \frac{Q_{LP,lkv} + Q_{LP,tilat}}{W_{LP} + W_{apu}} \quad (34)$$

missä

$Q_{LP,lkv}$	lämpöpumpun tuottama vuotuinen käyttöveden lämmitysenergia, kWh (ks. luku 2.5.9)
$Q_{LP,tilat}$	lämpöpumpun tuottama vuotuinen tilojen lämmitysenergia, kWh (ks.luku 2.5.13)
W_{LP}	lämpöpumpun kuluttama sähköenergia, kWh (ks. luku 2.5.14)
W_{apu}	lämpöpumpun apulaitteiden kuluttama sähköenergia, kWh (ks. luku 2.5.15).

2.5.17 Lisälämmitysenergia

Mikäli lämpöpumppu ei pysty tuottamaan kaikkea tarvittavaa käyttöveden ja tilojen lämmitysenergiaa, tarvitaan lisälämmitystä. Lisälämmitys voidaan toteuttaa esimerkiksi lämminvesivaraajassa olevalla sähkövastuksella tai muulla lämmitysjärjestelmällä. Vuotuinen lisälämmitysenergian tarve lasketaan seuraavan kaavan avulla:

$$Q_{lisälämmitys} = Q_{lämmitys,lkv} + Q_{lämmitys,tilat} - Q_{LP,lkv} - Q_{LP,tilat} \quad (35)$$

missä

$Q_{lämmitys,\ lkv}$	käyttöveden lämmityksen lämpöenergian tarve, kWh (ks. luku 2.3.2)
$Q_{lämmitys,\ tilat}$	tilojen lämmityksen lämpöenergian tarve, kWh (ks. luku 2.3.3)
$Q_{LP,\ lkv}$	lämpöpumpun tuottama käyttöveden lämmitysenergia, kWh (ks. luku 2.5.9)
$Q_{LP,\ tilat}$	lämpöpumpun tuottama tilojen lämmitysenergia, kWh (ks. luku 2.5.13).

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LIITE 1

Suureesta X riippuvan suureen A(X) arvo voidaan interpoloida lineaarisesti kahden tunnetun pisteen X_i ja X_{i+1} välillä, kun suureen arvot tunnetaan näissä pisteissä $A(X_i)$ ja $A(X_{i+1})$. Suureen arvot A(X) näiden kahden pisteen välillä voidaan laskea seuraavan kaavan (L1) avulla:

$$A(X) = A(X_i) + \frac{A(X_{i+1}) - A(X_i)}{X_{i+1} - X_i}(X - X_i), \qquad \text{(L1)}$$

missä

$A(X_i)$	suureen A arvo pisteessä i
$A(X_{i+1})$	suureen A arvo pisteessä i+1
X_i	suureen X pisteessä i
X_{i+1}	suureen X pisteessä i+1.

LIITE 2

Mikäli ilman absoluuttista kosteutta ei tunneta, se voidaan laskea ilman suhteellisen kosteuden ja lämpötilan avulla käyttäen seuraavia kaavoja:

Ilman vesihöyryn osapaine ph (t) voidaan laskea seuraavan kaavan avulla, missä

$$p_h(t) = \frac{RH(t) \cdot p_{hs}(t)}{100} \qquad \text{(L2)}$$

missä

RH(t)	ilman suhteellinen kosteus, %
$p_{hs}(t)$	vesihöyryn kyllästymispaine, kPa.

Kaavassa (L2) tarvittava vesihöyryn kyllästymispaine $P_{hs}(t)$ voidaan laskea likimääräisesti esimerkiksi seuraavan kaavan avulla

$$p_{hs}(t) = \frac{\exp\left(77.345 + 0.0057 \cdot T(t) - \frac{7235}{T(t)}\right)}{1000 \cdot T(t)^{8.2}} \qquad \text{(L3)}$$

missä

T	ilman lämpötila, K.

Ilman absoluuttinen kosteus x (t) voidaan laskea seuraavan kaavan avulla

$$x(t) = 0.622 \frac{p_h(t)}{p - p_h(t)} \quad \text{(L4)}$$

missä

$p_h(t)$	vesihöyryn osapaine, kPa
p	ilman kokonaispaine, kPa.

Kaavassa (L4) ilman kokonaispaineen p arvona voidaan käyttää ilman normaali-paineen arvoa 101.3 kPa.

Appendix B: Data used for NEEAP and NREAP calculation in 2013

The data below was generated in the project as preliminary results aimed for the NEEAP and NREAP calculation for the ministry of employment and the economy.

Table B1. Renewable energy use and energy savings by building type in 2010.

Renewable energy and energy savings in 2010, GWh					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total**
Ground source	921	2	0	17	941
Exhaust air	88	10	0	5	103
Air/air	1152	184	69	115	1521
Air/water	73	0	0	0	73
Sum of renewable energy	2146	186	70	133	2535
Sum of energy savings	2234	197	70	138	2638

Table B2. Renewable energy use and energy savings by building type in 2016.

