# Foreword

Measures implemented and in preparation at the EU level for reducing energy consumption by 2020 are having a comprehensive impact in the construction sector, on both building products and construction work. Provisions concerning eco-design, product markings and the promotion of renewable energy sources are to enter into force for residential solid fuel burning appliances in the near future. There are also requirements in preparation for the efficiency, emissions and energy classification of residential solid fuel burning appliances (Ecodesign and Labelling LOT 20, planned to enter into force in 2018).

For the purpose of developing the national building code, a joint research project with operators in the residential solid fuel burning appliances manufacturing sector is needed for assessing with reliable methods the functioning of inset appliances sealed to a chimney, particularly in detached houses. The purpose of the present project was to explore the capacity for using renewable energy in slow heat release residential solid fuel burning appliances in detached houses and to determine the parameters of such use. The project involved studying the impact of slow heat release residential solid fuel burning appliances and of structures with varying energy efficiency properties on their heating effectiveness and efficiency so that such appliances can be better and more reliably taken into account in national energy regulations.

The project was funded by Tekes – the Finnish Funding Agency for Innovation (ERDF funding), the Finnish Fireplace and Chimney Association (TSY), Turun Uunisepät Oy, Tulikivi plc, the Finnish Brick Industry Association and Nunnauuni Oy. The project was implemented by VTT Technical Research Centre of Finland, and its steering group involved Onni Ovaskainen (chairman, Tulikivi plc), Pekka Kalliomäki (Ministry of the Environment), Johannes Uusitalo (Nunnauuni Oy), Mervi Sihvonen (Turun Uunisepät Oy), Juhani Jyrkiäinen (Finnish Fireplace and Chimney Association TSY) and Raimo Pohjola (Finnish Brick Industry Association).

Espoo, 30 September 2014

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**Liitteet:**

# List of symbols

| | |
|---|---|
| $q$ | Non-dimensional heating capacity estimated using the log-normal distribution [ - ] |
| $t$ | Log-normal distribution time from the start of the burn [h] |
| $t_{50}$ | Log-normal distribution parameter measuring the time during which the appliance has released half of the net thermal energy in the burned wood charge into the surrounding space [h] |
| $\sigma$ | Log-normal distribution parameter depicting the dispersion of the distribution [ - ] |
| $t$ 100 % | Time from the start of the burning of the wood charge at which the heating capacity released by the appliance into the surrounding space is at its maximum [h] |
| $t$ 50 % | Time from the start of the burning of the wood charge at which the heating power released by the appliance into the surrounding space is half of the maximum [h] |
| $t$ 25 % | Time from the start of the burning of the wood charge at which the heating capacity released by the appliance into the surrounding space is one fourth of the maximum [h] |
| $Q_{appliance}$ | Thermal energy produced by the appliance [kWh/a] |
| $Q_{fuel}$ | Thermal energy input into the appliance as fuel [kWh/a] |
| $\eta_{appliance}$ | Overall efficiency of the appliance [ - ] |
| $\eta_{combustion}$ | Combustion efficiency of the appliance [ - ] |

| | |
|---|---|
| $\eta_{heatrelease}$ | Heat release efficiency of the appliance [ - ] |
| $\eta_{combustion\ CE}$ | Efficiency of the appliance according to the CE marking [ - ] |
| $\eta_{heating}$ | Heating efficiency taking into account the heat loss caused by the temperature increase in the space [ - ] |
| $\eta_{stratification}$ | Efficiency taking into account the heat loss caused by vertical stratification in the indoor air [ - ] |
| $\eta_{building}$ | Efficiency taking into account heat loss to outdoor air through the building envelope [ - ] |
| $Q_{ref}$ | Heating energy consumption of spaces in the building without the appliance [kWh] |
| $Q_{heating}$ | Heating energy consumption of spaces in the building with the appliance in use [kWh] |

# 1. Background and objectives of the project

Measures implemented and in preparation at the EU level for reducing energy consumption by 2020 are having a comprehensive impact in the construction sector, on both building products and construction work (Figure 1). Provisions concerning eco-design, product markings and the promotion of renewable energy sources are to enter into force for residential solid fuel burning appliances in the near future. There are also requirements in preparation for the efficiency, emissions and energy classification of residential solid fuel burning appliances (Ecodesign and Labelling LOT 20, planned to enter into force in 2018).


Renewable Energy Sources Directive (RES)
Energy Performance of Buildings Directive (EPBD)
Objective 2020 :: Greenhouse gas emissions -20% :: Renewable energy sources +20% :: Energy efficiency +20%
Eco-design of energy-using products Directive (EuP)
Energy Efficiency Directive (EEP)

**Figure 1.** EU measures to improve the energy efficiency of buildings and to promote the use of renewable energy sources.

According to part D3 of the Finnish National Building Code (Energy management in buildings), which entered into force in summer 2012, calculations of the total energy consumption of a building (the ‘E value) to demonstrate compliance with the Code may include heating energy released by slow heat release residential solid fuel burning appliances to a maximum of 2,000 kWh per year per appliance (National Building Code, part D3, 2012). Similarly, the overall annual efficiency for delivered energy use from slow heat release residential solid fuel burning appliances relative to purchased energy is 0.60 by default, unless more accurate data are available (National Building Code, part D5, 2012).

There is a standard for slow heat release residential solid fuel burning appliances (SFS-EN 15250), giving the minimum requirements and testing and calculation methods for combustion efficiency and the heat release time profile.

There is a draft revision for standard EN 15250 that addresses the determination of the output and efficiency of residential solid fuel burning appliances connected to a heating system, on the basis of which it is possible to take such appliances connected to a heating system into account in the calculation of the 'E value', to a limited extent.

Although 6.7 million cubic metres of firewood are burned in detached houses in Finland every year, amounting to 15 TWh and therefore covering about 40% of the overall heating demand of detached houses (Torvelainen 2009), no systematic analyses of the use of slow heat release residential solid fuel burning appliances at the building level have been conducted. Therefore, for the purpose of developing the national building code, a joint research project with operators in the residential solid fuel burning appliances manufacturing sector is needed for assessing with reliable methods the functioning of inset appliances sealed to a chimney, particularly in detached houses.

The purpose of the present project was to explore the capacity for using renewable energy in slow heat release residential solid fuel burning appliances in detached houses and to determine the parameters of such use. In the project, the impact of three residential solid fuel burning appliances with different heat release properties on heating effectiveness and heating efficiency in renovation sites and new buildings of various kinds was explored with a view to enabling residential solid fuel burning appliances to be taken better and more accurately into account in forthcoming national energy regulations.

# 2. Definitions of residential solid fuel burning appliances

## 2.1 Slow heat release residential solid fuel burning appliance

A slow heat release residential solid fuel burning appliance is an intermittently heated residential solid fuel burning appliance that has thermal storage capacity in its mass such that it will release heat for a declared period of time after the fire has gone out, as specified by the manufacturer and satisfying the minimum heat storage requirement specified in the standard SFS-EN 15250.

An appliance may be referred to as a slow heat release residential solid fuel burning appliance if it fulfils the thermal storage capacity requirements. The standard SFS-EN 15250 specifies that the minimum time period from the appliance achieving the maximum differential surface temperature to falling to 50% of that maximum value in a performance test must be at least four hours (Figure 2). It should be noted that the required four-hour period begins from the time when the maximum differential surface temperature is attained (not from the time when the fire goes out). The heat storage capacity is demonstrated with a performance test where the appliance is used according to the performance test at nominal heat output defined in section A.4.6 of the standard SFS-EN 15250.

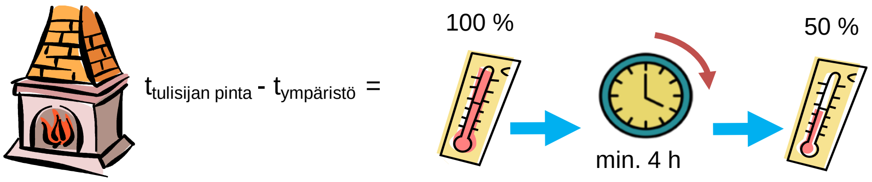



**Figure 2.** The duration of the maximum differential surface temperature of a slow heat release residential solid fuel burning appliance falling to 50% of the maximum value must be at least four hours.

## 2.2 Solid fuel burning room heater

A solid fuel burning room heater is an appliance that releases heat into the space more quickly than a slow heat release residential solid fuel burning appliance, i.e. the duration of the maximum differential surface temperature of the appliance falling to 50% of the maximum value is less than four hours.

The heat output and efficiency of a room heater for the purposes of the CE marking is determined according to the standard SFS-EN 13240.

## 1.1 Classification of residential solid fuel burning appliances

For the purposes of the present project, residential solid fuel burning appliances were classified as follows on the basis of their heat storage capacity:

1. appliances with quick heat release (room heaters)
2. slow heat release appliances, time to 50% of maximum differential between 4 h and 15 h
3. very slow heat release appliances, time to 50% of maximum differential more than 15 h

The time to 50% of maximum differential is given in the CE marking of a slow heat release residential solid fuel burning appliance.

# 3. Efficiency of residential solid fuel burning appliances

## 3.1 Heat generation of a residential solid fuel burning appliances

A residential solid fuel burning appliance differs from other heating systems in two ways: firstly, its thermal output into the space where it is installed is unregulated; and secondly, its heating effect is restricted to that space. Because the thermal output is unregulated and limited to one space, the appliance overheats the space in which it is installed, causing convection currents between spaces because of air density differentials, which in turn conveys the heating effect to other spaces too. Overheating causes an increase in conductive heat loss through the walls, ceiling and floor, in heat loss due to infiltration and in heat loss through ventilation. The heat loss through ventilation depends on the efficiency of heat recovery in extraction ventilation. In D5 calculations, the thermal energy produced by a slow heat release residential solid fuel burning appliance is calculated as the energy input into the appliance (firewood) times the overall efficiency of the appliance (Equation 1).

$$Q_{appliance} = Q_{fuel} \eta_{appliance} \quad (1)$$

where

| | |
|---|---|
| $Q_{appliance}$ | is the thermal energy produced by the appliance [kWh/a] |
| $Q_{fuel}$ | is the thermal energy input into the appliance as fuel [kWh/a] |
| $\eta_{appliance}$ | is the overall efficiency of the appliance, kWh/a. |

The overall efficiency of a slow heat release residential solid fuel burning appliance includes the combustion efficiency and heat release efficiency of the appliance. The default value for the overall efficiency in D5/2012 is 0.6. A more favourable value may be used if determined for instance on the basis of the calculations specified in the present publication.

Also, the net rated output of a slow heat release residential solid fuel burning appliance in calculations to demonstrate compliance of a building with the Code pursuant to D3 is limited to $Q_{appliance}$ = 2,000 kWh.

Using the default values gives the volumes of firewood shown in Table 1 as the fuel consumption of a slow heat release residential solid fuel burning appliance.

**Table 1.** Volumes of firewood per annum corresponding to the net energy output of a slow heat release residential solid fuel burning appliance pursuant to D3 (2,000 kWh/a) for different types of wood, calculated using the default overall efficiency of the appliance as per D5 ($\eta_{appliance}$=0,6).

| Wood | Volume of wood kg/a | Volume of wood stacked m³/a |
|---|---|---|
| Birch | 803 | 2,0 |
| Pine | 803 | 2,5 |
| Fir | 813 | 2,5 |
| Alder | 823 | 2,7 |
| Aspen | 833 | 2,5 |

## 3.2 Overall efficiency of the residential solid fuel burning appliances

The overall efficiency of a residential solid fuel burning appliance is calculated by taking into account both combustion heat loss and heat release heat loss. The overall efficiency of an appliance is calculated as follows:

$$\eta_{appliance} = \eta_{combustion}\eta_{heatrelease} \quad (2)$$

where

$\eta_{appliance}$ is the overall efficiency of the appliance
$\eta_{combustion}$ is the combustion efficiency of the appliance
$\eta_{heat\ release}$ is the heat release efficiency of the appliance

The combustion efficiency is obtained from the value given by the manufacturer of the appliance (CE marking) and the value defined as per the standard SFS-EN 15250.

### 3.2.1 Simple calculation method for overall efficiency

The simple calculation method is based on the heating efficiency given under 'Other appliances' in Table 6.2 in the National Building Code part D5/2012, $\eta_{heatrelease}$ = 0.8. This takes into account heat release losses and the effects of regulation and of thermal layering of indoor air. The other input is the combustion efficiency determined for the CE marking, which is individual for each appliance. The overall efficiency of the appliance is calculated as follows:

$$\eta_{appliance} = \eta_{combustion} \times 0.8 \quad (3)$$

where

$\eta_{appliance}$ is the overall efficiency of the appliance

$\eta_{combustion}$ is the efficiency of the appliance according to the CE marking

0.8 is the heat release efficiency of the appliance (under 'Other appliances' in Table 6.2 in the National Building Code, part D5/2012)

Therefore, an overall efficiency better than 0.60 may be used in E value calculations for appliances that have a CE marking efficiency higher than 0.75 (National Building Code, part D5/2012).

### 3.2.2 Determining the overall efficiency through simulation

Examining complex physical phenomena obviously requires advanced simulation software capable of modelling all the interaction relationships described above.

There are no standards on how to define the heat release efficiency of a residential solid fuel burning appliance, and thus this value must be determined on a case-by-case basis. Heat release efficiency depends on the heat release properties of the appliance examined and the properties of the building examined. The heat release properties of the appliance depend above all on its thermal storage capacity. The relevant properties of the building include space massing, the openness of the space containing the residential solid fuel burning appliances vis-à-vis other spaces in the building, and the ratio of the heat demand of the spaces within the sphere of effect of the appliance to the heat release of the appliance.

The heat release efficiency includes the temperature increase caused by operating the appliance and increased conductive heat loss through the building envelope caused by thermal layering of indoor air, increased heat loss through infiltration and changes in ventilation heating needs. In a building equipped with heat recovery in extraction ventilation, the use of a slow heat release residential solid fuel burning appliance reduces the need for heating intake air. The heat release efficiency does not take into account cold bridge losses in flues or eventual heat losses in the combustion gas flue, which must be considered separately.

The heat release efficiency of a residential solid fuel burning appliance is calculated using the following (Formula 4), which is analogous to that used for heat emitters (*Lämmitysjärjestelmät ja lämmin käyttövesi – laskentaopas* [Heating systems and hot water – calculation guide], 2011).

$$\eta_{heatrelease} = \frac{1}{\frac{1}{\eta_{heating}} + \frac{1}{\eta_{stratification}} + \frac{1}{\eta_{building}} - 2} \qquad (4)$$

where

| | |
|---|---|
| $\eta_{heatrelease}$ | is the heat release efficiency of the appliance |
| $\eta_{heating}$ | accounts for heat loss caused by the temperature increase in the space |
| $\eta_{stratification}$ | accounts for heat loss caused by vertical layering in the indoor air |
| $\eta_{building}$ | accounts for heat loss directly to outdoor air through the building envelope |

The heat release efficiency of a slow heat release residential solid fuel burning appliance is determined as follows when using simulation software. The calculation can be performed either including or excluding the heat distribution system and its regulators; in the latter case, the efficiency of the regulation must be evaluated separately. In case the simulation software does not take into account the additional heat loss caused by thermal layering of indoor air, that loss must also be evaluated separately, as must the additional heat loss from an inset appliance in the building structure.

1. Calculate the heating energy consumption in the spaces of the building analysed over the desired time period without the appliance ($Q_{ref}$).
2. Model the time-dependent heat release profile of the appliance analysed (see chapter 5).
3. Place the appliance in the relevant space and define a usage profile with charge volumes and frequency of use (daily/weekly).
4. Calculate the heating energy consumption in the spaces of the building analysed with the appliance in use ($Q_{tulisija}$).
5. Calculate the heating efficiency using the formula:

$$\eta_{heatrelease} = \frac{Q_{ref} - Q_{appliance}}{Q_{fuel}\eta_{combustion}} \qquad (5)$$

where

| | |
|---|---|
| $\eta_{heatrelease}$ | is the heat release efficiency of the appliance |
| $Q_{ref}$ | is the heating energy consumption of spaces in the building without the appliance [kWh] |
| $Q_{appliance}$ | is the heating energy consumption of spaces in the building with the appliance [kWh] |
| $Q_{fuel}$ | is the specific heat of the wood input into the appliance [kWh] |
| $\eta_{combustion}$ | is the combustion efficiency of the appliance |

If the simulation software does not account for the additional heat loss caused by thermal layering of indoor air, the efficiency of that layering must be evaluated separately. How to do this is shown in the guide *Lämmitysjärjestelmät ja lämmin käyttövesi – laskentaopas* [Heating systems and hot water – calculation guide] (2011) published by the Ministry of the Environment.

If the simulation does not account for any additional heat loss directly through structures, caused by the placement of the appliance, this must be evaluated separately. This issue is relevant for instance in the case of an inset appliance integrated into the building envelope.

#### 3.2.3 Temperature

It must be noted in performing the calculations that the temperature of the space in which the residential solid fuel burning appliance is placed must not rise too much. Temperature increase is due to the heat release from the appliance exceeding the heating need in the space, which will cause the room temperature to rise even if the heating regulation system shuts off the heating in that space. This limits the volume of wood to be burned in the appliance and also the net heating energy to be produced using the appliance. Guidelines issued by the Ministry of Social Affairs and Health state that room temperature must not exceed 26 °C except if this occurs due to the outdoor air temperature. During the heating season, room temperature should not exceed 23–24 °C. The conclusion from the above is that during the heating season the room temperature may momentarily rise up to 26 °C, but the long-term average must remain under 24 °C.

# 4. Research methods used

## 4.1 Computation tool used for analyses

The analyses for the present project were conducted using VTT Talo, a building simulation tool developed at VTT. This computation application takes into account the various heat transfer mechanisms (convection, conduction and radiation) and resolves the time-dependent mass, momentum and energy balances for the determined computation network using the PCG sparse matrix method. The reliability of this tool was previously evaluated in a doctoral dissertation (Tuomaala 2002), and the tool has been used in various research and development projects (e.g. COMBI, Thermal Comfort, Hot and cold, NEMUS, Hattivatti, Virtual Space 4D, the indoor environment research programme of RYM Oy, EU/SME Airlog).

## 4.2 Input data for the computation

When using precise computational methods for evaluating thermodynamic behaviour, the required input data are the geometric details and material properties of the structures; the specific thermal and flow characteristics of the building services; weather data; and usage timetables. For evaluating the thermal yield potential of residential solid fuel burning appliances, the following data are required: thermal properties of the structures in the buildings analysed (dimensions and material layers); parameters of the log-normal distribution describing the thermodynamic behaviour of the appliance (average and dispersion); the wood charges and replenishment intervals for the burn (programmed checks to ensure that, for instance, no wood is added if the maximum room temperature has been exceeded); other building services equipment in the building analyse and their regulation; and weather data for the locations analysed (Helsinki and Sodankylä).

## 4.3 Verification of the computation tool

The VTT Talo computation tool selected for the present project enables the computational evaluation of the thermodynamic interaction between a residential solid fuel burning appliance and the structures of a building using a variety of usage and weather input data. Computation of the thermodynamic behaviour of the structures and the indoor airflows in the building was verified at the start of the present project by comparing the results given by VTT Talo to the results given by the IDA/ICE computing tool. The efficiency and energy results obtained for the buildings analysed were compatible in the applications compared once the parameters had been correctly selected for the VTT Talo computations, particularly for air flows in the stairwell of the new two-storey building.

# 5. Description of parameters in the computation cases

Because residential solid fuel burning appliances differ widely in their heating properties, particularly their thermal storage and heat release properties, three different appliances were analysed for their thermodynamic behaviour in various circumstances of heating and usage in the present project. The effect of the various appliances on heating effectiveness and heating efficiency was evaluated for renovated buildings and new buildings. In order to improve the general comparability of the results, the renovated buildings and new buildings selected for analysis were the same as the objects included in the earlier Costoptimal project (energy efficiency); and for both types of object, the thermodynamic behaviour of the appliances was analysed at two energy efficiency levels: basic and energy-efficient. The simulations conducted were based on Helsinki weather data, commonly used for demonstrating compliance of buildings with energy efficiency requirements (National Building Code, part D3, 2012).

## 5.1 Residential solid fuel burning appliances

Figure 3 shows the measured heat release of a typical residential solid fuel burning appliance over time. The heat released by the appliance into the surrounding space initially increases as the structures of the appliance heat up. The heat release rate maximum is typically attained within a few hours, depending on the structures and mass of the appliance (for the product described here, *t (100%)* is at 4.5 hours from the start of the burn). Thereafter, the temperature of the structures of the appliance, and therefore the heating capacity, decreases in a profile unique for each appliance.

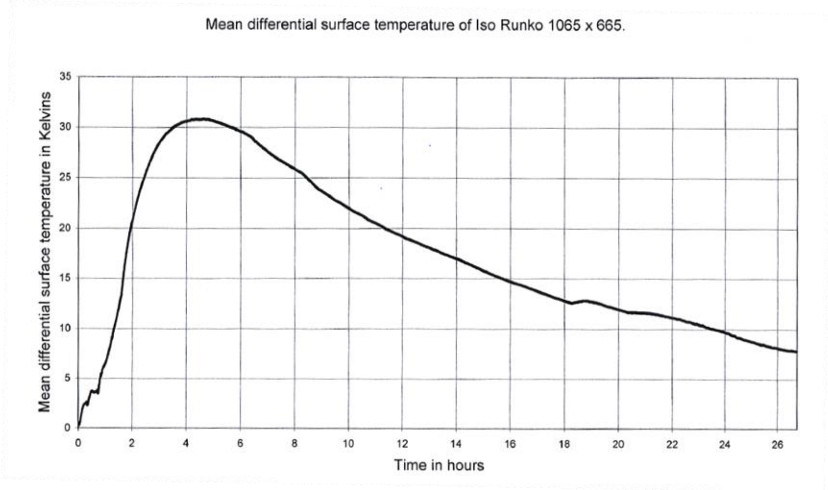
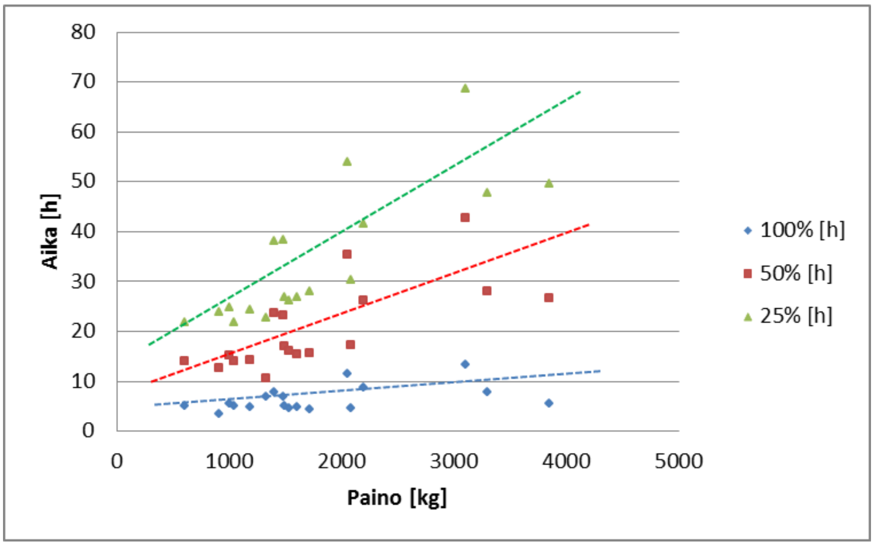



**Figure 3.** Example of laboratory-measured heat release rates of a residential solid fuel burning appliance during a burn test.

Figure 4 shows results from official measurements conducted on various residential solid fuel burning appliances for their CE markings. The horizontal axis shows the weight of each appliance, and the graph plots the values measured for each appliance: 100% (time from the start of the test when maximum heat release rate is attained), 50% (time from the start of the test when the heat release rate has fallen to half of the maximum) and 25% (time from the start of the test when the heat release rate has fallen to one fourth of the maximum). The graph also shows dotted lines representing linear approximations of the values measured. Individual parameter readings particularly for heavy appliances may differ quite considerably from the linear approximations, due to differences in materials and structure between the products. Nevertheless, the general trend is quite clear and logical: the more thermal mass a product has, the more slowly it releases the thermal energy of the burned wood charge into the surrounding space.




Time [h]
Weight [kg]

**Figure 4.** Results of heat release rate measurements of residential solid fuel burning appliances of various weights, conducted for CE markings.

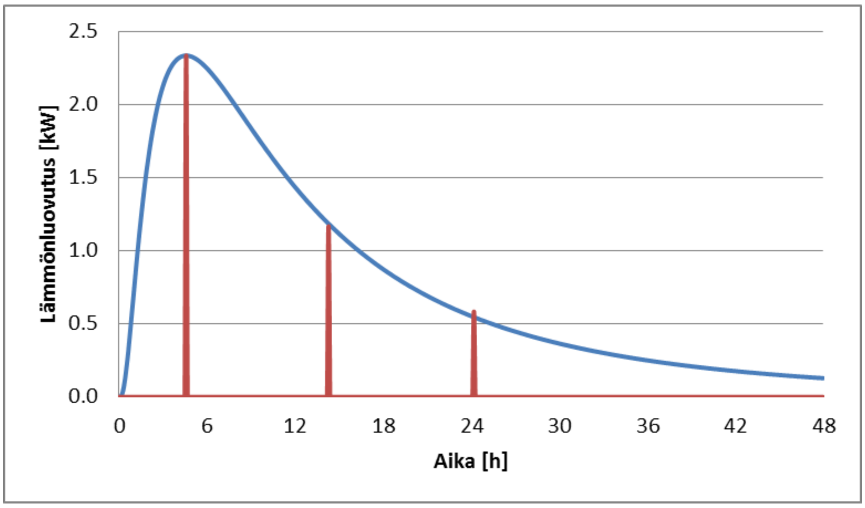
Based on the measurements for CE markings, residential solid fuel burning appliances differ quite widely from one another in terms of their heat release properties over time. The heat release rate of various appliances into the surrounding space was estimated in the present study using the log-normal distribution:

$$q(t) = \frac{1}{t(\ln\sigma)\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln((t)/t_{50})}{\ln\sigma}\right)^2\right] \qquad (6)$$

where

- $q$ is the non-dimensional heating capacity estimated using the log-normal distribution
- $t$ is the time from the start of the burn [h]
- $t_{50}$ is the average time [h]
- $\sigma$ is the dispersion

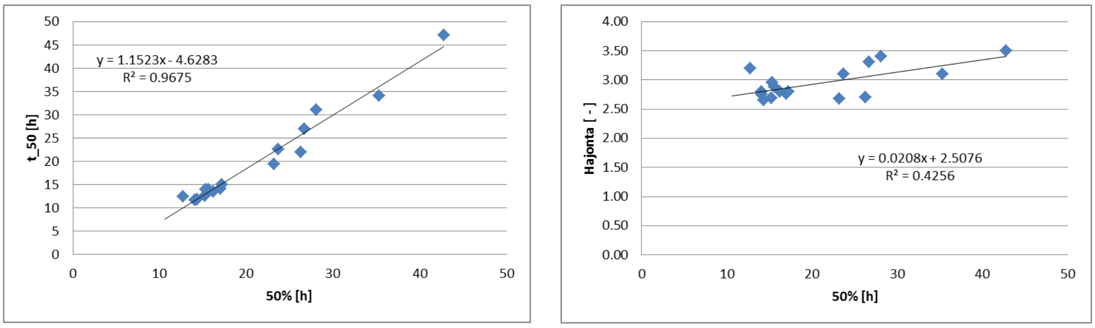
This method allows reliable evaluation of the heat release rate of various appliances at any given point in time and for any given volume of fuel once two parameters of the distribution are defined for each appliance: average time ($t_{50}$) and dispersion ($\sigma$). These parameters were defined using the appliance measurements conducted for CE markings. Figure 5 illustrates an individual specimen product from the measurements of which the parameters of the log-normal distribution were derived.




Heat release [kW]
Time [h]

**Figure 5.** Sample residential solid fuel burning appliance whose measurements for the CE marking were established as follows: heat release rate 100% = 4.6 h; 50% = 14.3 h; and 25% = 24.2 h (red columns). On the basis of these, parameters for the log-normal distribution were determined: $t_{50}$ = 11.9 h and σ = 2.65 (blue curve, the energy released by the appliance being 42.1 kWh).

Figure 6 shows the log-normal distribution parameter values determined for 17 different appliances as functions of the 50% times derived from CE measurements. The results show that there is a remarkably strong correlation ($R^2$ = 0.97) between the $t_{50}$ and 50% times but a clearly weaker correlation between the dispersion and the 50% time.



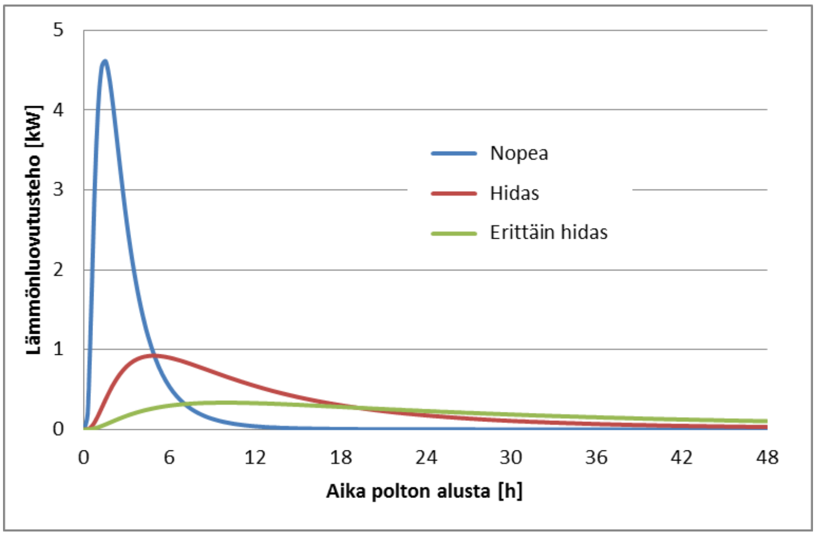

Dispersion [-]<}100{>**Figure 6.** Correlation between the log-normal distribution parameters determined for individual residential solid fuel burning appliances (average time t50 on the left and dispersion on the right) and the 50% times derived from measurements made for CE markings.

In order to take the differences in heat storage and heat release properties between appliances into account, three types of appliance were selected for the analyses in the present study: appliances with quick, slow and very slow heat release. The log-normal distribution parameter values for the selected appliance types are given in Table 2; they are consistent with the parameters obtained for individual appliances.

**Table 2.** Log-normal distribution parameters for different types of residential solid fuel burning appliance and the 50–100% time that measures the heat storage capacity of the appliance (i.e. the time during which the heat release rate falls to half of the maximum; for slow heat release appliances, this parameter must be more than 4 h).

| Appliance | $t_{50}$ [h] | $\sigma$ [ - ] | 100% [h] | 50% [h] | 25% [h] | 50–100% [h] |
|---|---|---|---|---|---|---|
| **Fast** | 2.30 | 2.50 | 1.5 | 3.25 | 4.5 | 1.8 |
| **Slow** | 10.52 | 2.68 | 5.0 | 13.75 | 21.0 | 8.8 |
| **Very slow** | 28.52 | 3.05 | 10.0 | 33.25 | 55.0 | 23.3 |

Figure 7 shows the log-normal distribution heat release rates for the different types of appliance selected for detailed analysis with an identical wood charge (4 kg). The differences in heat storage and heat release properties are clearly discernible even though the surface area delimited by each curve is equal to the net energy content of the wood burned, 14.5 kWh.




Heat release rate [kW]
Time from start of burn [h]
Fast :: Slow :: Very slow

**Figure 7.** Log-normal distribution heat release rates for the selected types of residential solid fuel burning appliance with different thermal storage capacities over a period of 48 h from the ignition of a 4 kg wood charge.

## 5.2 Buildings

Dynamic hourly simulations were run using two building models (Figure 8). For the ‘new building’, a two-storey detached house was used. The simulation of a new building was conducted at two levels of energy efficiency: the first assuming a building constructed according to the current building code, and the second assuming a highly energy-efficient building, almost a passive house. The thermal properties of the new building were simulated under weather conditions in Helsinki and, in order to ascertain the sensitivity of the results, under weather conditions in Sodankylä.

The ‘renovated building’ was simulated using a single-storey detached house model. As with the new building, the simulation of a renovated building was conducted at two levels: the original building and a building where energy efficiency enhancement measures had been carried out.

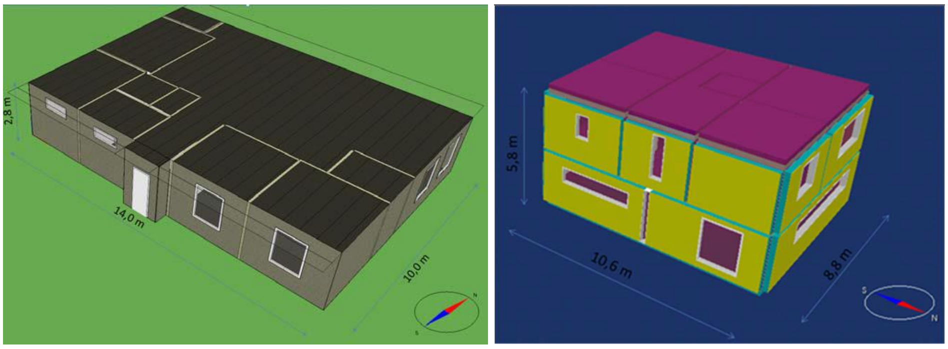



**Figure 8.** Building used in the analyses: the renovated building (left) and the new building (right).

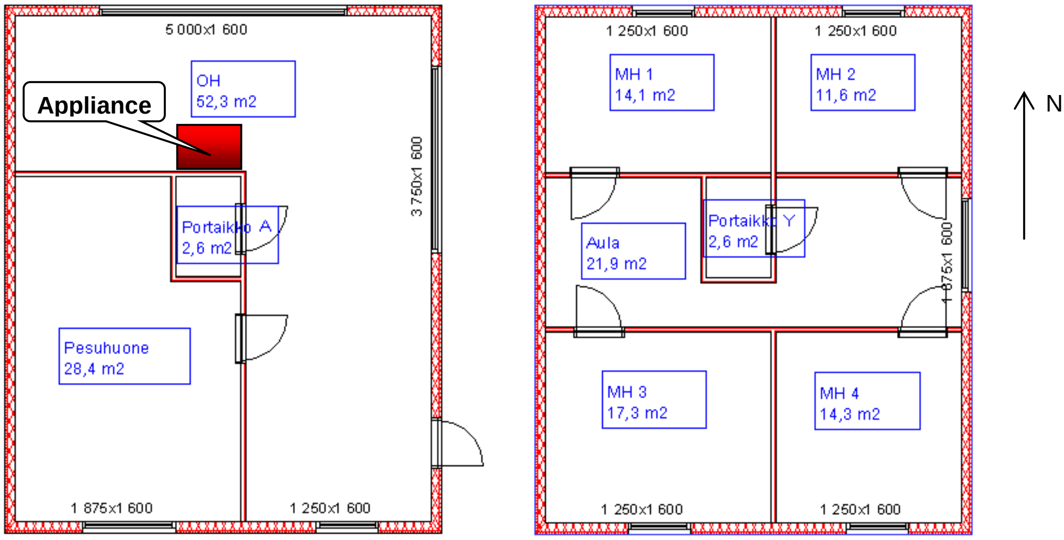
The baseline assumptions and buildings used in the simulations are described in sections 5.2.1 and 5.3.1. Both buildings are assumed to house a family of four, two adults and two children.

In the simulation, all bedroom doors and the stairwell doors in the two-storey building were open, but the doors of the WCs, bathrooms and walk-in closets were closed. The propagation of heat from the residential solid fuel burning appliances in the buildings is shown in examples given in Appendix D.

A total of 83 simulated cases were computed. The majority of these (72) involved variations in appliance type, charge volume, energy efficiency of the building and indoor temperature at the start of the burn. The thermal behaviour of each building was also simulated without the effect of a solid fuel appliance. Also, the sensitivity of the analysis was verified by computing six simulations in the weather conditions of Sodankylä.

### 5.2.1 Detached house, new building

The model used for the new building was a two-storey detached house model. The floor plan is shown in Figure 9. The appliance was placed in the most open space in the building, in this case the living room.




Appliance
Living room 52.3 $m^2$
Stairwell lower 2.6 $m^2$
Washroom 28.4 $m^2$
Bedroom 1 14.1 $m^2$
Bedroom 2 11.6 $m^2$
Hall 21.9 $m^2$
Stairwell upper 2.6 $m^2$
Bedroom 3 17.3 $m^2$
Bedroom 4 14.3 $m^2$

**Figure 9.** Floor plan and residential solid fuel burning appliance placement, standard two-storey detached house.

The principal specifications for the building are given in the following tables (Table 3 and Table 4).

**Table 3.** Principal specifications for standard detached house.

| | |
|---|---|
| Building volume | 468 cu.m |
| Floor area | 165.2 sq.m |
| Building envelope surface area | 363 sq.m |

**Table 4.** Surface area of structures of standard detached house by orientation.

| **Orientation** | **External wall** | **Window** | **Door sq.m** |
|---|---|---|---|

| | sq.m | sq.m | |
|---|---|---|---|
| North | 32.4 | 12.0 | - |
| West | 53.4 | 0.0 | - |
| South | 35.4 | 9.0 | - |
| East | 44.4 | 9.0 | 2.2 |
| Total | 165.6 | 30.0 | 2.2 |

The surface areas of the other structures were:

- Ceiling area 81.9 sq.m
- Ground floor area 83.3 sq.m
- Inside walls surface area 105.2 sq.m
- Inside doors surface area 14.6 sq.m

The following table (Table 5) shows the U values for structures used in standard detached house simulations in the case of a house built to code and a highly energy-efficient house. The standard detached house is equipped with mechanical intake and extraction ventilation with ventilation heat recovery. The annual efficiency of ventilation heat recovery was assumed to be 45% for a standard house and 80% after energy-efficiency measures. It was assumed in the simulation that ventilation in the kitchen could be boosted with a separate extractor fan in the cooker hood. The air from the cooker hood was conveyed straight to the roof was not subject to heat recovery. The intake and extraction air flows for each room are shown in Table 6.

**Table 5.** U values of structures.

| Building component | U value, W/m$^2$K | |
|---|---|---|
| | Normal level | Highly energy-efficient |
| External wall | 0.17 | 0.08 |
| Ceiling | 0.09 | 0.05 |
| Ground floor | 0.16 | 0.10 |
| Windows | 1.0 | 0.8 |
| External doors | 1.0 | 0.8 |

**Table 6.** Ventilation air flows. Continuous operation, 24 h per day and 7 days per week.

| Space | Intake air flow dm$^3$/s | Extraction air flow dm$^3$/s | Ventilation boost dm$^3$/s |
|---|---|---|---|
| Living room | 26 | - | 25 *) |

| | | | |
|---|---|---|---|
| Washroom | - | 33 | - |
| Stairwell | 2 | 7 | - |
| Bedroom 1 | 7 | - | - |
| Bedroom 2 | 6 | - | - |
| Bedroom 3 | 9 | - | - |
| Bedroom 4 | 7 | - | - |
| Entry hall | 9 | 29 | - |
| Total | 66 | 69 | |

*) Run time 2 h per day.

## 5.3 Building heating energy requirement

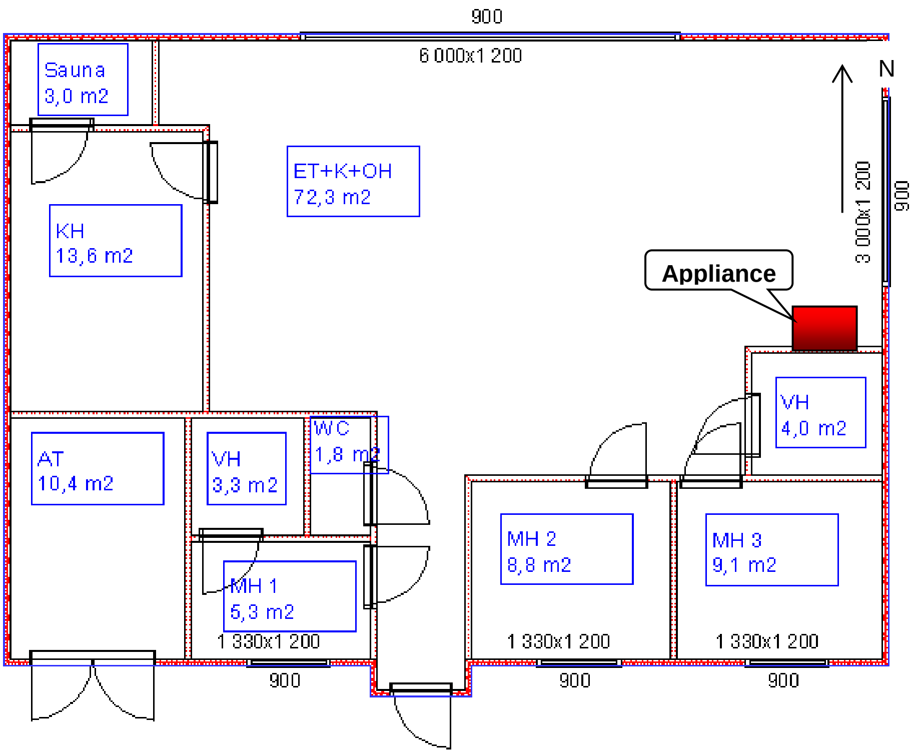
The monthly heating energy consumption for each room obtained from a dynamic year simulation computed for each analysis case without a residential solid fuel burning appliance is given in Table 7.

**Table 7.** Monthly heating energy requirements for the detached house cases without a residential solid fuel burning appliance .

| | **Heating energy requirement for rooms and ventilation, kWh** | | |
|---|---|---|---|
| **Month** | **Normal level, Helsinki** | **Highly energy-efficient, Helsinki** | **Highly energy-efficient, Sodankylä** |
| Jan | 2,320 | 1,127 | 1,701 |
| Feb | 2,096 | 975 | 1,383 |
| Mar | 1,374 | 463 | 848 |
| Apr | 865 | 149 | 358 |
| May | 307 | 53 | 70 |
| Jun | 0 | 0 | 0 |
| Jul | 12 | 0 | 0 |
| Aug | 0 | 0 | 0 |
| Sep | 304 | 0 | 136 |
| Oct | 1,047 | 313 | 802 |
| Nov | 1,378 | 596 | 952 |
| Dec | 1,933 | 907 | 1,264 |
| **Annual** | **11,638** | **4,583** | **7,514** |

### 5.3.1 Detached house, renovated building

The model used for the renovated building was a two-storey detached house model. The floor plan is shown in Figure 10. The appliance was placed in the most open space in the building, in this case the living room.




Sauna 3.0 $m^2$
Bathroom 13.6 $m^2$
Hall + kitchen + living room 72.3 $m^2$
Appliance
Garage 10.4 $m^2$
Walk-in closet 3.3 $m^2$
WC 1.8 $m^2$
Bedroom 1 5.3 $m^2$
Walk-in closet 4.0 $m^2$
Bedroom 2 8.8 $m^2$
Bedroom 3 9.1 $m^2$

**Figure 10.** Floor plan and residential solid fuel burning appliance placement, standard single-storey detached house.

The principal specifications for the building are given in the following tables (Table 8 and Table 9).

**Table 8.** Principal specifications for standard detached house.

| | |
|---|---|
| Building volume | 352 cu.m |
| Floor area | 132 sq.m |
| Building envelope surface area | 392 sq.m |

**Table 9.** Surface area of structures of standard detached house by orientation. The surface areas were calculated using the total internal dimensions.

| Orientation | External wall sq.m | Window sq.m | Door sq.m |
|---|---|---|---|
| North | 45.9 | 7.2 | - |
| West | 33.9 | 0.0 | - |
| South | 48.3 | 4.8 | 6.9 |
| East | 37.5 | 3.6 | - |
| Total | 165.6 | 15.6 | 6.9 |

The surface areas of the other structures were:

- The ceiling and ground floor areas same as the floor area, 132 sq.m each.
- Inside walls surface area 97.0 sq.m
- Inside doors surface area 16.8 sq.m

Table 10 shows the U values for structures used in standard detached house simulations in the case of a house built to code and a highly energy-efficient house.

**Table 10.** U values of structures.

| Building component | U value, $W/m^2K$ | |
|---|---|---|
| | Not renovated | Renovated |
| External wall | 0.50 | 0.17 |
| Upper floor | 0.27 | 0.09 |
| Ground floor | 0.38 | 0.38 |
| Windows | 2.5 | 2.5 |
| External doors | 1.1 | 1.1 |

Both the original and the renovated standard detached house model have mechanical extraction ventilation. The computation was based on the assumption that the original standard single-storey detached house was only renovated with regard to the heat insulation properties of the building envelope. The intake and extraction air flows for each room are shown in Table 11. It was assumed in the simulation that ventilation in the kitchen could be boosted with a separate extractor fan in the cooker hood.

**Table 11.** Ventilation air flows. Continuous operation, 24 h per day and 7 days per week.

| Space | Intake air flow $dm^3/s$ | Extraction air flow $dm^3/s$ | Ventilation boost $dm^3/s$ |
|---|---|---|---|
| Garage | - | 3 | - |
| Front hall, kitchen, living room | - | 7 | 25 *) |
| Bathroom | - | 10 | - |
| Bedroom 1 | - | 3 | - |
| Bedroom 2 | - | 3 | - |
| Bedroom 3 | - | 3 | - |
| Sauna | - | 10 | - |
| WC | - | 7 | - |
| Walk-in closet 3.3 sq.m | - | 3 | - |
| Walk-in closet 4.0 sq.m | - | 3 | - |
| Total | | 52 | |

*) Run time 2 h per day.

## 5.4 Building heating energy requirement

The monthly heating energy consumption for a standard detached house computed for each analysis case without a residential solid fuel burning appliance is given in Table 12. It was assumed in the simulation that the house has direct electrical heating equipped with electronic precision temperature control in each room.

**Table 12.** Monthly heating energy requirements for the detached house cases without a residential solid fuel burning appliance.

| Month | Heating energy requirement for rooms and ventilation, kWh | |
|---|---|---|
| | **Original** | **Renovated** |
| Jan | 4,140 | 2,989 |
| Feb | 3,837 | 2,744 |
| Mar | 2,896 | 2,076 |
| Apr | 2,163 | 1,530 |
| May | 1,049 | 740 |
| Jun | 328 | 201 |
| Jul | 533 | 392 |
| Aug | 355 | 215 |
| Sep | 1,274 | 860 |
| Oct | 2,314 | 1,638 |
| Nov | 2,683 | 1,948 |
| Dec | 3,582 | 2,575 |
| **Annual** | **25,154** | **17,908** |

## 5.5 Other parameters used in the computation

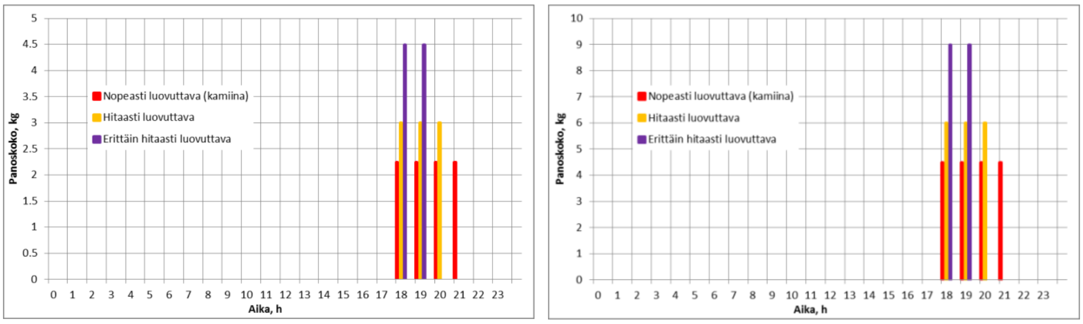
The annual usage time for a residential solid fuel burning appliance was defined with the assumption that the appliance is not used outside the heating season, i.e. between 1 Jun and 31 Aug. In the simulations, the appliance was operated every day except if the temperature in the room with the appliance exceeded the predefined maximum, which was checked whenever a charge was input or replenished. If the room temperature exceeded the limit, the charge was not replenished; instead, this was deferred to the next replenishment time. The simulations were conducted with three maximum room temperatures for each case: 21.5 °C, 22 °C and 25 °C.

For the volume of wood to be used during any given day, two cases were simulated for each type of appliance. The volumes of wood used were 9 kg and 18 kg, divided into batches to be input at intervals of one hour. The number of batches depended on the type of appliance. The burn was assumed to start at 18.00 every day. The daily timetable for the burn and the volume of the charges are shown in Table 13 and Figure 11.

The combustion efficiency used in the simulation was 100%; the actual size of the charge can thus be obtained by dividing the charge used in the simulation by the combustion efficiency given in the CE marking of the appliance.

**Table 13.** Charge volumes and burn timetable for the various types of residential solid fuel burning appliance.

| Appliance | Charge volume | Fuel replenishment | Burn time | Burn start |
|---|---|---|---|---|
| Quick release (room heater) | 9 kg per day<br>18 kg per day | 2.25 kg every hour<br>4.50 kg every hour | 4 h<br>4 h | 18.00<br>18.00 |
| Slow release | 9 kg per day<br>18 kg per day | 3 kg every hour<br>6 kg every hour | 3 h<br>3 h | 18.00<br>18.00 |
| Very slow release | 9 kg per day<br>18 kg per day | 4.5 kg every hour<br>9.0 kg every hour | 2 h<br>2 h | 18.00<br>18.00 |




Charge, kg
Time, h
Fast (room heater) :: Slow :: Very slow
**Figure 11.** Residential solid fuel burning appliance daily usage profile. Daily wood volume 9 kg (left) or 18 kg (right).