Renewable energy and energy savings in 2016, GWh					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total**
Ground source	2477	5	1	47	2530
Exhaust air	162	19	0	10	190
Air/air	2258	361	135	226	2980
Air/water	365	0	0	0	365
Sum of renewable energy	5099	367	136	273	5875
Sum of energy savings	5261	386	136	282	6065

Table B3. Renewable energy use and energy savings by building type in 2020.

Renewable energy and energy savings in 2020, GWh					
	Detached houses	**Attached houses**	**Blocks of flats**	**Free time residences**	**Total**
Ground source	3871	8	2	73	3954
Exhaust air	216	25	0	13	254
Air/air	2358	377	141	236	3112
Air/water	629	0	0	0	629
Sum of renewable energy	6858	386	143	309	7695
Sum of energy savings	7074	411	143	322	7949

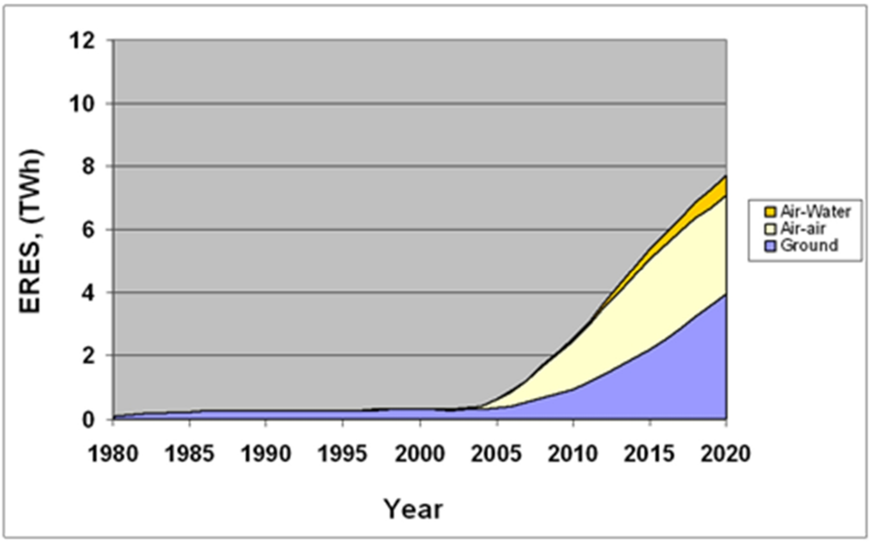

Figure B1. Prognosis of the use of the renewable energy by heat pumps by 2020.

	Series title and number **VTT Technology 164**

Title	**Renewable energy production of Finnish heat pumps** **Report of the SPF-project**
Author(s)	Ari Laitinen, Pekka Tuominen, Riikka Holopainen, Pekka Tuomaala, Juha Jokisalo, Lari Eskola & Kai Sirén
Abstract	The SPF project defined a national hourly seasonal performance factor calculation method for air to air heat pumps, air to water heat pumps, ground source heat pumps and exhaust air heat pumps in co-operation with international Annex 39 work. The energy use of the Finnish building stock was estimated using standard building types further adapted to different decades: a detached house, an apartment building, an office building and a summer cottage. The energy use of these standard building types was calculated with different heat pump types leading to energy saving and renewable energy use of the heat pumps in different buildings. The current and future cumulative energy consumption of the building stock was modelled using the REMA model developed at VTT. The future effects of heat pumps on the energy use and emissions of the Finnish building stock were modelled comparing with the REMA model a conservative Business as Usual scenario with a Heat Pump scenario.
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Nimeke	**Suomalaisten lämpöpumppujen uusiutuvan energian tuotto** **SPF-hankkeen loppuraportti**
Tekijä(t)	Ari Laitinen, Pekka Tuominen, Riikka Holopainen, Pekka Tuomaala, Juha Jokisalo, Lari Eskola & Kai Sirén
Tiivistelmä	SPF-hankkeessa määriteltiin kansallinen tunnittainen kausihyötysuhteen laskentamenetelmä ilmalämpöpumpuille, ilma-vesilämpöpumpuille, maalämpöpumpuille sekä poistoilmalämpöpumpuille yhteistyössä kansainvälisen Annex 39-ohjelman kanssa. Suomen rakennuskannan energiankulutusta arvioitiin eri vuosikymmenille määriteltyjen tyyppirakennusten avulla jotka edustivat pientaloa, kerrostaloa, toimistotaloa sekä vapaa-ajan rakennusta. Näille tyyppirakennuksille arvioitiin energiansäästöpotentiaali ja uusiutuvan energian tuotto eri lämpöpumppuvaihtoehdoilla. Koko rakennuskannan nykyistä ja kumulatiivista energiankulutusta arvioitiin VTT:n kehittämällä REMA-mallilla. Lämpöpumppujen tulevaa vaikutusta suomalaisen rakennuskannan energiankulutukseen ja päästöihin arvioitiin vertaamalla perinteistä Business as Usual-skenaariota lämpöpumppujen nopeampaa yleistymistä kuvaavaan lämpöpumppuskenaarioon.
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