In the dynamic hourly simulations, the hourly weather data for Helsinki and Sodankylä in the test year obtained from the Finnish Meteorological Institute were used.

# 6. Principal results

The computational analyses were conducted for detached houses with different heat consumption levels and different masses: a single-storey building and a two-storey building. The single-storey building represents old building stock, and the two-storey building represents new building stock. For both buildings, two different levels of heat consumption were used for the analyses. For the single-storey building, one version featured the heat insulation properties of the original structures, which meant a high heat demand in the rooms; the other version featured the heat insulation properties of a renovated building, resulting in a considerably lower heat demand. For the two-storey building, one version featured structures built to current code (2013), while the other featured passive-house structures.

The buildings are remarkably different not only in the heat demand in their rooms but also in their floor plans. The single-storey building is quite spacious, meaning that the heat from the residential solid fuel burning appliance can easily spread over a wide area. The two-storey building has a much more enclosed interior, and the heat from the appliance primarily spreads over a much smaller area.

All three types of appliance were used in both buildings: fast, slow and very slow. Also, two different charges were used for the appliances, a 9 kg charge and a 18 kg charge. The aim was to use the appliances as much as possible, albeit with an upper limit to the room temperature. In each simulation, a maximum value was entered for room temperature; if the temperature was above the maximum at the ignition time specified for the appliance, ignition was deferred. The time of ignition was set at 18.00 for every day. All analyses were computed with three maximum values for the room temperature: 21.5 °C, 22 °C and 25 °C.

The simulations with the fast appliance and the two-storey passive house were also rerun in the weather conditions for Sodankylä, the purpose here being to examine how the climate affected the use of the appliance.

The following is a summary of the results by building type; a more detailed discussion of the results may be found in the appendices. Results are given only for those scenarios and those operating periods where the temperature conditions in the living room were acceptable: spot temperatures rarely over +26 °C, and the long-term room temperature does not exceed +24 °C. Because ‘long-term exceeding of +24 °C’ is not specifically defined (*Asumisterveysohje* [Housing health guide], 2003) and could not be defined in detail in the simulations, this criterion is based on rough estimates.

The net heat output of the appliances was calculated as follows: the reference is the building's heating energy consumption (heating of rooms + heating of ventilation after heat recovery) without the use of the appliance, and subtracting the actual heating energy consumption in the various cases where an appliance was in operation gives the heating energy output by the appliance.

The heat release efficiency was determined using Formulas 4 and 5 as shown in section 3.2.2. The efficiency of layering was in all cases assumed to be a constant, $\eta_{stratification} = 0.95$.

In calculating wood consumption, it was assumed that all appliances have a combustion efficiency of 80% and that the specific energy of the wood is 1,330 kWh per stacked cu.m.

## 6.1 Single-storey old building

All three types of appliance were used in the building: fast, slow and very slow. Also, two different charges were used for the appliances, a 9 kg charge and an 18 kg charge. The aim was to use the appliances as much as possible, albeit with an upper limit to the room temperature. In each simulation, a maximum value was entered for room temperature; if the temperature was above the maximum at the ignition time specified for the appliance, ignition was deferred; or if the maximum was exceeded during the burn, the charge was not replenished at the set time. The time of ignition was set at 18.00 for every day. All analyses were computed with three maximum values for the room temperature: 21.5 °C, 22 °C and 25 °C.

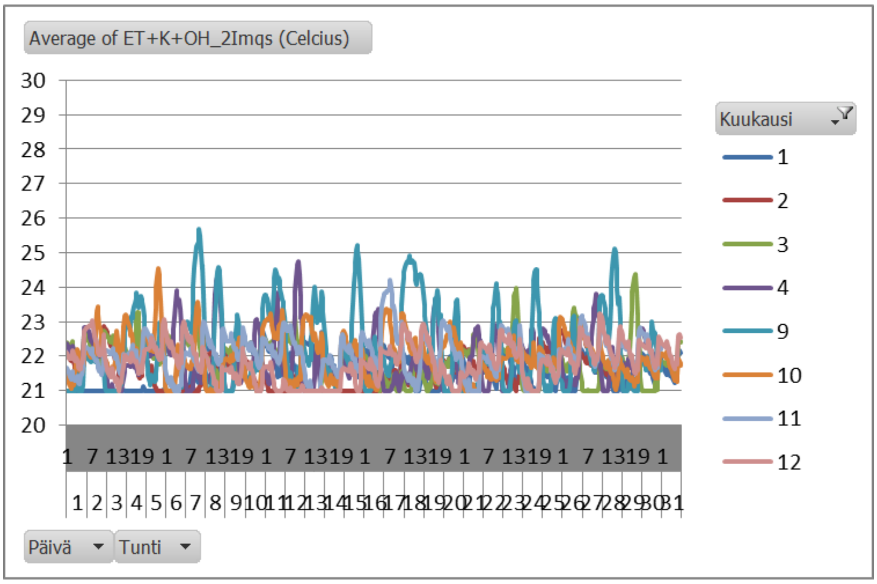
### 6.1.1 Temperature

There were five simulation scenarios each for the very slow and slow appliance that were acceptable in terms of their temperature conditions, and two for the fast appliance (Table 14).

**Table 14.** Simulation scenarios where temperature in the living room was acceptable.

| **Appliance** | **Charge** | **Living room temperature maximum** | | |
|---|---|---|---|---|
| | | 21.5 °C | 22 °C | 25 °C |
| Very slow | 9 kg | Acceptable | Acceptable | Acceptable |
| | 18 kg | Acceptable | Acceptable | X |
| Slow | 9 kg | Acceptable | Acceptable | Acceptable |
| | 18 kg | Acceptable | Acceptable | X |
| Fast | 9 kg | Acceptable | Acceptable | X |
| | 18 kg | X | X | X |

Figure 12 shows as an example how the temperature in the living room varied during the months in which the appliance was in operation in the scenario where the net heat release in the single-storey old house was the greatest (very slow appliance, charge 18 kg, room temperature maximum 22 °C). For comparison, Figure 13 shows the same scenario without the use of the appliance. The temperature conditions are described in more detail in Appendix A, where the living room temperatures by month are give for all appliances and several scenarios.




Month
Day :: Hour

**Figure 12.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 22 °C, charge 18 kg.

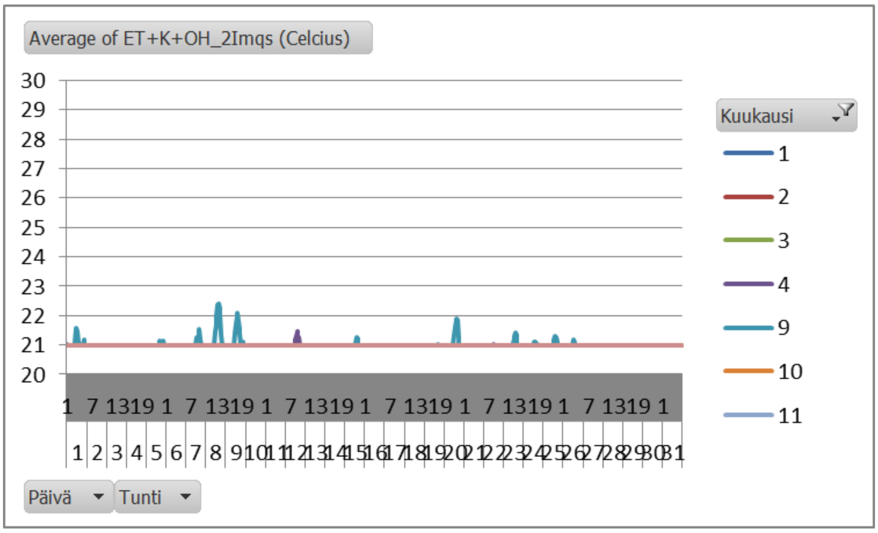
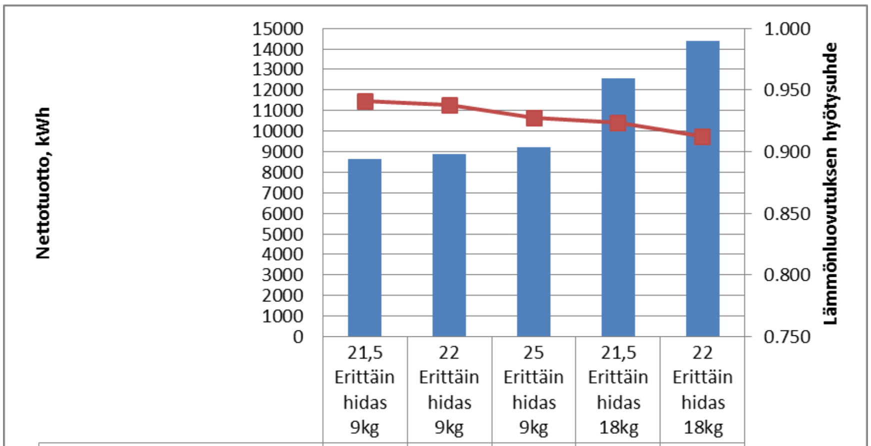



**Figure 13.** Living room temperatures during the heating season (September to April), residential solid fuel burning appliance not in use.

### 6.1.2 Residential solid fuel burning appliances: net heat release, percentage of total heat demand and wood consumption

For the very slow (Figure 14) and slow (Figure 16) appliance, the annual net heat output is over 14,000 kWh at its highest; this figure is attained with a heat release efficiency of about 90%. For the fast appliance (Figure 18), the net heat output is less than a third of that of the very slow and slow appliances, at best just over 4,000 kWh per year with a heat release efficiency of about 90%.

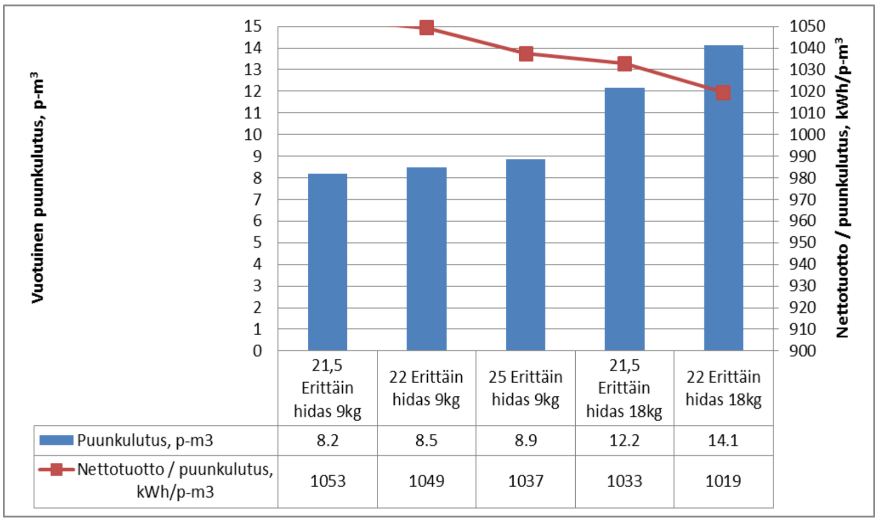
The very slow (Figure 14) and slow (Figure 16) appliances contribute over 55% of the total heating demand of the rooms in the building at their best, while the fast appliance (Figure 18) does not go much above 15%. The wood consumption for each appliance is shown in Figures 15, 17 and 19.




| | 21,5 Erittäin hidas 9kg | 22 Erittäin hidas 9kg | 25 Erittäin hidas 9kg | 21,5 Erittäin hidas 18kg | 22 Erittäin hidas 18kg |
|---|---|---|---|---|---|
| Nettotuotto, kWh | 8648 | 8883 | 9196 | 12550 | 14390 |
| Hyötysuhde | 0.941 | 0.938 | 0.927 | 0.923 | 0.912 |
| Osuus lämmöntarpeesta, % | 34 % | 35 % | 37 % | 50 % | 57 % |

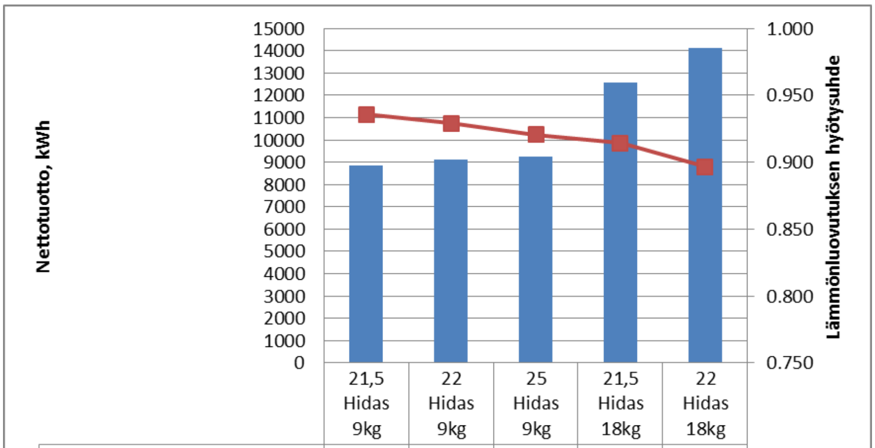
Net output, kWh
Heat release efficiency
21.5 Very slow 9 kg :: 22 Very slow 9 kg :: 25 Very slow 9 kg :: 21.5 Very slow 18 kg :: 22 Very slow 18 kg
Net output, kWh
Efficiency
Percentage of total energy demand

**Figure 14.** Net heating energy output, heat release efficiency and percentage of net output out of the total heating demand of the rooms in the building, very slow appliance.



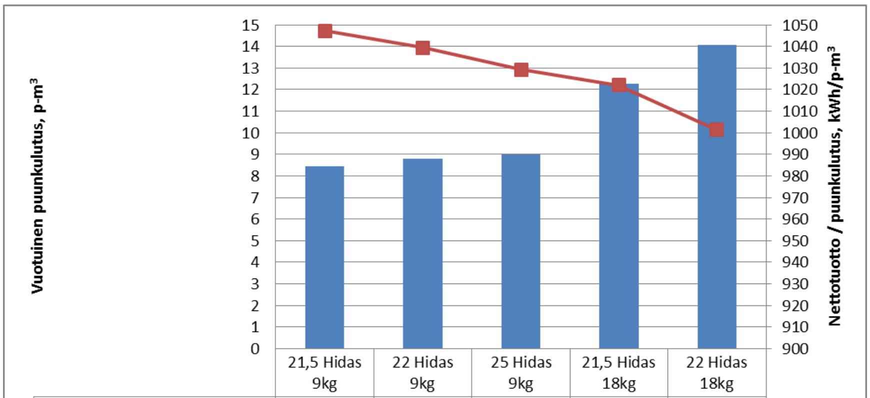

Annual wood consumption, stacked cu.m
Net output / wood consumption, kWh per stacked cu.m
21.5 Very slow 9 kg :: 22 Very slow 9 kg :: 25 Very slow 9 kg :: 21.5 Very slow 18 kg :: 22 Very slow 18 kg
Wood consumption, stacked cu.m
Net output / wood consumption, kWh per stacked cu.m

**Figure 15.** Wood consumption and specific net output (net output divided by wood consumption), very slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.




| | 21,5 Hidas 9kg | 22 Hidas 9kg | 25 Hidas 9kg | 21,5 Hidas 18kg | 22 Hidas 18kg |
|---|---|---|---|---|---|
| Nettotuotto, kWh | 8836 | 9135 | 9266 | 12553 | 14102 |
| Hyötysuhde | 0.936 | 0.929 | 0.920 | 0.914 | 0.897 |
| Osuus lämmöntarpeesta, % | 35 % | 36 % | 37 % | 50 % | 56 % |

**Figure 16.** Net heating energy output and heat release efficiency, slow appliance.




| | 21,5 Hidas 9kg | 22 Hidas 9kg | 25 Hidas 9kg | 21,5 Hidas 18kg | 22 Hidas 18kg |
|---|---|---|---|---|---|
| Puunkulutus, p-m3 | 8.4 | 8.8 | 9.0 | 12.3 | 14.1 |
| Nettotuotto / puunkulutus, kWh/p-m3 | 1047 | 1039 | 1029 | 1022 | 1001 |

**Figure 17.** Wood consumption and specific net output (net output divided by wood consumption), slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

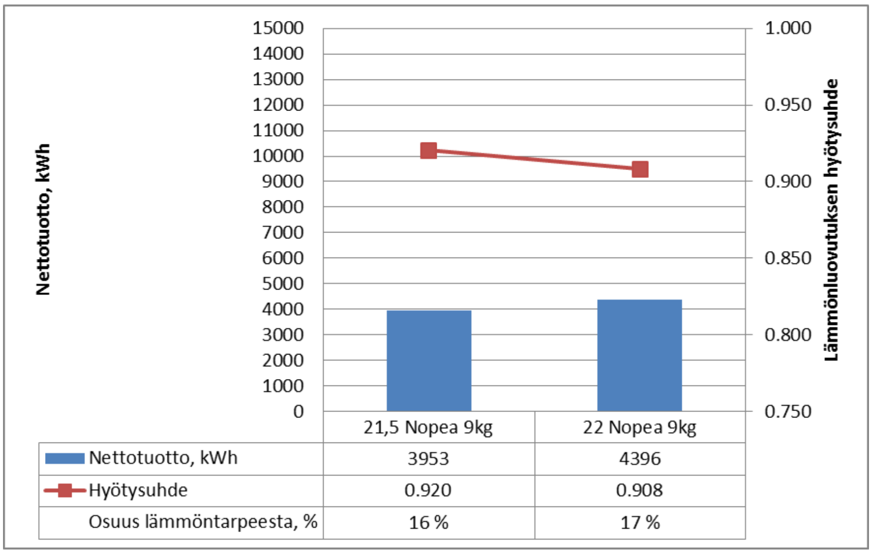



**Figure 18.** Net heating energy output and heat release efficiency, fast appliance.

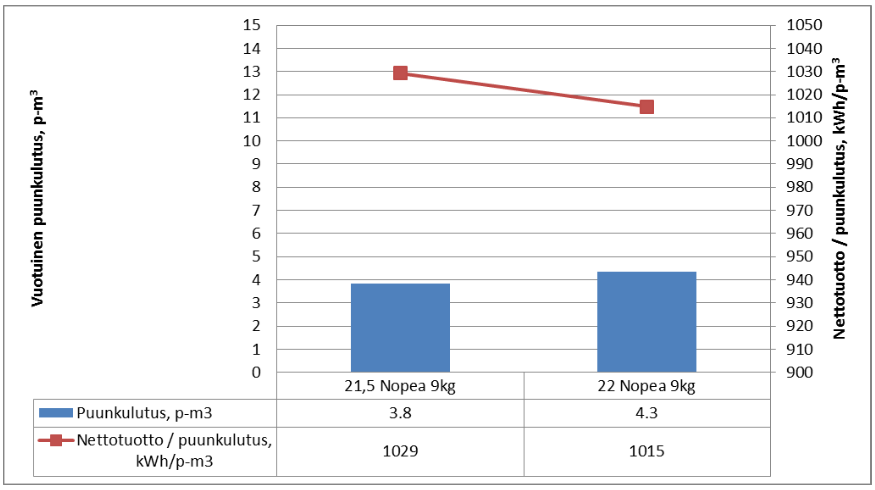


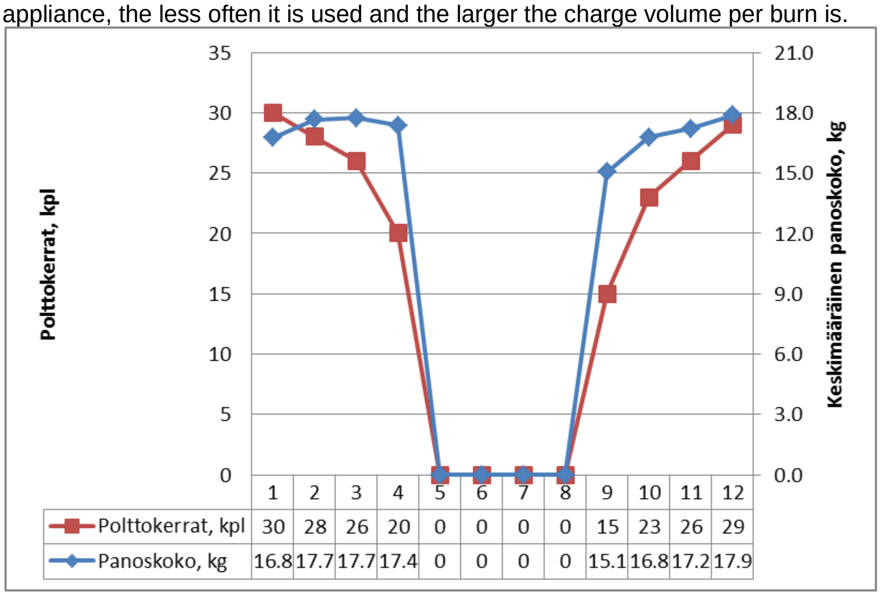

**Figure 19.** Wood consumption and specific net output (net output divided by wood consumption), fast appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

### 6.1.3 Burns and charges

The following illustrates how many times per month the residential solid fuel burning appliances were ignited and what the average charge volumes were for each burn in the computational analysis scenario where the greatest net output was achieved for each appliance (Figures 20–22). The net output figures are given in the previous section.

The average charges were in several cases smaller than the maximum charge. This is because the maximum charge was divided into two or more batches in the simulations: two for the very slow, three for the slow and four for the fast appliance (see Table 13 for details). If the living room temperature rose above the maximum value between the adding of charge batches to the fire, the charge was not replenished.

The single-storey old building has such a high heat demand that all appliances were used often. As a general observation, we may note that the slower the appliance, the less often it is used and the larger the charge volume per burn is.




Number of burns
Average charge, kg
Number of burns
Charge, kg

**Figure 20.** Monthly burns and average charge volumes per burn, very slow appliance, room temperature maximum value +22 °C, charge 18 kg.

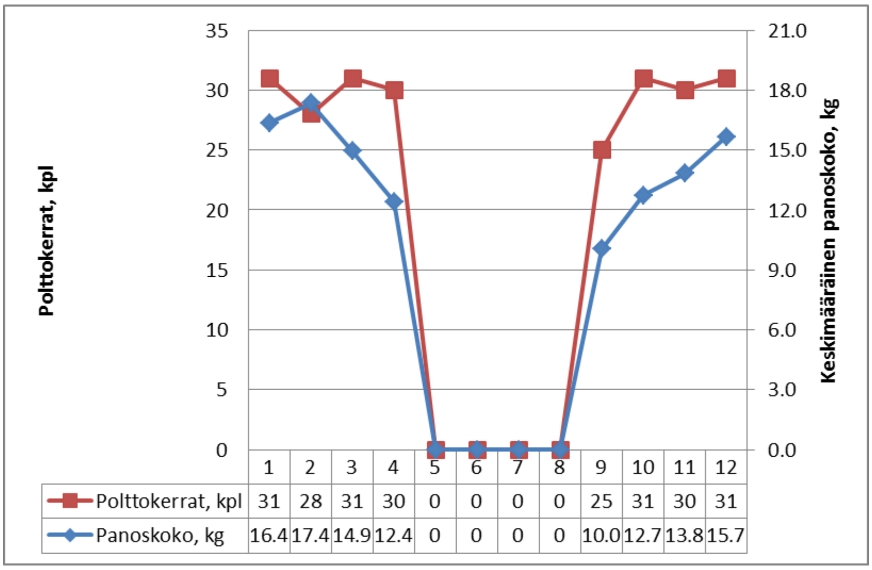



**Figure 21.** Monthly burns and average charge volumes per burn, slow appliance, room temperature maximum value +22 °C, charge 18 kg.

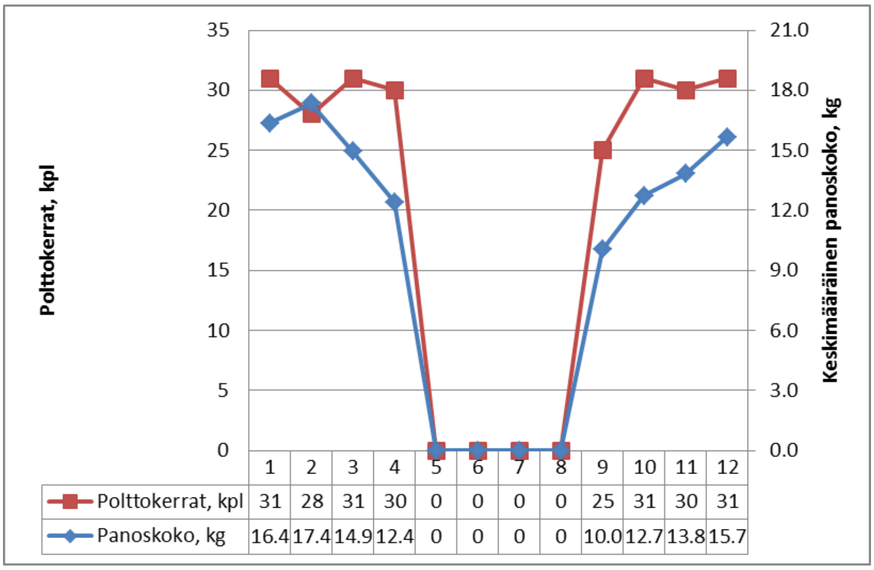



**Figure 22.** Monthly burns and average charge volumes per burn, fast appliance, room temperature maximum value +22 °C, maximum charge 9 kg.

Annual number of burns and annual average charge volumes are shown in Table 15.

**Table 15.** Annual burns and average charge volumes.

| Appliance | Average charge kg | Average number of burns per year |
|---|---|---|
| Very slow | 17.2 | 197 |
| Slow | 14.2 | 237 |
| Fast | 4.3 | 242 |

## 6.2 Single-storey renovated building

All three types of appliance were used in the building: fast, slow and very slow. Also, two different charges were used for the appliances, a 9 kg charge and an 18 kg charge.

The aim was to use the appliances as much as possible, albeit with an upper limit to the room temperature. In each simulation, a maximum value was entered for room temperature; if the temperature was above the maximum at the ignition time specified for the appliance, ignition was deferred; or if the maximum was exceeded during the burn, the charge was not replenished at the set time. The time of ignition was set at 18.00 for every day. All analyses were computed with three maximum values for the room temperature: 21.5 °C, 22 °C and 25 °C.

### 6.2.1 Temperature

There were three simulation scenarios each for the very slow and slow appliances that were acceptable in terms of their temperature conditions, and two for the fast appliance (Table 16).

**Table 16.** Simulation scenarios where temperature in the living room was acceptable.

| Appliance | Charge | Living room temperature maximum | | |
|---|---|---|---|---|
| | | 21.5 °C | 22 °C | 25 °C |
| Very slow | 9 kg | Acceptable | Acceptable | X |
| | 18 kg | Acceptable | X | X |
| Slow | 9 kg | Acceptable | Acceptable | X |
| | 18 kg | Acceptable | X | X |
| Fast | 9 kg | Acceptable | Acceptable | X |
| | 18 kg | X | X | X |

Figure 23 shows as an example how the temperature in the living room varied during the months in which the appliance was in operation in the case where the net heat output in the single-storey renovated house was the greatest (very slow appliance, charge 18 kg, room temperature maximum 21.5 °C). For comparison, Figure 24 shows the same scenario without the use of the appliance. The temperature conditions are described in more detail in Appendix A, where the living room temperatures by month are give for all appliances and several scenarios.

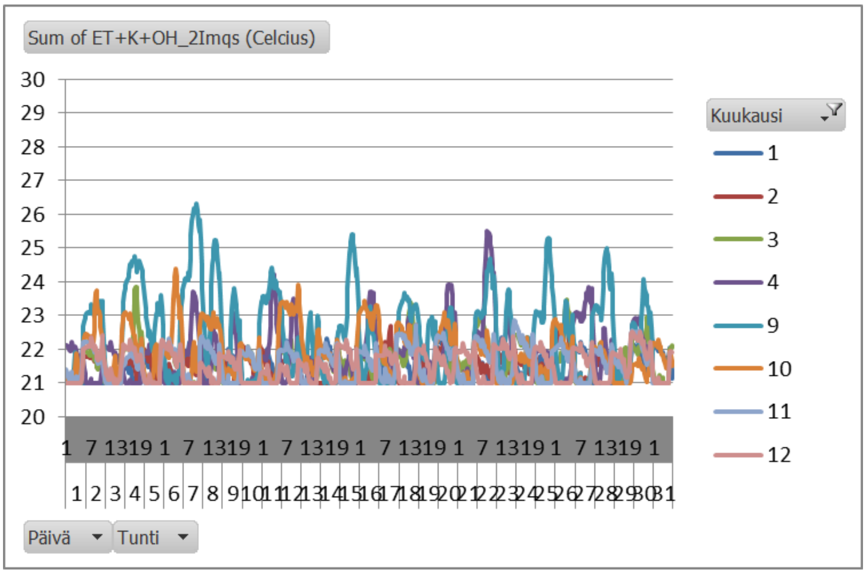



**Figure 23.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

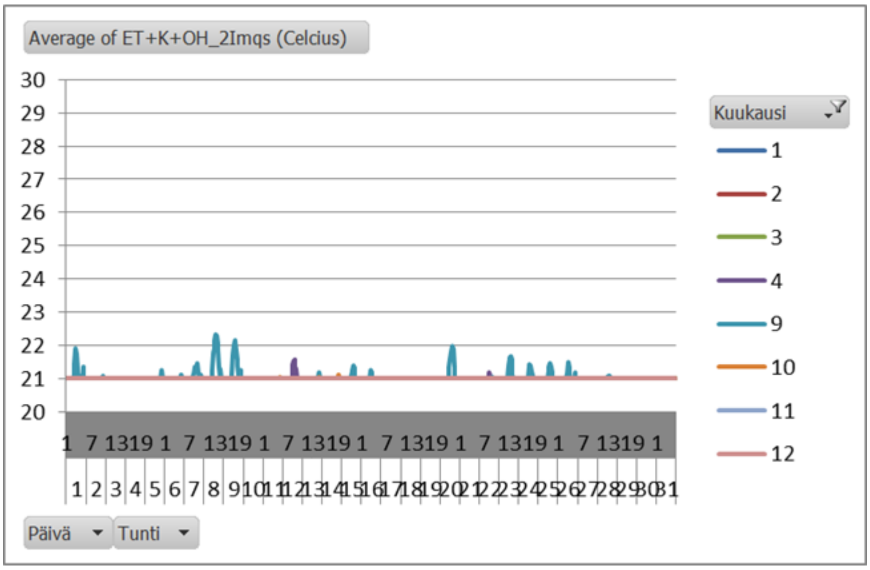



**Figure 24.** Living room temperatures during the heating season (September to April), appliance not in use.

### 6.2.2 Residential solid fuel burning appliances: net heat release, percentage of total heat demand and wood consumption

For the very slow (Figure 25) and slow (Figure 26) appliances, the annual net heat output is about 10,000 kWh at its highest; this figure is attained with a heat release efficiency of about 90%. For the fast appliance (Figure 27), the net heat output is a little over a third of that of the very slow and slow appliances, at best almost 3,500 kWh per year with a heat release efficiency of about 90%.

The very slow (Figure 25) and slow (Figure 26) appliances contribute about 55% of the total heating demand of the rooms in the building at their best, while the fast appliance (Figure 27) remains below 20%.

Wood consumption corresponding to the net output of the appliances is shown in Figures 26, 28 and 30.

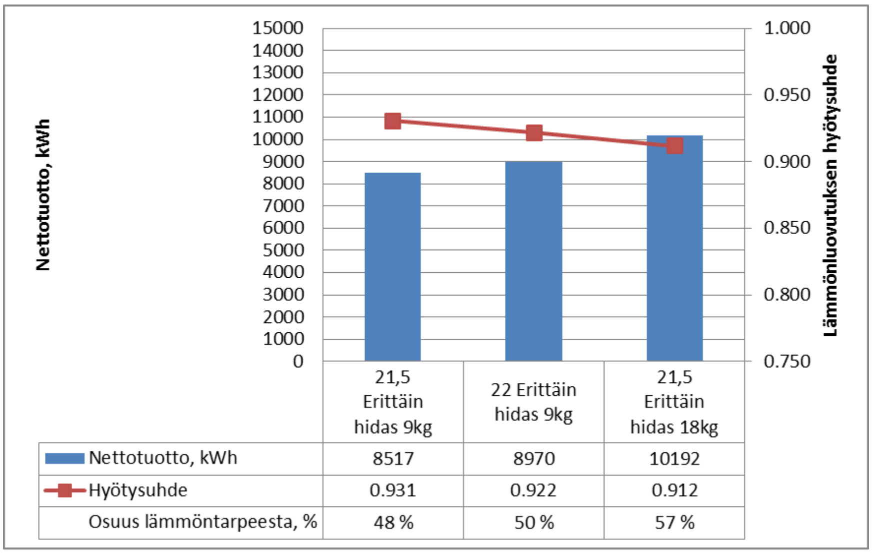



**Figure 25.** Net heating energy output, heat release efficiency and percentage of net output out of the total heating demand of the rooms in the building, very slow appliance.

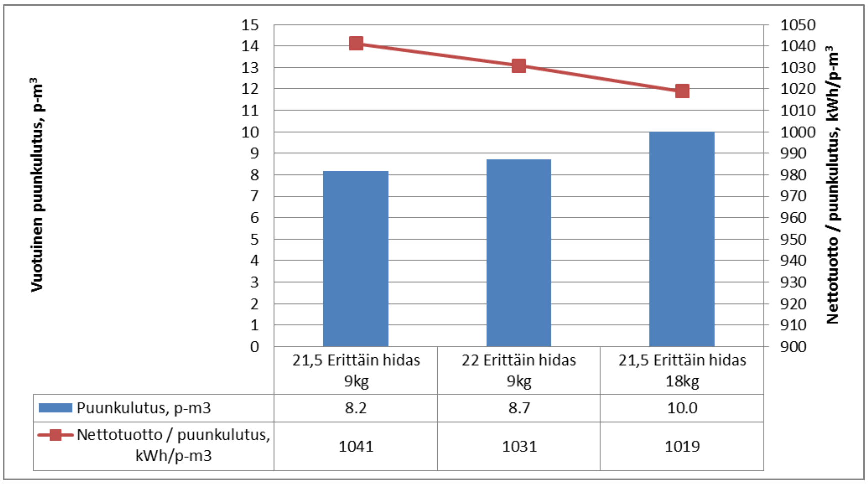



**Figure 26.** Wood consumption and specific net output (net output divided by wood consumption), very slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

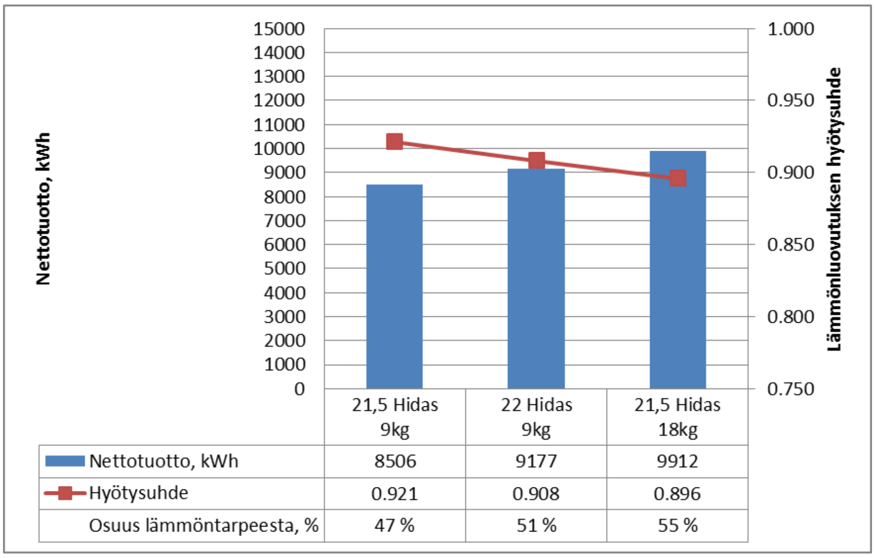



**Figure 27.** Net heating energy output and heat release efficiency, slow appliance.


**Figure 28.** Wood consumption and specific net output (net output divided by wood consumption), slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

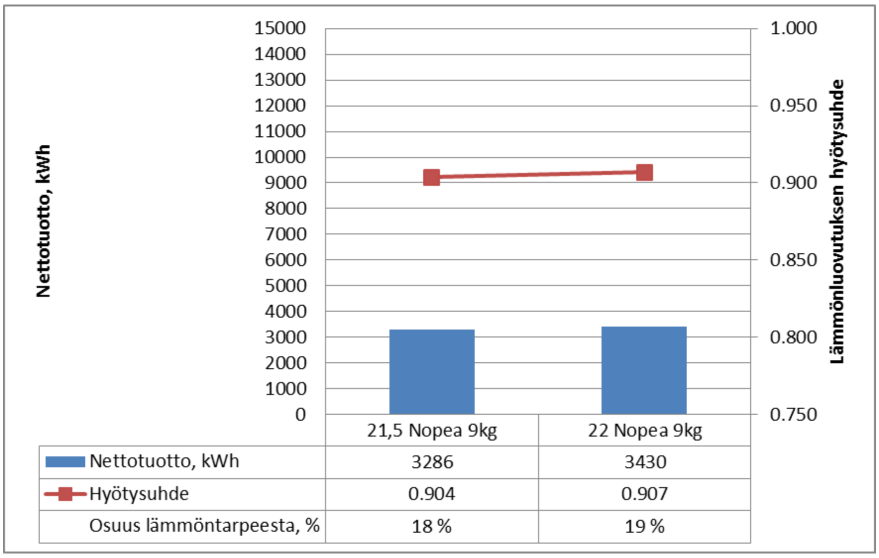



**Figure 29.** Net heating energy output and heat release efficiency, fast solid fuel appliance.

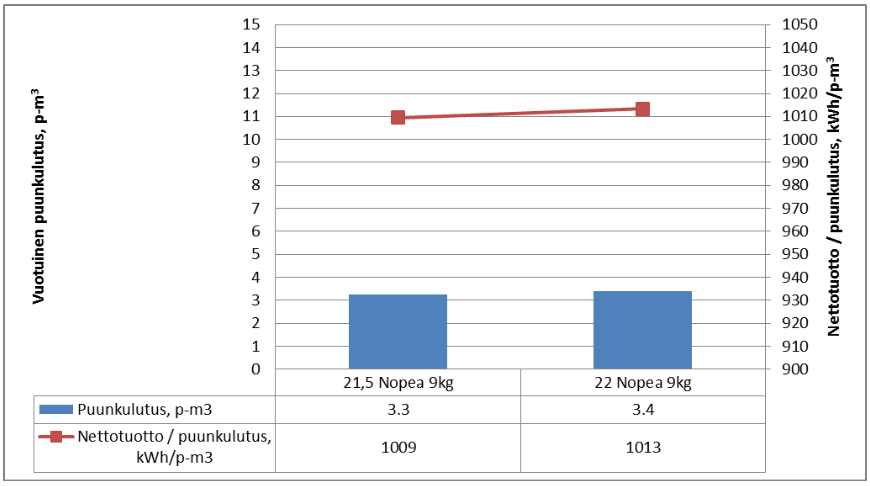



**Figure 30.** Wood consumption and specific net output (net output divided by wood consumption), fast appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

### 6.2.3 Burns and charges

The following illustrates how many times per month the residential solid fuel burning appliances were ignited and what the average charge volumes were for each burn in the computational analysis scenario where the greatest net output was achieved for each appliance (Figures 31–33). The net output figures are given in the previous section.

The average charges were in several cases smaller than the maximum charge. This is because the maximum charge was divided into two or more batches in the simulations: two for the very slow, three for the slow and four for the fast appliance (see Table 13 for details). If the living room temperature rose above the maximum value between the adding of charge batches to the fire, the charge was not replenished.

The single-storey renovated building has such a high heat demand that all appliances were used often. As a general observation, we may note that the slower the appliance, the less often it is used and the larger the charge volume per burn is.

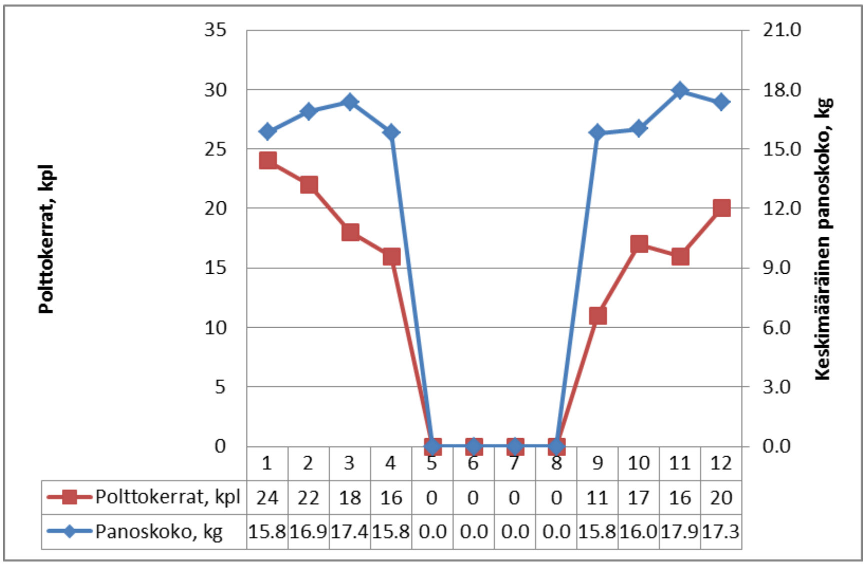



**Figure 31.** Monthly burns and average charge volumes per burn, very slow appliance, room temperature maximum value +21.5 °C, charge 18 kg.

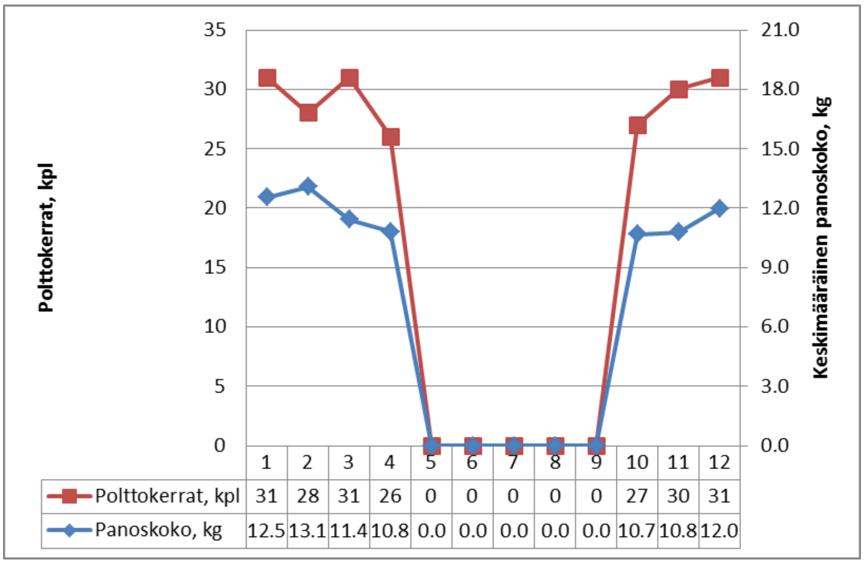



**Figure 32.** Monthly burns and average charge volumes per burn, slow appliance, room temperature maximum value +21.5 °C, charge 18 kg.

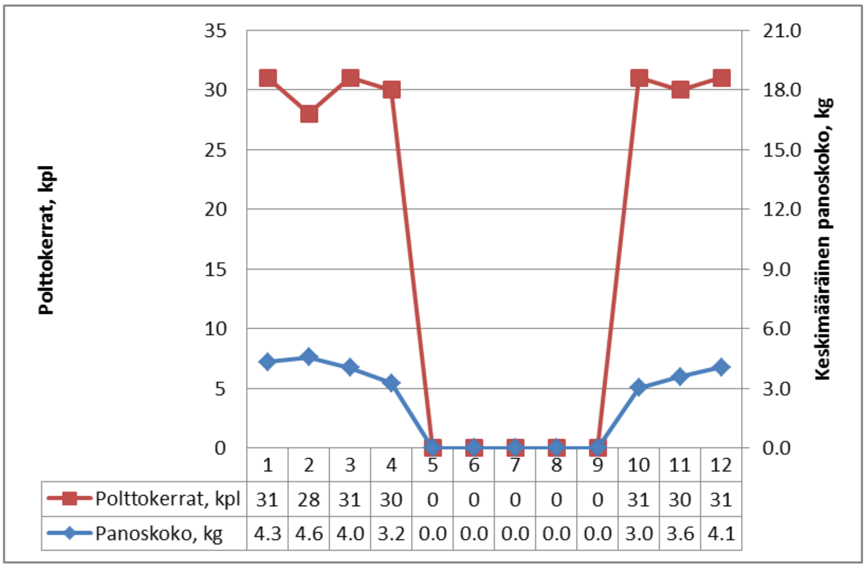



**Figure 33.** Monthly burns and average charge volumes per burn, fast appliance, room temperature maximum value +22 °C, maximum charge 9 kg.

Annual number of burns and annual average charge volumes are shown in Table 17.

**Table 17.** Annual burns and average charge volumes.

| Appliance | Average charge kg | Average number of burns per year |
|---|---|---|
| Very slow | 16.6 | 144 |
| Slow | 11.6 | 204 |
| Fast | 3.8 | 212 |

## 6.3 Two-storey new building

All three types of appliance were used in the building: fast, slow and very slow. Also, two different charges were used for the appliances, a 9 kg charge and an 18 kg charge.

The aim was to use the appliances as much as possible, albeit with an upper limit to the room temperature. In each simulation, a maximum value was entered for room temperature; if the temperature was above the maximum at the ignition time specified for the appliance, ignition was deferred. If the maximum value was exceeded during the burn, the charge was not replenished. The time of ignition was set at 18.00 for every day. All analyses were computed with three maximum values for the room temperature: 21.5 °C, 22 °C and 25 °C.

### 6.3.1 Temperature

There were two simulation scenarios for the very slow appliance that were acceptable in terms of their temperature conditions, and only one each for the slow and fast appliance (Table 18).

**Table 18.** Simulation scenarios where temperature in the living room was acceptable.

| Appliance | Charge | Living room temperature maximum | | |
|---|---|---|---|---|
| | | 21.5 °C | 22 °C | 25 °C |
| Very slow | 9 kg | Acceptable | Acceptable | X |
| | 18 kg | X | X | X |
| Slow | 9 kg | Acceptable | X | X |
| | 18 kg | X | X | X |
| Fast | 9 kg | Acceptable | X | X |
| | 18 kg | X | X | X |

Figure 34 shows as an example how the temperature in the living room varied during the months in which the appliance was in operation in the scenario where the net heat output in the two-storey new building was the greatest (very slow appliance, charge 9 kg, room temperature maximum 22 °C). For comparison, Figure 35 shows the same scenario without the use of the appliance. The temperature conditions are described in more detail in Appendix A, where the living room temperatures by month are give for all appliances and several scenarios.

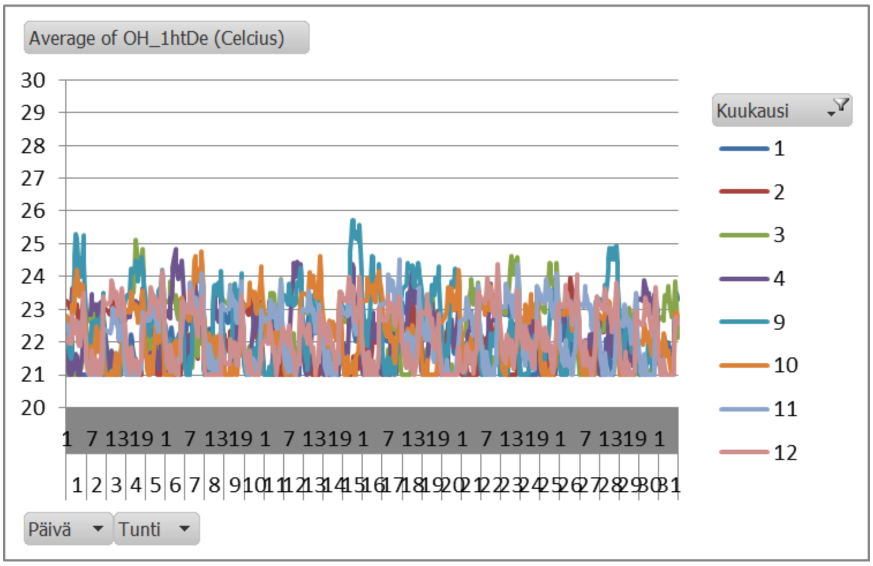



**Figure 34.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 22 °C, charge 9 kg.

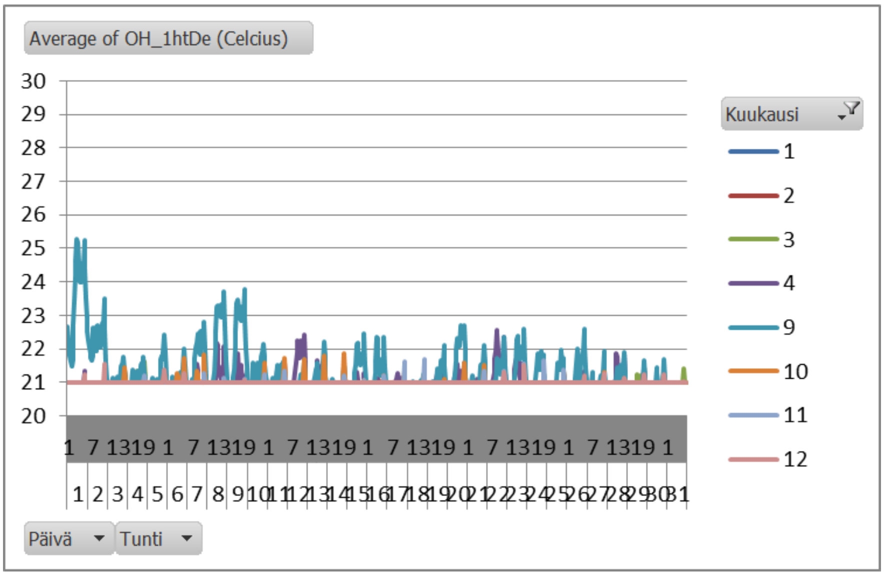



**Figure 35.** Living room temperatures during the heating season (September to April), appliance not in use.

### 6.3.2 Residential solid fuel burning appliances: net heat release, percentage of total heat demand and wood consumption

For the very slow (Figure 36) and slow (Figure 38) appliances, the annual net heat output is about 4,000 kWh at its highest; this figure is attained with a heat release efficiency of about 90%. For the fast appliance (Figure 40), the net heat output is less than one fourth of that of the very slow and slow appliances, at best less than 900 kWh per year with a heat release efficiency of about 90%.

The very slow (Figure 36) and slow (Figure 38) appliances contribute just over 40% of the total heating demand of the rooms in the building in the best scenarios, while the fast appliance (Figure 40) remains under 10%.

The operating season for the very slow and slow appliances is from September to April, but for the fast appliance it is only three months, from December to February.

Wood consumption corresponding to the net output of the appliances is shown in Figures 37, 39 and 41.

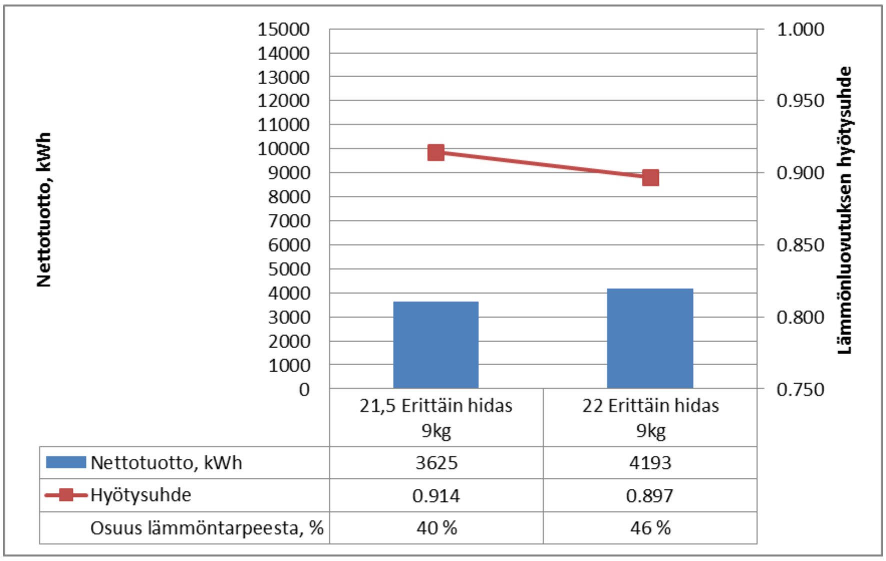



**Figure 36.** Net heating energy output, heat release efficiency and percentage of net output out of the total heating demand of the rooms in the building, very slow appliance.

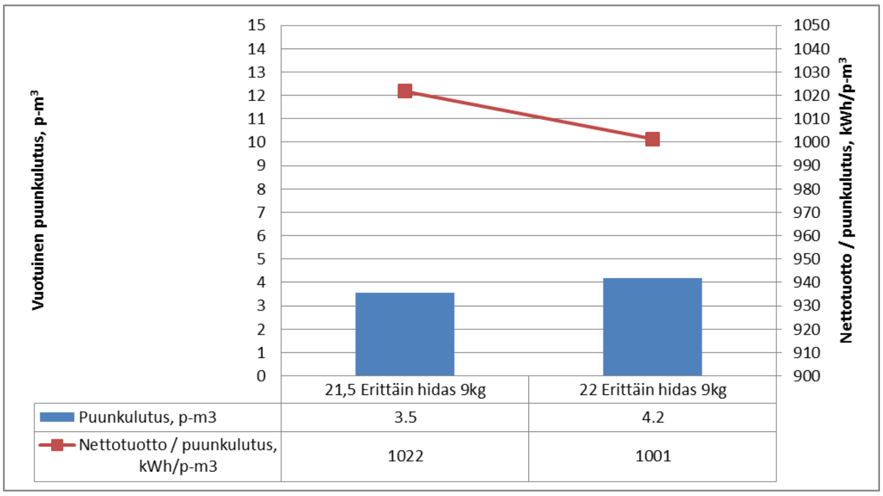



**Figure 37.** Wood consumption and specific net output (net output divided by wood consumption), very slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

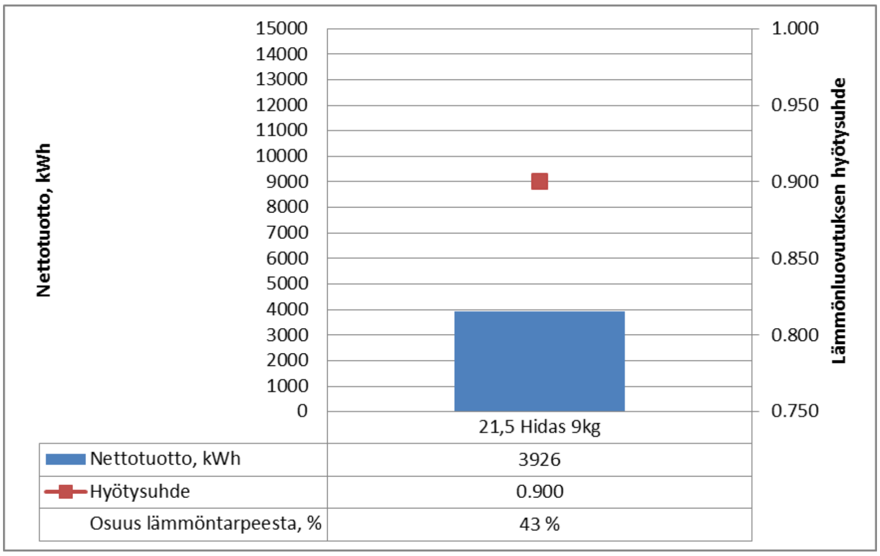



**Figure 38.** Net heating energy output and heat release efficiency, slow appliance.

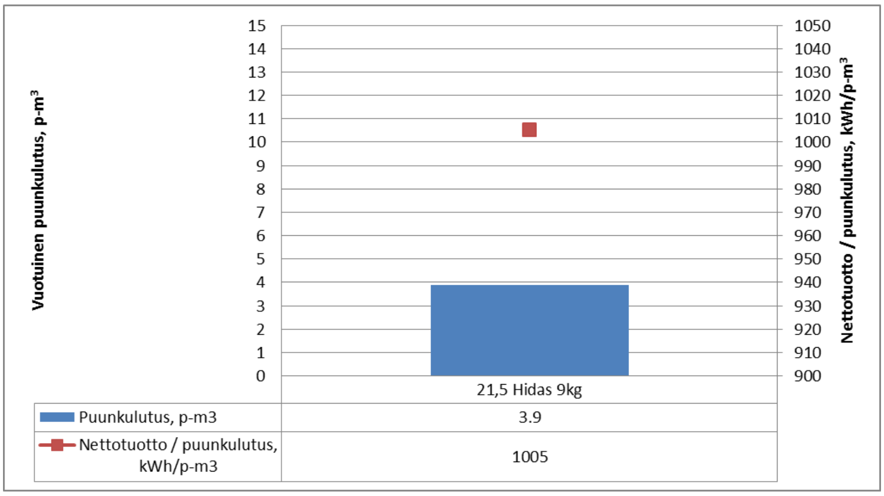



**Figure 39.** Wood consumption and specific net output (net output divided by wood consumption), slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

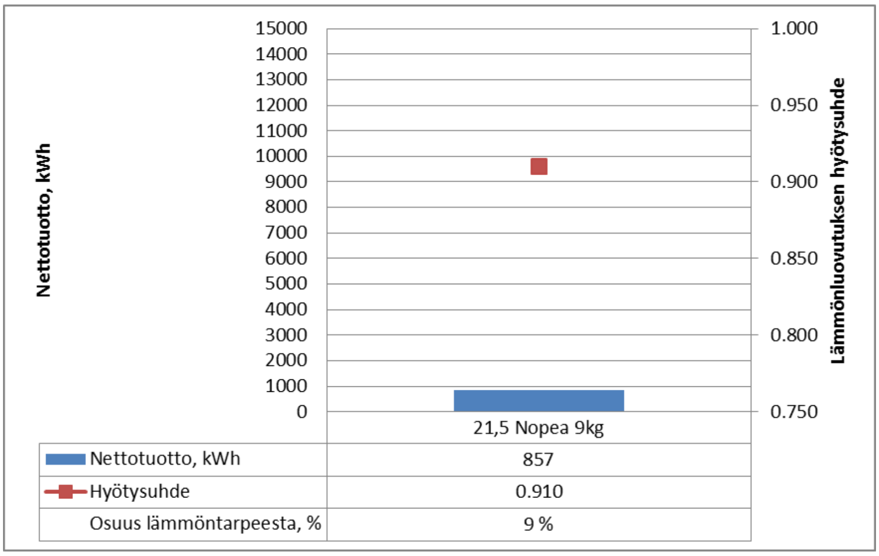



**Figure 40.** Net heating energy output and heat release efficiency, fast appliance.

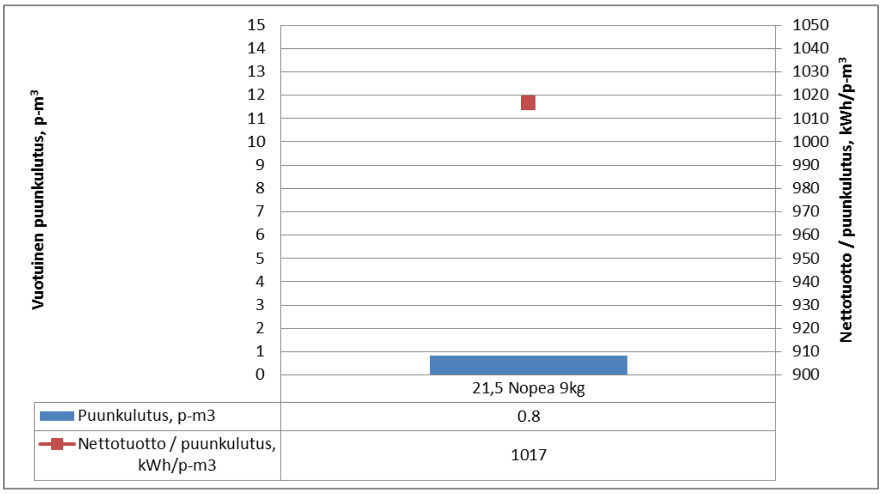



**Figure 41.** Wood consumption and specific net output (net output divided by wood consumption), fast appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

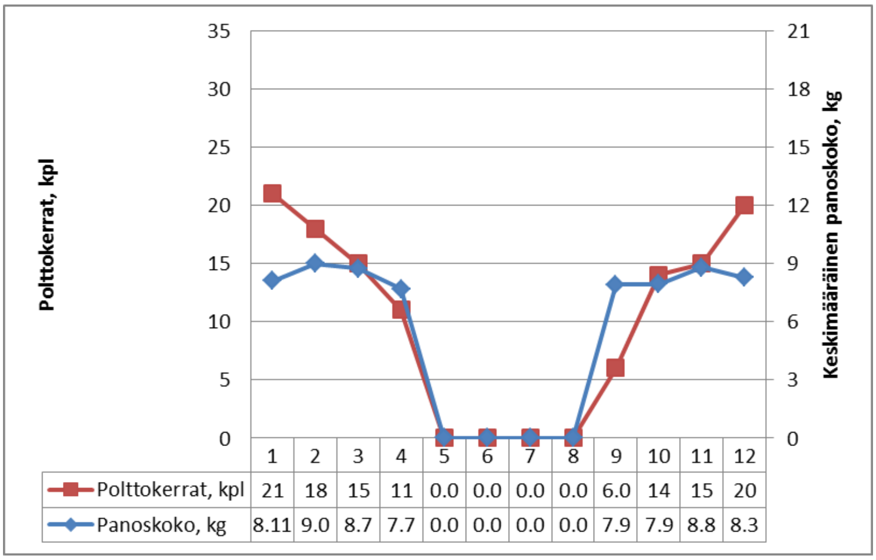
### 6.3.3 Burns and charges

The following illustrates how many times per month the residential solid fuel burning appliances were ignited and what the average charge volumes were for each burn in the computational analysis scenario where the greatest net output was achieved for each appliance (Figures 42–44). The net output figures are given in the previous section.

The average charges were in several cases smaller than the maximum charge. This is because the maximum charge was divided into two or more batches in the simulations: two for the very slow, three for the slow and four for the fast appliance (see Table 13 for details). If the living room temperature rose above the maximum value between the adding of charge batches to the fire, the charge was not replenished.

The heat demand in the two-storey new building is considerably lower than in the single-storey old building. Nevertheless, all appliances were used often; however, the actual charge volumes for the slow and fast appliances remained much smaller than the maximum charges. As a general observation, we may note that the slower the appliance, the less often it is used and the larger the charge volume per burn is.

We should also note that the operating seasons for the various appliances differ: the very slow and slow appliances are in use from September to April, while the fast appliance is only in use for three months, from December to February.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Polttokerrat, kpl | 21 | 18 | 15 | 11 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 14 | 15 | 20 |
| Panoskoko, kg | 8.11 | 9.0 | 8.7 | 7.7 | 0.0 | 0.0 | 0.0 | 0.0 | 7.9 | 7.9 | 8.8 | 8.3 |

**Figure 42.** Monthly burns and average charge volumes per burn, very slow appliance, room temperature maximum value +22 °C, maximum charge 9 kg.

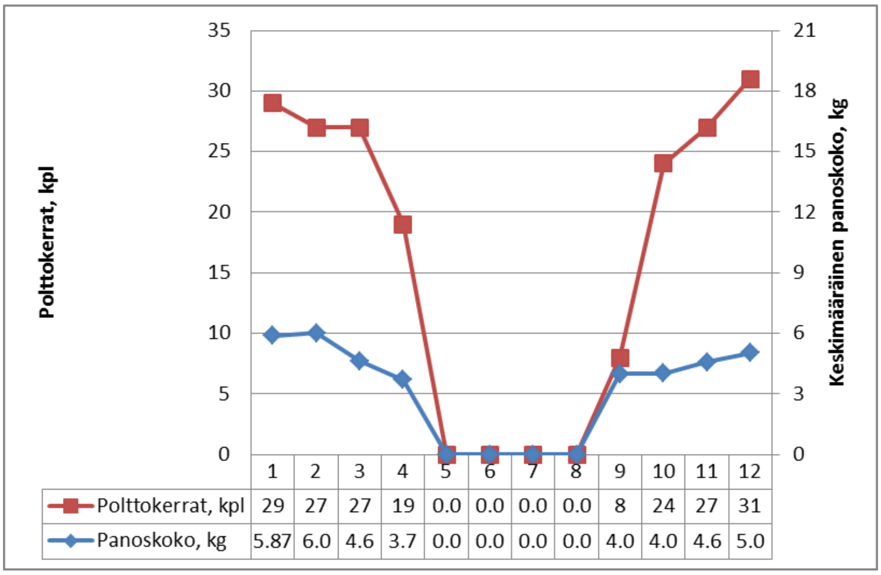



**Figure 43.** Monthly burns and average charge volumes per burn, slow appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg.

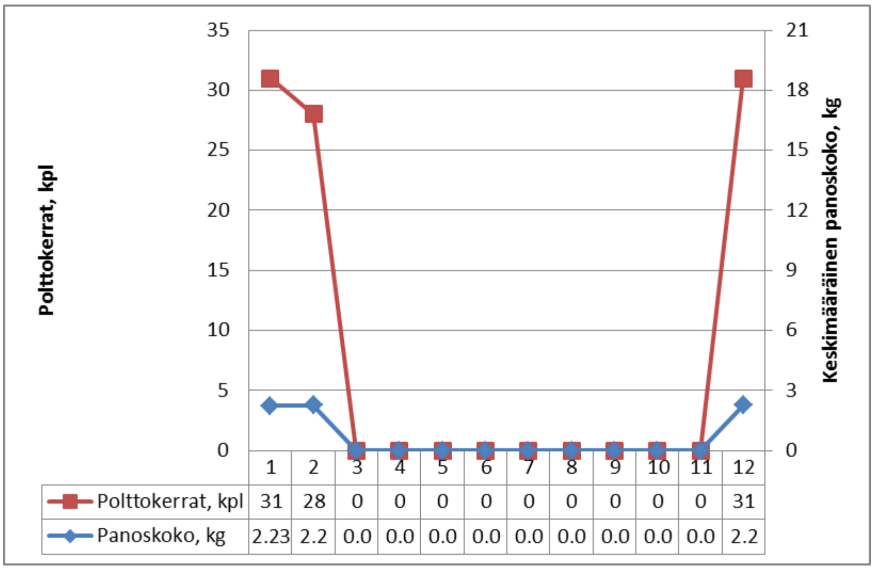



**Figure 44.** Monthly burns and average charge volumes per burn, fast appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg.

Annual number of burns and annual average charge volumes are shown in Table 19.

**Table 19.** Annual burns and average charge volumes.

| Appliance | Average charge kg | Average number of burns per year |
|---|---|---|
| Very slow | 8.7 | 120 |
| Slow | 4.9 | 192 |
| Fast | 2.2 | 90 |

## 6.4 Two-storey passive building

All three types of appliance were used in the building: fast, slow and very slow. Also, two different maximum charges were used for the appliances, a 9 kg charge and an 18 kg charge.

The aim was to use the appliances as much as possible, albeit with an upper limit to the room temperature. In each simulation, a maximum value was entered for room temperature; if the temperature was above the maximum at the ignition time specified for the appliance, ignition was deferred. If the maximum value was exceeded during the burn, the charge was not replenished. The time of ignition was set at 18.00 for every day. All analyses were computed with three maximum values for the room temperature: 21.5 °C, 22 °C and 25 °C.

### 6.4.1 Temperature

{0>Here, for each appliance only one simulation scenario was found that was acceptable in terms of temperature conditions (Table 20).

**Table 20.** Simulation scenarios where temperature in the living room was acceptable.

| Appliance | Charge | Living room temperature maximum | | |
|---|---|---|---|---|
| | | 21.5 °C | 22 °C | 25 °C |
| Very slow | 9 kg | Acceptable | X | X |
| | 18 kg | X | X | X |
| Slow | 9 kg | Acceptable | X | X |
| | 18 kg | X | X | X |
| Fast | 9 kg | Acceptable | X | X |
| | 18 kg | X | X | X |

Figure 45 shows as an example how the temperature in the living room varied during the months in which the appliance was in operation in the scenario where the net heat output in the two-storey passive building was the greatest (very slow appliance, charge 9 kg, room temperature maximum 21.5 °C). For comparison, Figure 46 shows the same scenario without the use of the appliance. The temperature conditions are described in more detail in Appendix A, where the living room temperatures by month are give for all appliances and several scenarios.

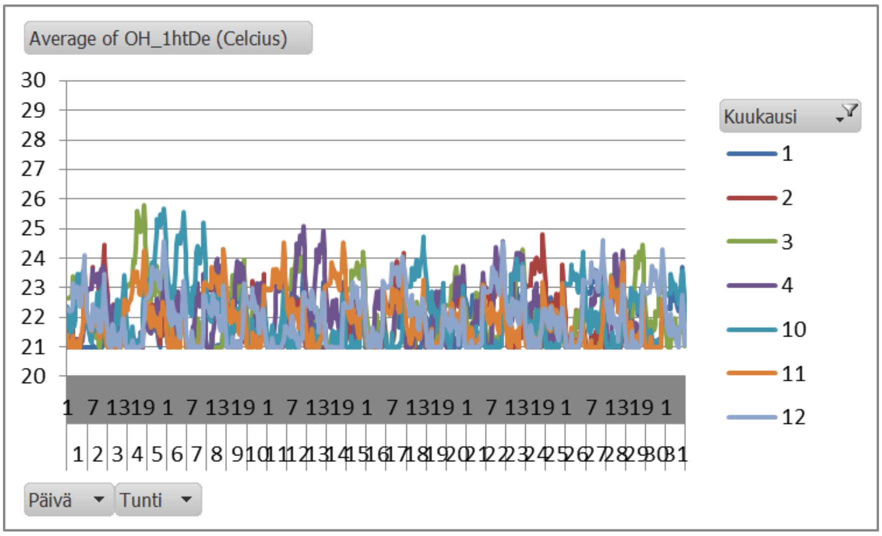



**Figure 45.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

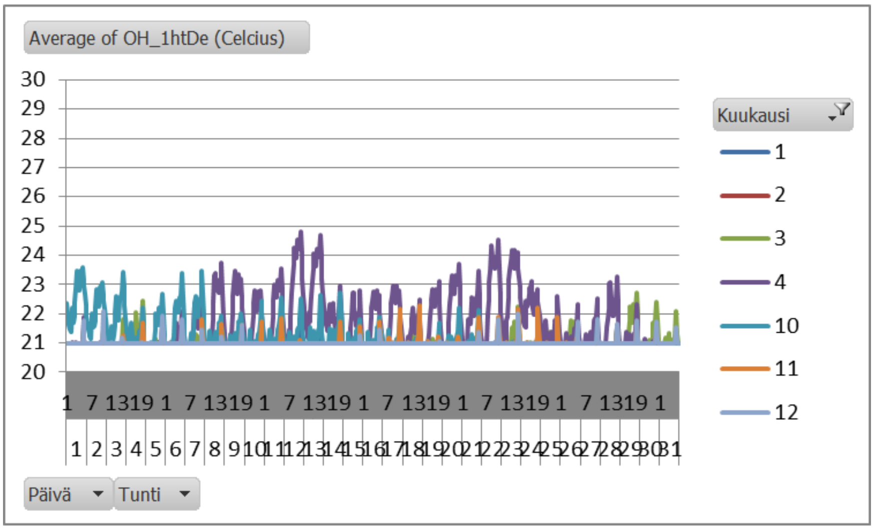



**Figure 46.** Living room temperatures during the heating season (October to April), appliance not in use.

### 6.4.2 Residential solid fuel burning appliances: net heat release, percentage of total heat demand and wood consumption

For the very slow (Figure 47) and slow (Figure 49) appliances, the annual net heat output is about 2,300 kWh at its highest; this figure is attained with a heat release efficiency of about 90%. For the fast appliance (Figure 51), the net heat output is less than one fourth of that of the very slow and slow appliances, at best just over 500 kWh per year with a heat release efficiency of less than 90%.

The very slow (Figure 47) and slow (Figure 49) appliances contribute just over 50% of the total heating demand of the rooms in the building at their best, while the fast appliance (Figure 51) does not go much above 10%.

The operating season for the very slow and slow appliances is from October to April, but for the fast appliance only two months, from January to February.

The behaviour of the passive building with the slow appliance was also analysed in the weather conditions of Sodankylä. The net output of the appliance in Sodankylä (Figure 53) was higher than in Helsinki (Figure 49), but the percentage of the net output out of the total heating demand of the rooms was roughly the same. The heat release efficiency was also very similar with the findings for Helsinki weather.

Wood consumption corresponding to the net output of the appliances is shown for Helsinki weather in Figures 48, 50 and 52 and for Sodankylä weather in Figure 54.

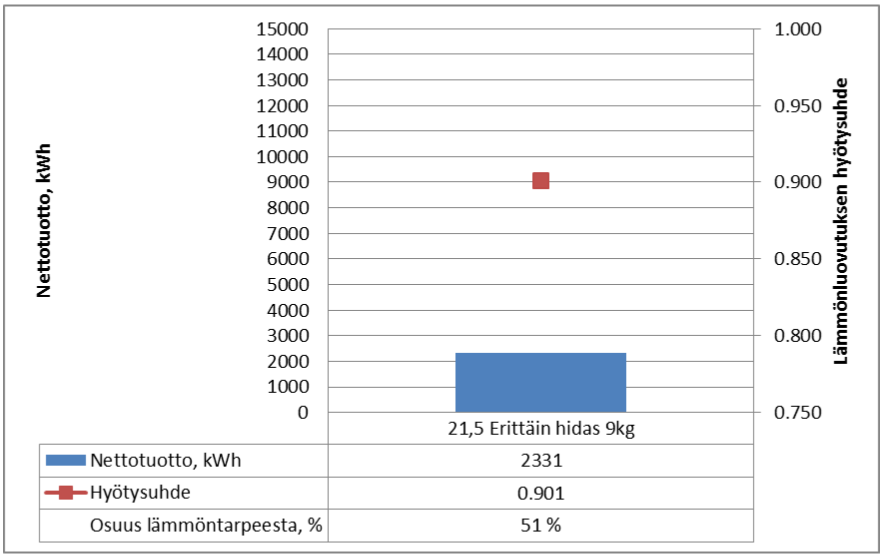



**Figure 47.** Net heating energy output, heat release efficiency and percentage of net output out of the total heating demand of the rooms in the building, very slow appliance.

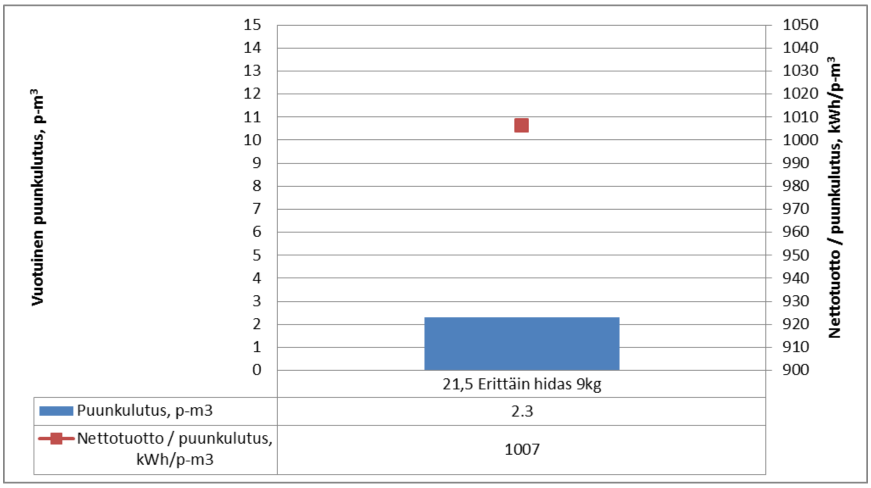



**Figure 48.** Wood consumption and specific net output (net output divided by wood consumption), very slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

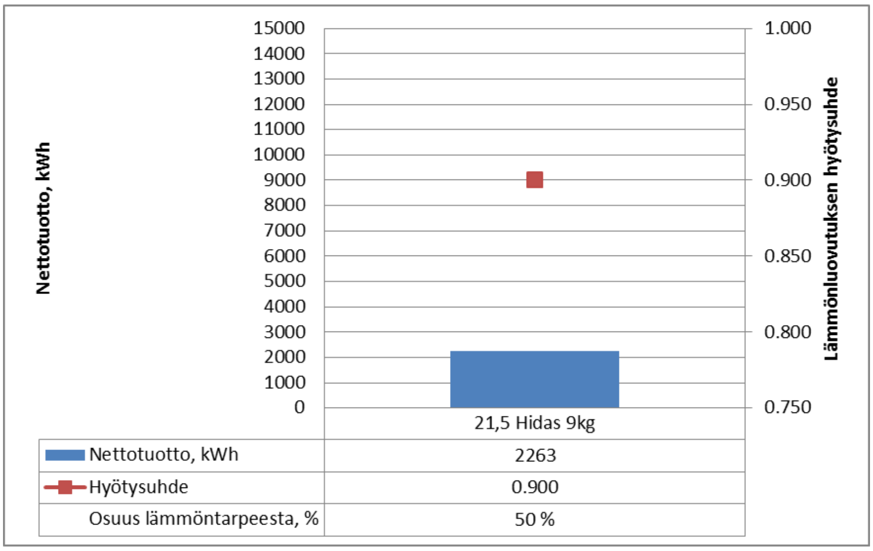



**Figure 49.** Net heating energy output and heat release efficiency, slow appliance.

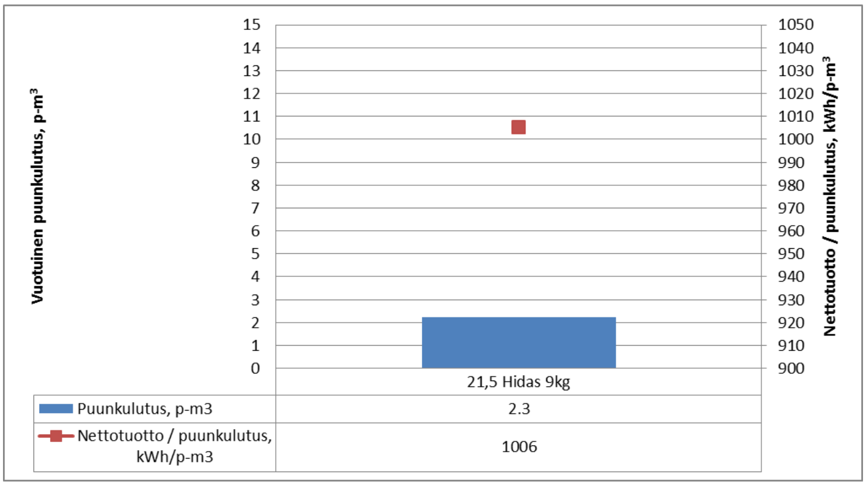



**Figure 50.** Wood consumption and specific net output (net output divided by wood consumption), slow appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

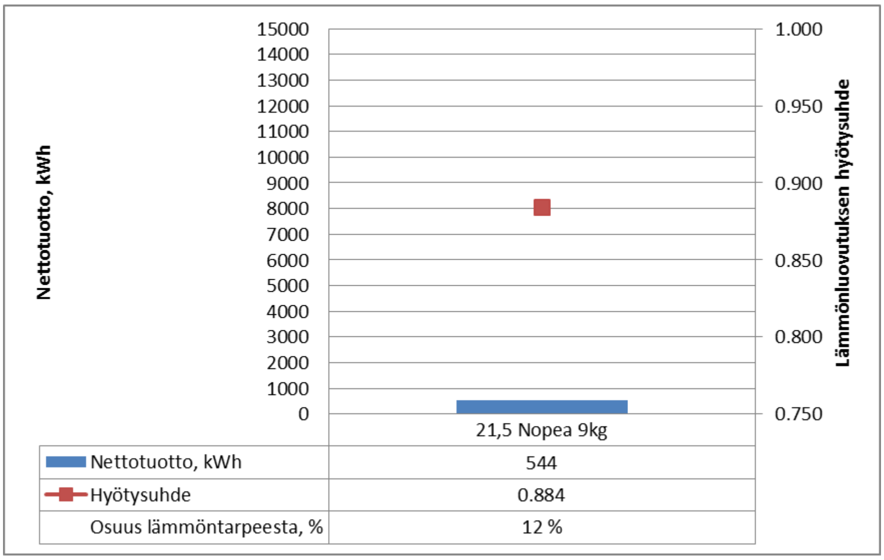



**Figure 51.** Net heating energy output and heat release efficiency, fast appliance.

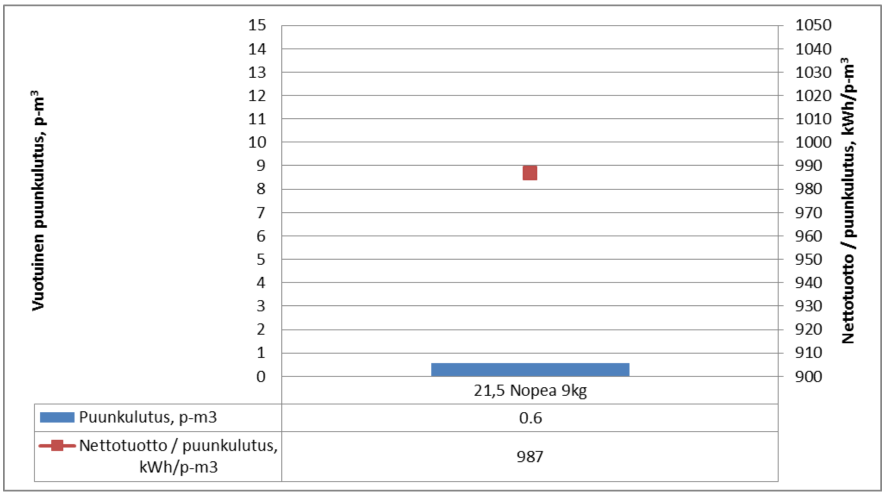



**Figure 52.** Wood consumption and specific net output (net output divided by wood consumption), fast appliance. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

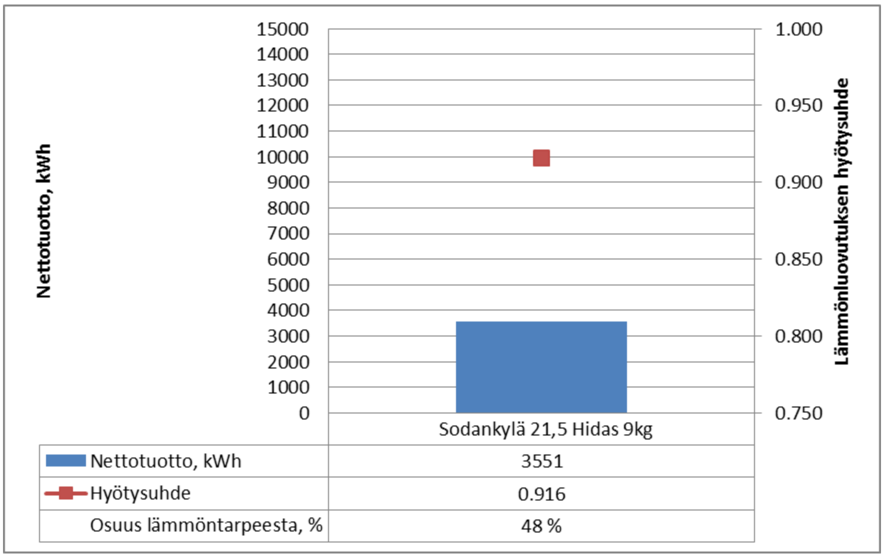



**Figure 53.** Net heating energy output and heat release efficiency, slow appliance, Sodankylä weather.

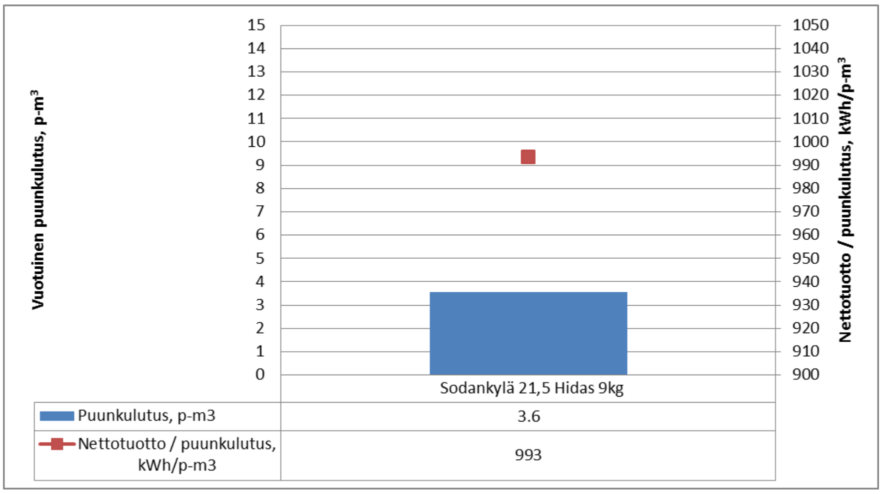



**Figure 54.** Wood consumption and specific net output (net output divided by wood consumption), slow appliance, Sodankylä weather. Combustion efficiency 80% and wood energy content 1,330 kWh per stacked cu.m.

### 6.4.3 Burns and charges

The following illustrates how many times per month the residential solid fuel burning appliances were ignited and what the average charge volumes were for each burn in the computational analysis scenario where the greatest net output was achieved for each appliance (Figures 55–58). The net output figures are given in the previous section.

The average charges were in several cases smaller than the maximum charge. This is because the maximum charge was divided into two or more batches in the simulations: two for the very slow, three for the slow and four for the fast appliance (see Table 13 for details). If the living room temperature rose above the maximum value between the adding of charge batches to the fire, the charge was not replenished.

The heat demand in the two-storey passive building is considerably lower than in the single-storey old building. Nevertheless, all appliances were used often; however, the actual charge volumes for the slow and fast appliances remained much smaller than the maximum charges. As a general observation, we may note that the slower the appliance, the less often it is used and the larger the charge volume per burn is.

We should also note that the operating seasons for the various appliances differ: the very slow and slow appliances are in use from October to April, while the fast appliance is only in use for two months, from January to February.

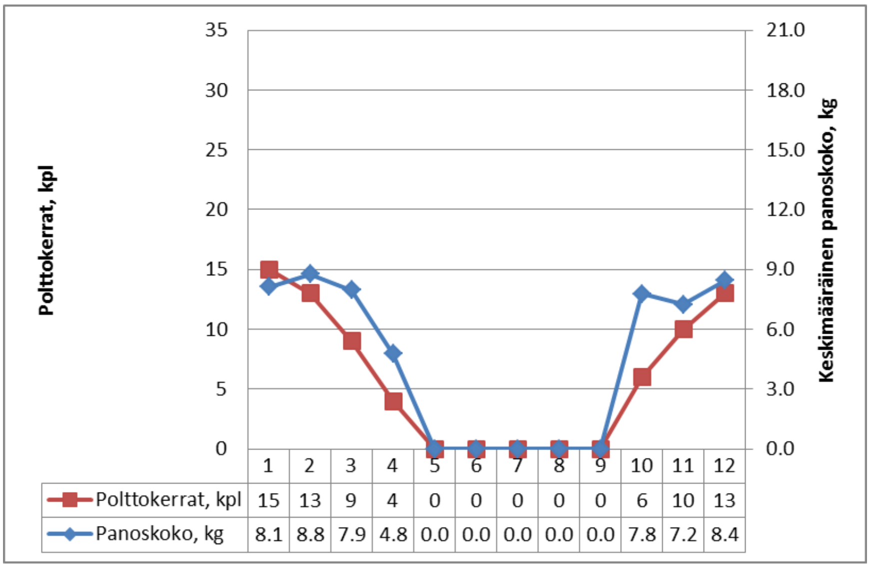



**Figure 55.** Monthly burns and average charge volumes per burn, very slow appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg.

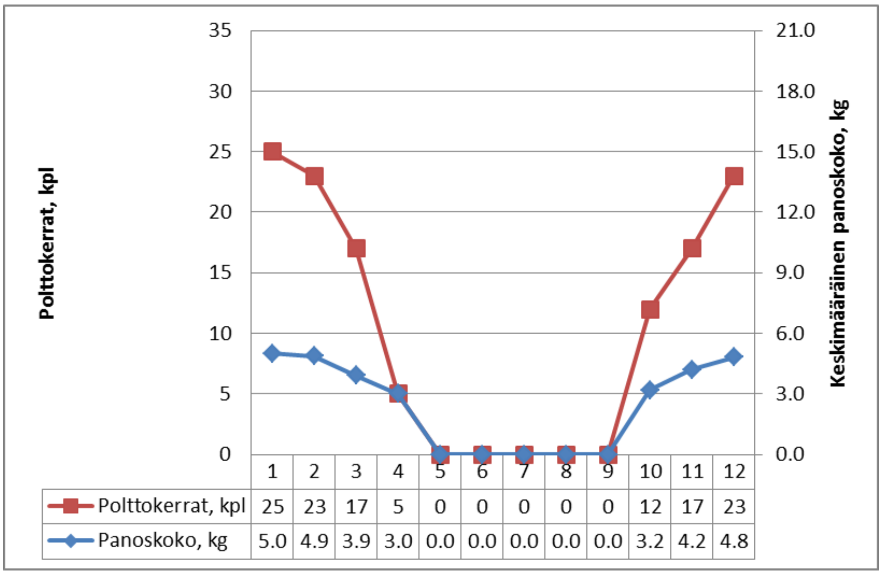



**Figure 56.** Monthly burns and average charge volumes per burn, slow appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg.

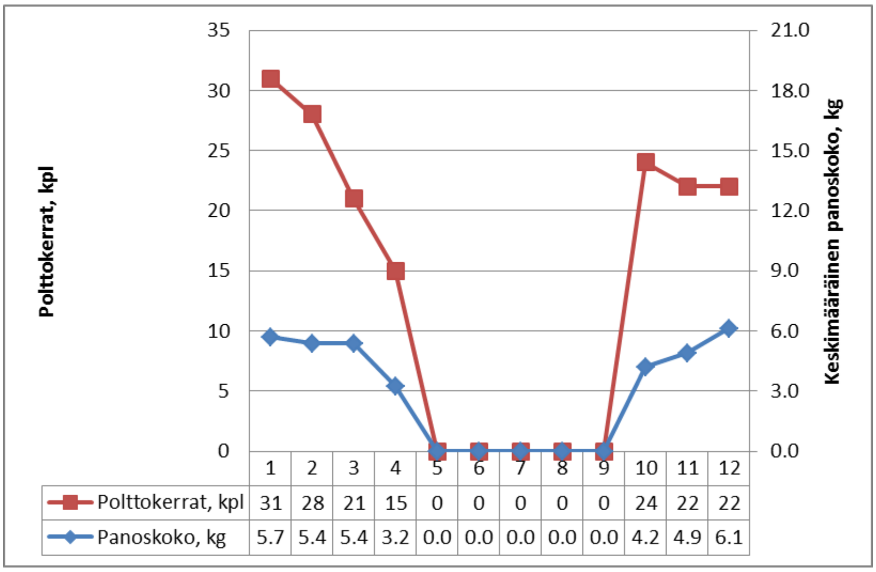



**Figure 57.** Monthly burns and average charge volumes per burn, slow appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg, Sodankylä weather.

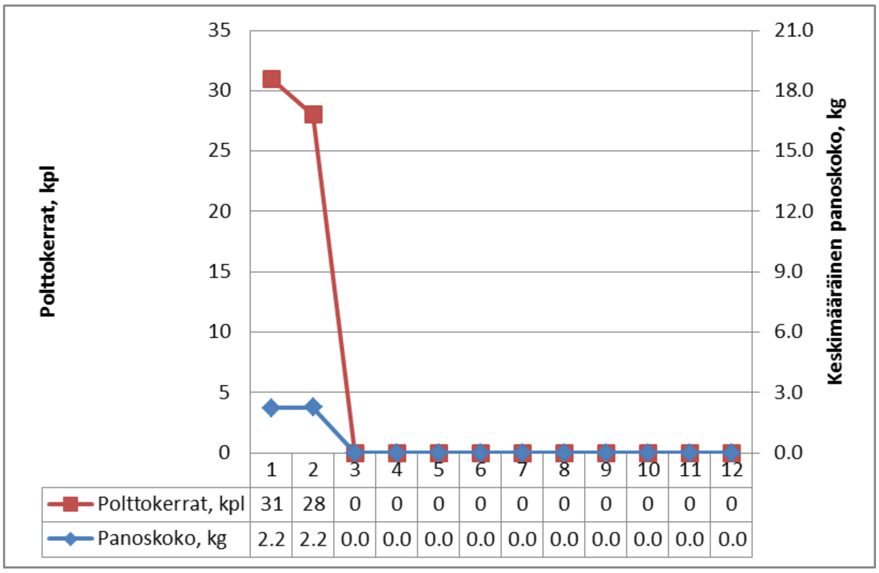



**Figure 58.** Monthly burns and average charge volumes per burn, fast appliance, room temperature maximum value +21.5 °C, maximum charge 9 kg.

Annual number of burns and annual average charge volumes are shown in Table 21. Scenarios with Sodankylä weather were only analysed for the slow appliance.

**Table 21.** Annual burns and average charge volumes. The impact of changing weather conditions was only analysed for the slow appliance.

| **Appliance** | **Average charge Helsinki / Sodankylä kg** | **Average number of burns Helsinki / Sodankylä per year** |
|---|---|---|
| Very slow | 7.9 | 70 |
| Slow | 4.4 / 5.1 | 122 / 163 |
| Fast | 2.2 | 59 |

### 6.4.4 Summary of net output, heat release efficiency and wood consumption

The principal objective of the project was to determine the maximum net output of heating energy of the residential solid fuel burning appliances studied and the corresponding heat release efficiency values. The following tables (Tables 22–24) contain a summary of the project computation results. The maximum net output values for heating energy can be achieved by active use of the appliance in all scenarios.

With the fast appliance in the two-storey buildings, where the heating demand was lower than in the single-storey building, the temperature in the living room easily exceeded the specified maximum even with small wood charges when the appliance was used. Therefore, indicative figures are given for the fast appliance in the two-storey buildings, only defined for a couple of winter months.

**Table 22.** Very slow appliance, maximum net output of heating energy, percentage of net output out of the total heating energy demand of the rooms, heat release efficiency and annual wood consumption. In calculating wood consumption, it was assumed that the appliance has a combustion efficiency of 80% and that the specific energy of the wood is 1,330 kWh per stacked cu.m.

| | **Single-storey old** | **Single-storey renovated** | **Two-storey new** | **Two-storey passive** |
|---|---|---|---|---|
| Appliance net output | 14,400 kWh/a | 10,200 kWh/a | 4,200 kWh/a | 2,300 kWh/a |
| Net output as percentage of total heating demand | 57 % | 57 % | 46 % | 51 % |
| Heat release efficiency | 91 % | 91 % | 90 % | 90 % |
| Wood consumption | 14.1 stacked cu.m / a | 10.0 stacked cu.m / a | 4.2 stacked cu.m / a | 2.3 stacked cu.m / a |
| Burns per year | 197 | 144 | 114 | 70 |

**Table 23.** Slow appliance, maximum net output of heating energy, percentage of net output out of the total heating energy demand of the rooms, heat release efficiency and annual wood consumption. In calculating wood consumption, it was assumed that the appliance has a combustion efficiency of 80% and that the specific energy of the wood is 1,330 kWh per stacked cu.m.

| | **Single-storey old** | **Single-storey renovated** | **Two-storey new** | **Two-storey passive** |
|---|---|---|---|---|
| Appliance net output | 14,100 kWh/a | 9,900 kWh/a | 3,900 kWh/a | 2,200 kWh/a |
| Net output as percentage of total heating demand | 56 % | 55 % | 43 % | 50 % |
| Heat release efficiency | 90 % | 90 % | 90 % | 90 % |
| Wood consumption | 14.1 stacked cu.m / a | 9.9 stacked cu.m / a | 3.9 stacked cu.m / a | 2.3 stacked cu.m / a |
| Burns per year | 237 | 204 | 192 | 122 |

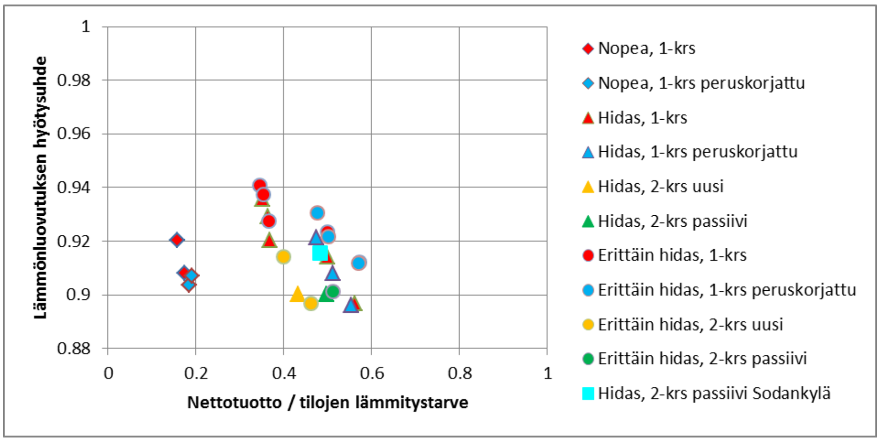
**Table 24.** Fast appliance, maximum net output of heating energy, percentage of net output out of the total heating energy demand of the rooms, heat release efficiency

and annual wood consumption. In calculating wood consumption, it was assumed that the appliance has a combustion efficiency of 80% and that the specific energy of the wood is 1,330 kWh per stacked cu.m.

| | **Single-storey old** | **Single-storey renovated** | **Two-storey new** | **Two-storey passive** |
|---|---|---|---|---|
| Appliance net output | 4,400 kWh/a | 3,400 kWh/a | 850 kWh/a | 550 kWh/a |
| Net output as percentage of total heating demand | 17 % | 19 % | 9 % | 12 % |
| Heat release efficiency | 91 % | 91 % | 91 % | 88 % |
| Wood consumption | 4.3 stacked cu.m / a | 3.4 stacked cu.m / a | 0.8 stacked cu.m / a | 0.6 stacked cu.m / a |
| Burns per year | 242 | 212 | 90 | 59 |

The figures below contain a summary of all the computation scenarios with acceptable temperature conditions. {0>{0>In these figures, the heat release efficiency (Figure 59) and heating energy net output (Figure 60) are given as dependent on the relative heating energy output. The heating energy output of an appliance comprises the output of heating energy for heating the rooms and the conservation of heating energy from ventilation reheating. Only the two-storey buildings have ventilation reheating. The relative heating energy output is calculated as the ratio of the net output of the appliance (when the appliance is in use) and the heating demand of the rooms (when the appliance is not in use).

Figure 61 shows the wood volume required for the net output of the appliances in each scenario; it was assumed that the appliances had a combustion efficiency of 80% and that the wood had a specific energy content of 1,330 kWh per stacked cu.m.




Heat release efficiency
Net output / room heating demand

Fast, 1-storey
Fast, 1-storey renovated
Slow, 1-storey
Slow, 1-storey renovated
Slow, 2-storey new
Slow, 2-storey passive
Very slow, 1-storey
Very slow, 1-storey renovated
Very slow, 2-storey new
Very slow, 2-storey passive
Slow, 2-storey passive, Sodankylä

**Figure 59.** Heat release efficiency as a function of relative output. The relative output is calculated as the ratio of the net output of the appliance (when the appliance is in use) and the heating demand of the rooms (when the appliance is not in use).

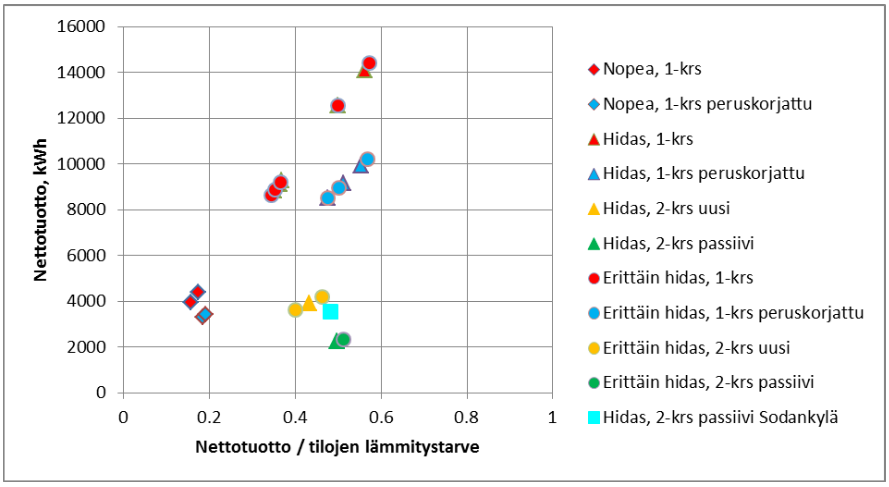



**Figure 60.** Dependence of appliance net output on relative output. The relative output is calculated as the ratio of the net output of the appliance (when the appliance is in use) and the heating demand of the rooms (when the appliance is not in use).

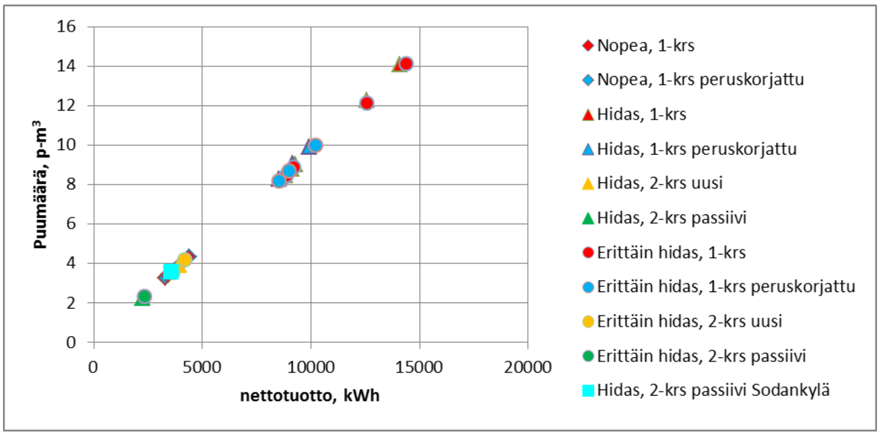



**Figure 61.** Dependence of the volume of wood required on the net output of the appliance. It is assumed that the combustion efficiency of the appliance is 80% and that the specific energy content of the wood is 1,330 kWh per stacked cu.m.

# 7. Conclusions

The purpose of the present study was to perform computational analyses of the maximum heating energy available from residential solid fuel burning appliances in detached houses with varying energy consumption and mass. As a limiting parameter for the maximum heating energy output, it was determined that the temperature in the living room (the room in which the appliance was installed) must not exceed a specified maximum value. The temperature parameter was derived from the housing health guide (*Asumisterveysohje* [Housing health guide], 2003): spot temperatures should not exceed +26 °C, and the long-term average temperature should not exceed +24 °C.

The computational analysis yielded the maximum heating energy output for each type of appliance shown in Table 25.

**Table 25.** Maximum heating energy output from the appliances analysed, and output as percentage of the total heating need.

| **Appliance** | **Heating energy output from the appliances analysed, and output as percentage of the total heating demand** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Single-storey old building | | Single-storey renovated building | | Two-storey new building | | Two-storey passive building | |
| | Output kWh | % | Output kWh | % | Output kWh | % | Output kWh | % |
| Very slow appliance | 14,400 | 57 | 10,200 | 57 | 4,000 | 44 | 2,300 | 51 |
| Slow appliance | 14,100 | 56 | 9,900 | 55 | 3,900 | 43 | 2,200 | 50 |
| Fast appliance | 4,600 | 18 | 3,400 | 19 | 850 (1 | 9 | 540 (1 | 12 |

(1 With the charges used in the analysis, the room temperature easily exceeded the specified maximum with the fast appliance. Therefore, the output for the fast appliance in the two-storey buildings was only calculated for the winter months: three months (December to February) for the new building and two months (January to February) for the passive building.

The maximum heating energy output depended above all on the heating demand of the building: the greater the heating demand, the greater the output of the appliance. The thermal properties of the appliances also played an obvious part: the greater the thermal storage capacity of the appliance, the greater its output potential; however, the difference in output potential between the very slow and the slow appliance was negligible. Naturally, the massing of the building also affects the output: the more open the space is where the appliance is installed, the greater the output potential of the appliance.

In the computation rules specified in the current building code (National Building Code, part D3, 2012), the available heating energy output of a slow heat release residential solid fuel burning appliance is defined as 2,000 kWh. The two-storey new building in the present analysis corresponds to a building built according to the current code; in this building, a slow heat release appliance yields about double the above figure in output. Of course, the maximum output requires that the appliance is in active use. Table 26 shows the volumes of wood required per year for maximum use of the appliances. The volume of wood required per year for a slow heat release appliance in a two-storey new building is over 4 stacked cu.m, and storing such a quantity of wood in an urban area may be challenging. However, as the heating demands of buildings continue to decrease, the volume of wood required for heating will also decrease, and residential solid fuel burning appliances may fill a significant percentage of heating demand with less wood.

**Table 26.** Volumes of wood per year corresponding to the maximum heating energy output in the buildings, and number of burns per year.

| **Appliance** | **Volume of wood required, stacked cu.m per year** [1] | | | |
|---|---|---|---|---|
| | Single-storey old building | Single-storey renovated building | Two-storey new building | Two-storey passive building |
| Very slow appliance | 14.1 | 10.0 | 4.2 | 2.3 |
| Slow appliance | 14.1 | 9.9 | 3.9 | 2.3 |
| Fast appliance | 4.3 | 3.4 | 0.8 [2] | 0.6 [2] |

[1] The volumes of wood were calculated on the basis of the assumptions used in the present study for heat release efficiency, combustion efficiency (80%) and the specific energy of the wood (1,330 kWh per stacked cu.m).

[2] With the charges used in the analysis, the room temperature easily exceeded the specified maximum with the fast appliance. Therefore, the output for the fast appliance in the two-storey buildings was only calculated for the winter months: three months (December to February) for the new building and two months (January to February) for the passive building.

In old buildings with a higher energy consumption, the output potential of the appliances is much greater than in new buildings, and the volume of wood required is thus also larger. The user must also use the appliance much more in an old building than in a new building (Table 27). However, the number of burns does not decrease proportionally to the appliance output: with a lower output the charges are also smaller, which means that the number of burns does not decrease as much.

**Table 27.** Burns per year for the appliances analysed.

| Appliance | Burns per year | | | |
|---|---|---|---|---|
| | Single-storey old building | Single-storey renovated building | Two-storey new building | Two-storey passive building |
| Very slow appliance | 197 | 144 | 114 | 70 |
| Slow appliance | 237 | 201 | 192 | 122 |
| Fast appliance | 242 | 212 | 90 | 59 |

One of the purposes of the present project was to determine the heat release efficiency of the appliances analysed. A residential solid fuel burning appliance does not generate heat in an optimum way: using such an appliance for heating always leads to an unnecessary increase in room temperature, which in turn increases heat loss through structures and ventilation. Also, the appliance has an unfavourable effect on the vertical thermal layering of indoor air: the temperature at the top of the space rises, leading to increased heat loss through structures and ventilation in the upper part of the room. The heat loss caused by vertical thermal layering of indoor air was not addressed in the present study; the phenomenon was accounted for by assigning to it a constant efficiency factor of $\eta_{stratification} = 0.95$. The regulation capacity of the heating system is also relevant for the heat release efficiency of the appliance, and in the present study that factor is included in the heat release efficiency values given. Accurate PI regulation was assumed for the room heating in the computational analyses.
The computed values for appliance heat release efficiency are given in Table 28. They are roughly equal for every building type and appliance type, though slightly better for old buildings with a high energy consumption than for new buildings with a low energy consumption.

**Table 28.** Heat release efficiency of the appliances analysed. These values represent the maximum heating energy available for release into the space under comparable conditions.

| Appliance | Heating energy released by the appliance into the space, kWh/year | | | |
|---|---|---|---|---|
| | Single-storey old building | Single-storey renovated building | Two-storey new building | Two-storey passive building |
| Very slow appliance | 0.91 | 0.91 | 0.90 | 0.90 |
| Slow appliance | 0.90 | 0.90 | 0.90 | 0.90 |
| Fast appliance | 0.91 | 0.91 | 0.91 (1 | 0.88 (1 |

[1] With the charges used in the analysis, the room temperature easily exceeded the specified maximum with the fast appliance. Therefore, the output for the two-storey buildings was only calculated for the winter months: three months (December to February) for the new building and two months (January to February) for the passive building.

# 8. Applying the results

The maximum heating energy output potential for a residential solid fuel burning appliance in a building may be calculated on the basis of the output percentages calculated in the previous chapter (Table 25) when the type of appliance and building and the energy demand of the building are known. The type of appliance may be determined by the difference between the t 100% and t 50% times given in the CE marking as shown in section 2.3 (fast, slow or very slow).

Example: For a very slow appliance in a single-storey renovated building, the heat output percentage is 57% (Table 25). If the heating energy demand of the building considered – representing a renovated old building – is 22,000 kWh, for instance, then the maximum heating energy output of the appliance may be calculated at 22,000 kWh * 0.57 = 12,540 kWh.

Whether the appliance selected for the building has a sufficient heat release capacity can be verified by calculating the energy output demand for a single burn, dividing the annual energy output by the number of burns given above (Table 27) and taking into account the heat release efficiency (Table 28). The heat release indicated in the CE marking of the appliance must be equal to or greater than the computed energy output demand.

Example: A very slow appliance in a one-storey renovated building is heated 144 times per year (Table 27), and the heat release efficiency of the appliance is 0.91 (Table 28). The heating energy released by the appliance thus amounts to 12,540 kWh / 144 / 0.91 = 96 kWh.

The volume of wood required per year and hence the space needed for storage may be calculated on the basis of the above output calculation and the product details in the CE marking. The maximum heating energy output of the appliance should be calculated as shown above. When this output is divided by the overall efficiency of the appliance, the heat release efficiency of the appliance (Table 27) and the combustion efficiency given in the CE marking, the overall requirement for energy input from firewood is obtained. Dividing this energy by the specific energy of a stacked cubic metre of wood will yield the annual wood consumption and hence the space needed for storage, in stacked cubic metres.

Example: If a very slow appliance in a single-storey renovated building has a maximum heating energy output of 22,000 kWh * 0,57 = 12,540 kWh per year, the required energy input from wood is 12,540 kWh / 0.91 / 0.8 = 17,225 kWh when the heat release efficiency of the appliance is 91% (Table 27) and the combustion efficiency according to the CE marking is 80%. Thus, the volume of firewood and storage capacity required per year is 17,225 kWh / 1,330 kWh/stacked cu.m = 12.95 stacked cu.m.

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# Appendix A: Temperature

The following is a detailed presentation of the living room temperatures in all the buildings analysed and for all types of residential solid fuel burning appliance analysed (very slow, slow and fast) during the heating season. The appliance is located in the living room. Temperature conditions are here shown not for all computed scenarios but only for those scenarios where the specified maximum temperature is exceeded in the living room. Also, reference temperatures for scenarios where the appliance is not in use are given for each building type.

## Single-storey old building

Figure A1 shows the living room temperature without the appliance during the heating season, from September to April. The figure shows that the living room temperature stays very close to the preset value of +21 °C. The small deviations, mainly in September and April, are due to the heat load (persons, devices and the sun) exceeding the heat demand.

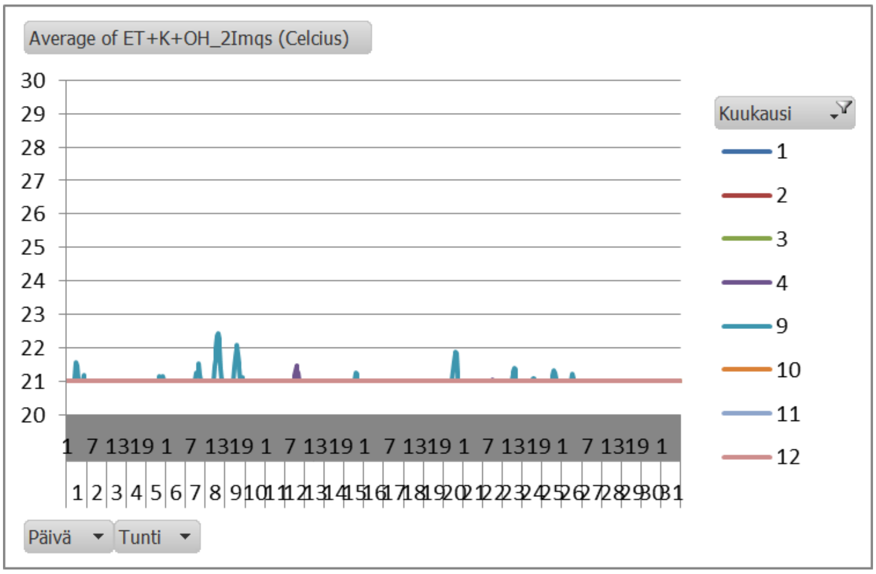



**Figure A1.** Living room temperatures during the heating season (September to April), appliance not in use.

### *Living room temperatures, very slow appliance*

With the very slow appliance, the living room temperature reaches critical limits only with the largest charge (18 kg of wood) and the highest specified maximum temperatures: +22 °C in Figure A2 and +25 °C in Figure A3. Particularly with the maximum value of +25 °C, the living room temperature rises far too much (in excess of +26 °C).

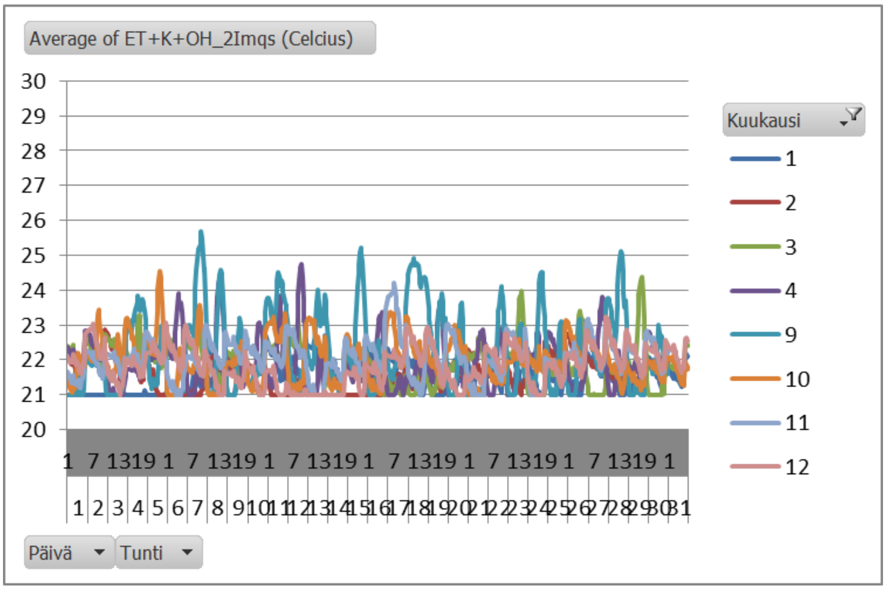



**Figure A2.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 22 °C, charge 18 kg.

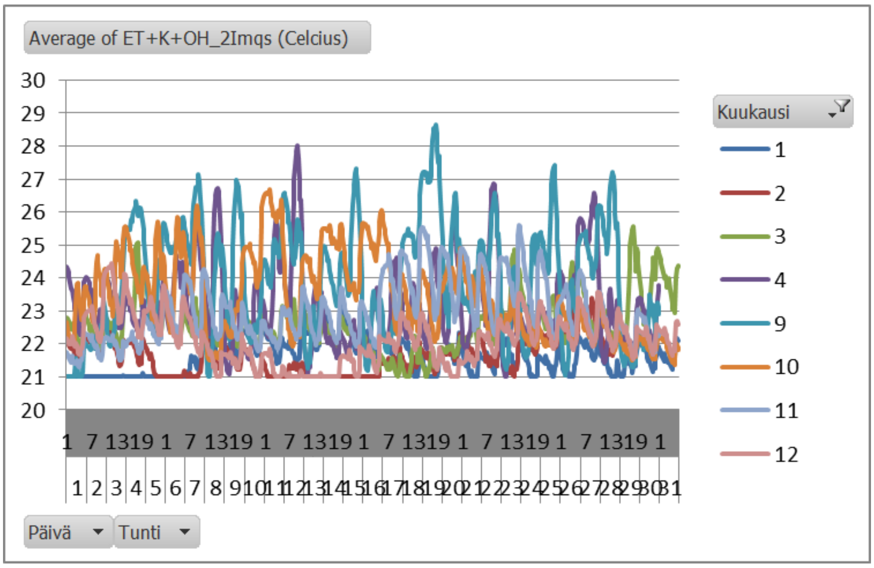



**Figure A3.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 25 °C, charge 18 kg.

*Living room temperatures, slow appliance*

With the slow appliance, as with the very slow appliance, the living room temperature reaches critical limits only with the largest charge (18 kg of wood) and the highest specified maximum temperatures: +22 °C in Figure A4 and +25 °C in Figure A5. With the maximum value of +22 °C and in September and April in particular, the living room temperatures exceed the maximum on a few days (in excess of +26 °C).

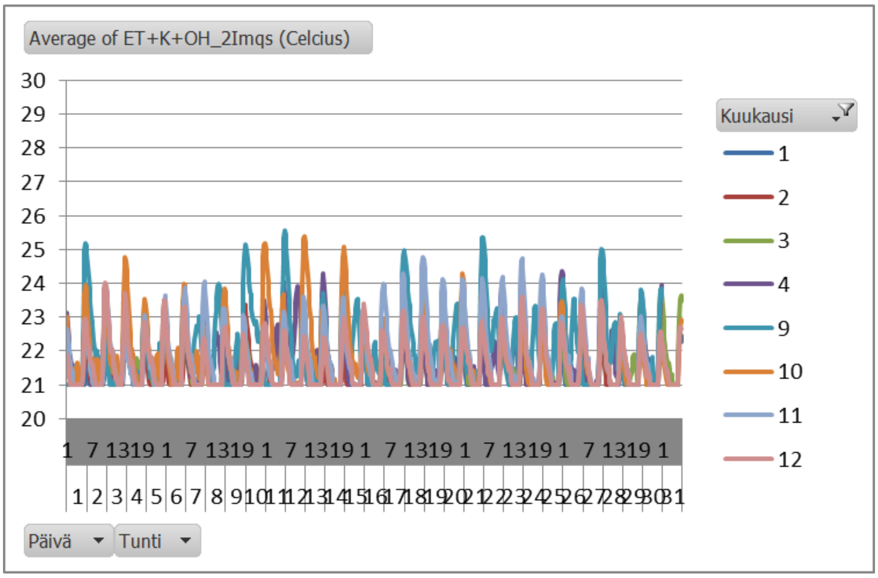



**Figure A4.** Living room temperatures during the heating season (September to April), slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

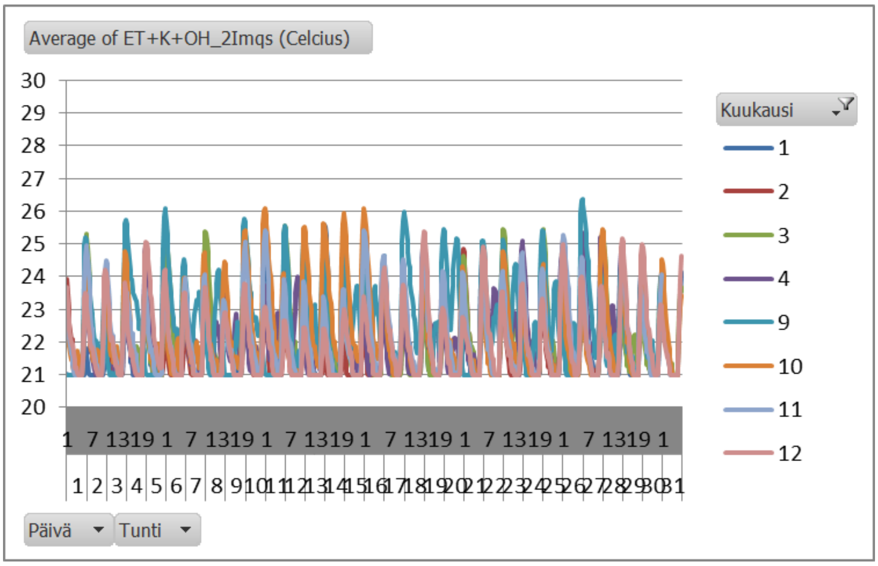



**Figure A5.** Living room temperatures during the heating season (September to April), slow appliance, room temperature maximum 22 °C, charge 18 kg.

### *Living room temperatures, fast appliance*

With the fast appliance, the living room temperatures rise critically even with the smaller charge (9 kg of wood) and the highest maximum temperature (+25 °C, Figure A7). With the maximum value of +25 °C, the living room temperature exceeds the maximum on many days in several months (in excess of +26 °C).

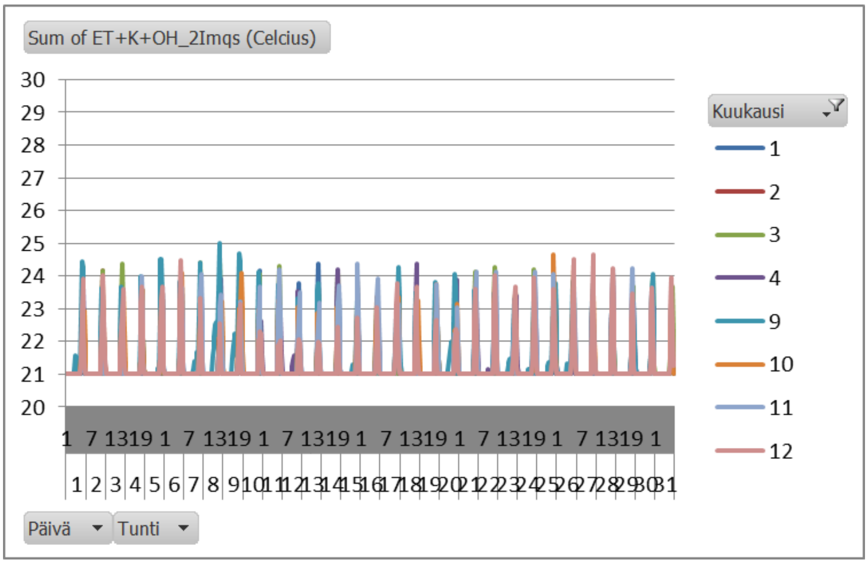



**Figure A6.** Living room temperatures during the heating season (September to April), fast appliance, room temperature maximum 22 °C, charge 9 kg.

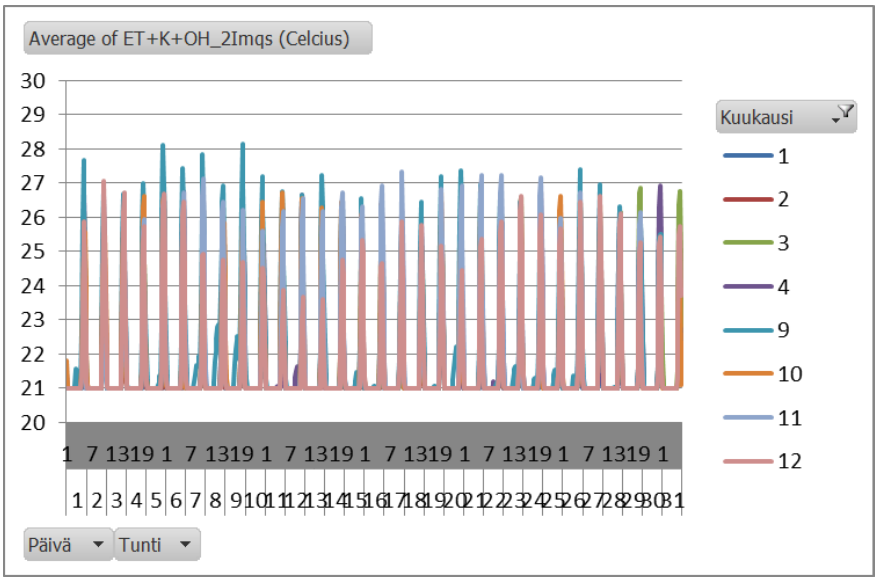



**Figure A7.** Living room temperatures during the heating season (September to April), fast appliance, room temperature maximum 25 °C, charge 9 kg.

## Single-storey renovated building

Figure A8 shows the living room temperature without the appliance during the heating season, from September to April. The figure shows that the living room temperature stays very close to the preset value of +21 °C, the main exceptions being in September. The deviations are due to the heat load (persons, devices and the sun) exceeding the heat demand. Comparing this scenario to the non-renovated building, we find an increase in the incidence and scope of temperature deviations, but the temperature still remains largely within the specified limits.

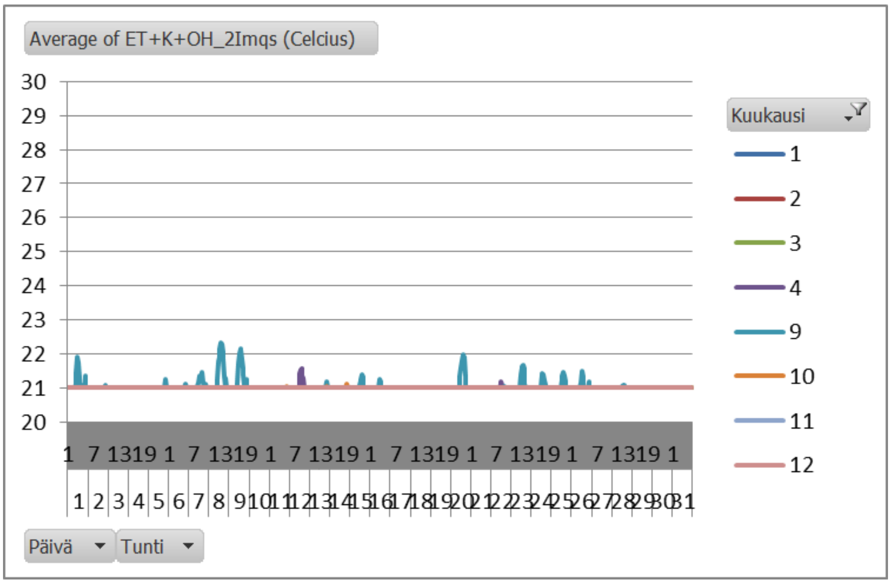



**Figure A8.** Living room temperatures during the heating season (September to April), appliance not in use.

### *Living room temperatures, very slow appliance*

With the very slow appliance, the living room temperature reaches critical limits only with the larger charge (18 kg of wood) and the highest specified maximum temperatures: +21.5 °C (Figure A9) and +22 °C (Figure A10). Particularly with the maximum value of +22 °C, the living room temperature rises to above +24 °C for extended periods of time, which is not acceptable.

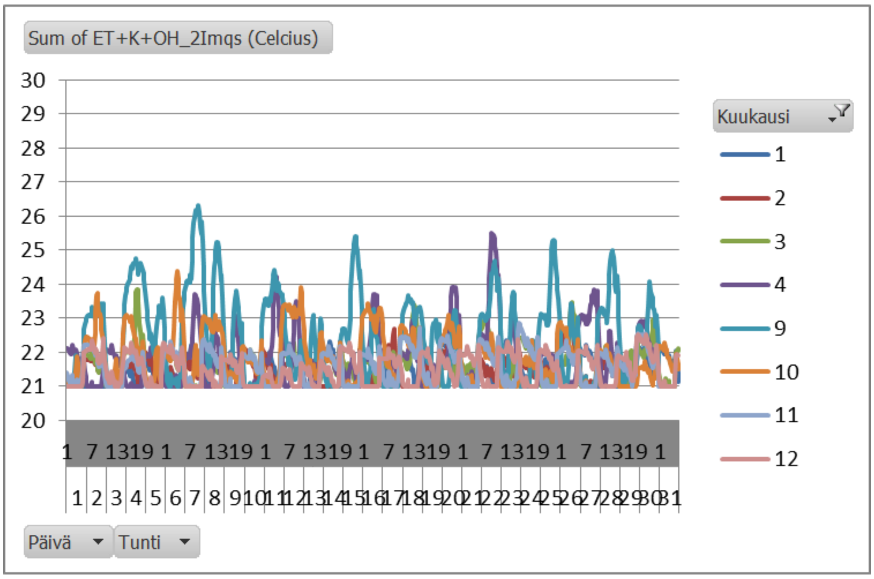



**Figure A9.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

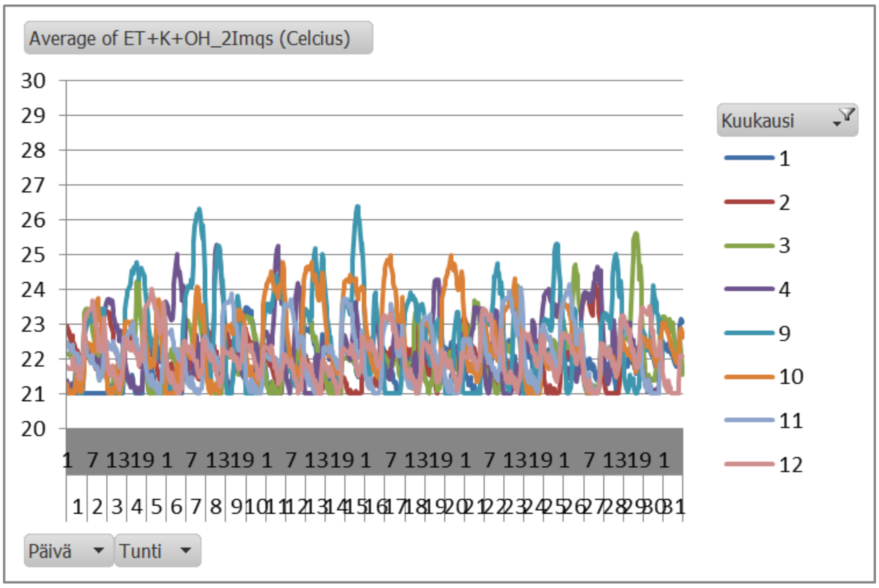



**Figure A10.** Living room temperatures during the heating season (September to April), very slow appliance, room temperature maximum 22 °C, charge 18 kg.

*Living room temperatures, slow appliance*

With the slow appliance, as with the very slow appliance, the living room temperature reaches critical limits only with the larger charge (18 kg of wood) but with the maximum temperatures +21.5 °C (Figure A11) and +22 °C (Figure A12). When the appliance is in use with the maximum temperature of +22 °C, spot temperatures in the living room are too high (in excess of +26 °C), and the temperature rises to above +24 °C for extended periods of time on several days, which is not acceptable.

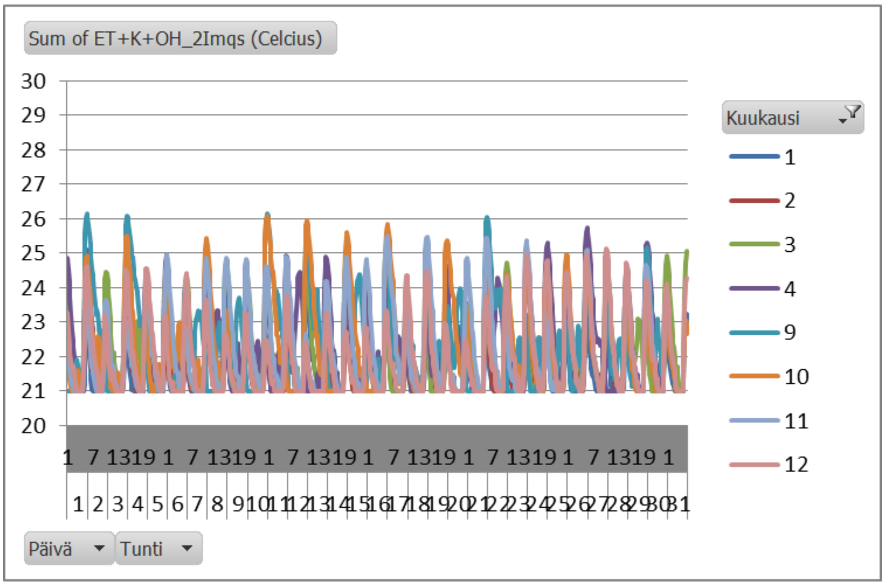



**Figure A11.** Living room temperatures during the heating season (September to April), slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

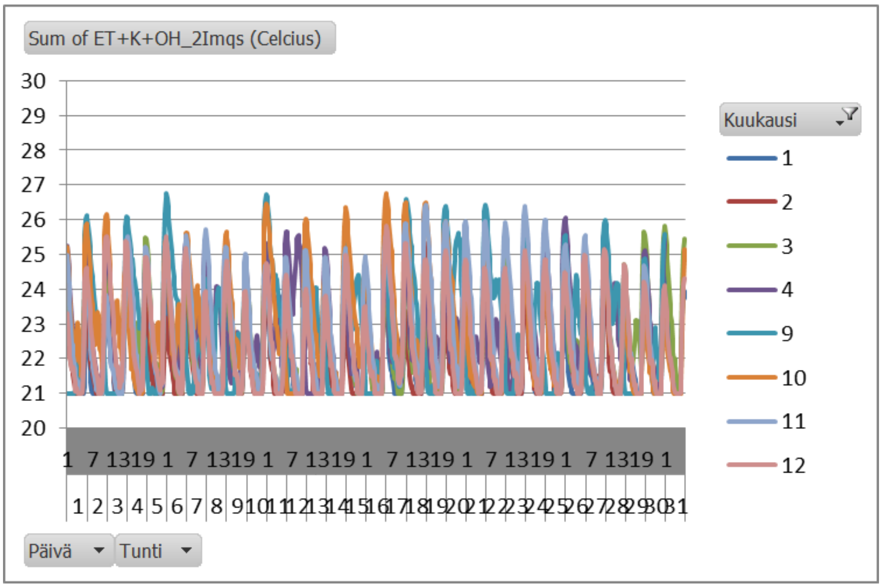



**Figure A12.** Living room temperatures during the heating season (September to April), slow appliance, room temperature maximum 22 °C, charge 18 kg.

### *Living room temperatures, fast appliance*

With the fast appliance, the living room temperature rises critically even with the smaller charge (9 kg of wood) and the highest maximum temperature (+25 °C, Figure A14). Spot temperatures exceed +26 °C in many days in several months, and the temperature rises to over +24 °C for extended periods of time, which is not acceptable.

Figure A15 shows the living room temperature with the larger charge (18 kg) and the lowest maximum temperature (+21.5 °C), a scenario that produces temperatures massively exceeding the maximum.

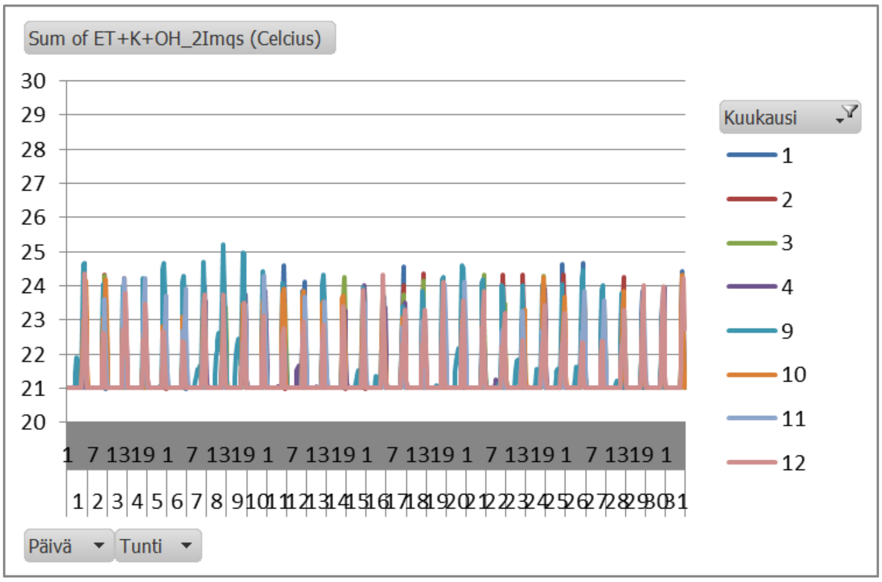



**Figure A13.** Living room temperatures during the heating season (September to April), fast appliance, room temperature maximum 22 °C, charge 9 kg.

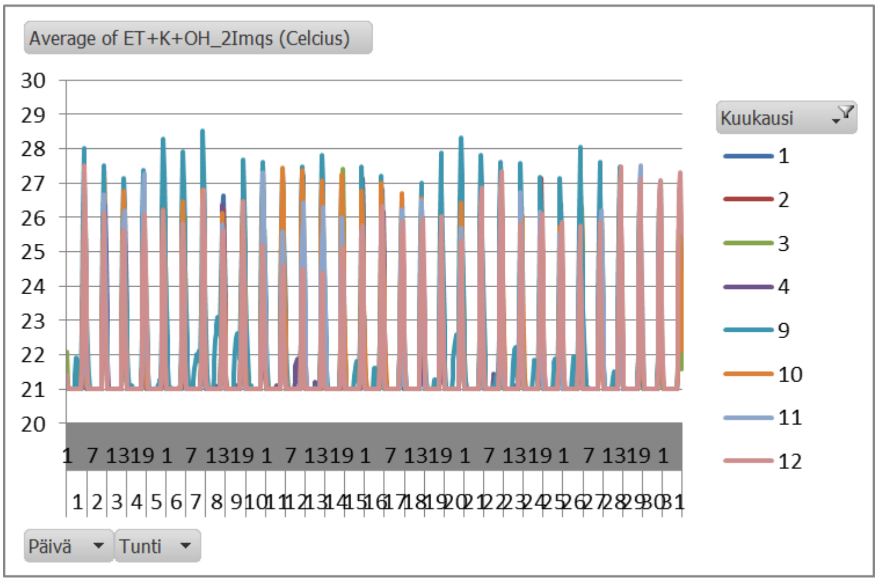



**Figure A14.** Living room temperatures during the heating season (September to April), fast appliance, room temperature maximum 25 °C, charge 9 kg.

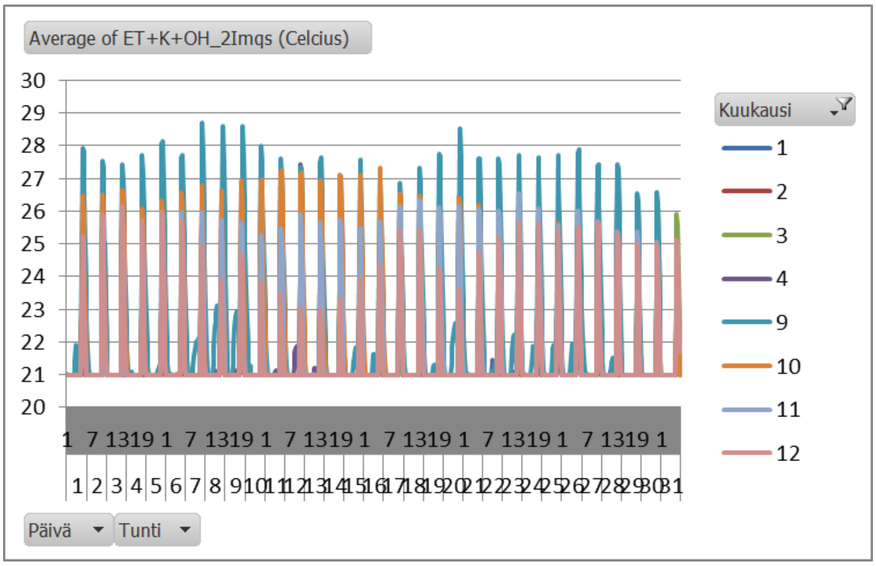



**Figure A15.** Living room temperatures during the heating season (September to April), fast appliance, room temperature maximum 21.5 °C, charge 18 kg.

## Two-storey new building

Figure A16 shows the living room temperature without the appliance during the heating season, from October to April. The figure shows that the living room temperature stays very close to the preset value of +21 °C. The deviations are due to the heat load (persons, devices and the sun) exceeding the heat demand. Compared to the single-storey old building, this scenario shows a clear increase in the incidence and scope of temperature deviations, but on the whole the temperature remains rather well within its preset bounds.

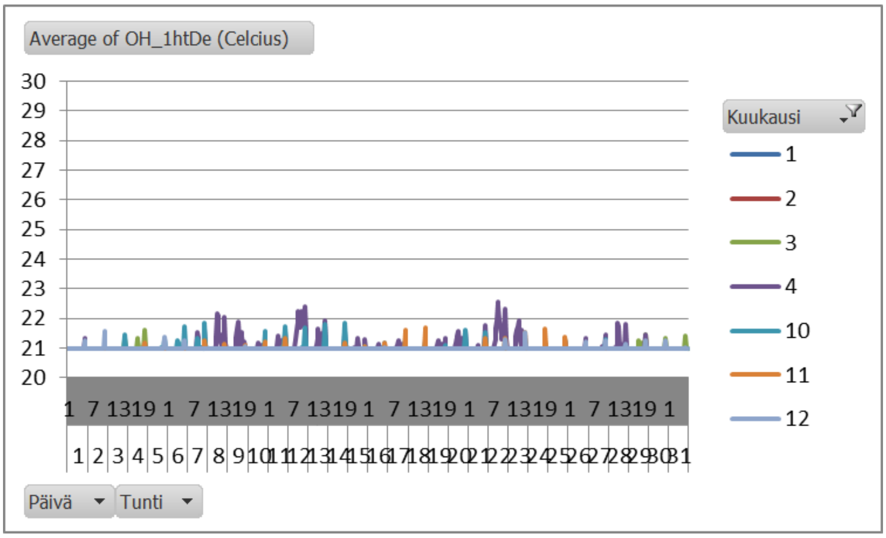



**Figure A16.** Living room temperatures during the heating season (October to April), appliance not in use.

### *Living room temperatures, very slow appliance*

With the very slow appliance, an acceptable temperature is achieved in the living room with the smaller charge and the lowest maximum temperature value (Figures A17 and A18).

The living room temperature rises critically with the smaller charge and the highest maximum temperature value (9 kg and +25 °C). With the larger charge (18 kg) and the lowest maximum temperature (+21.5 °C), the living room temperature exceeds the acceptable +24 °C for extended periods of time (Figure A19).

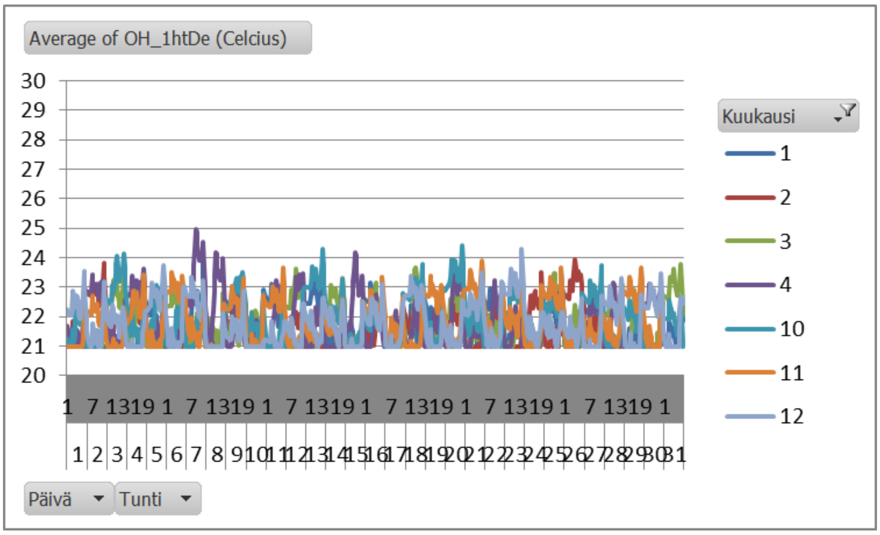



**Figure A17.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

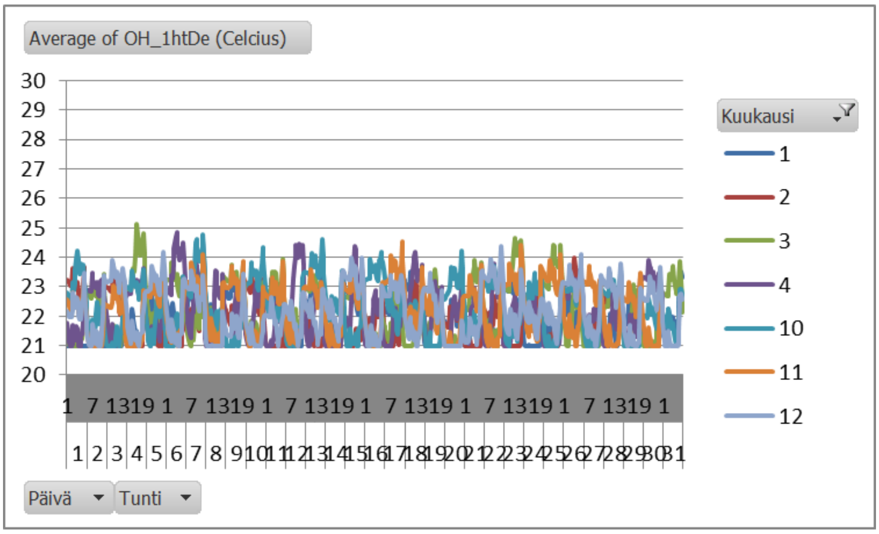



**Figure A18.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 22 °C, charge 9 kg.

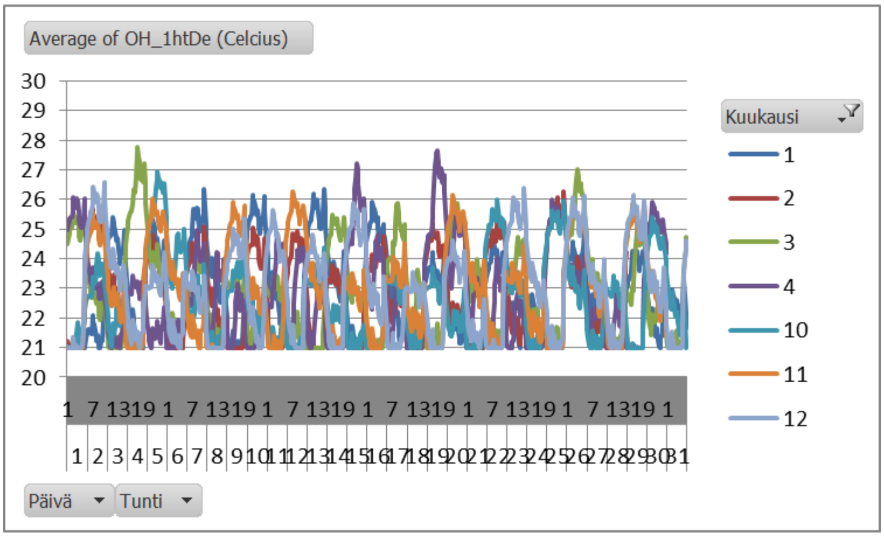



**Figure A19.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

*Living room temperatures, slow appliance*

With the slow appliance, the living room temperature remains acceptable only in the scenario with the smaller charge (9 kg) and the lowest maximum temperature (+21.5 °C), Figure A20.

The living room temperature approaches the limits of acceptability even with the smaller charge (9 kg) and the maximum temperature value of +22 °C, Figure A21. With the larger charge (18 kg) and the lowest maximum temperature (+21.5 °C), the living room temperature exceeds the acceptable +24 °C for extended periods of time (Figure A22).

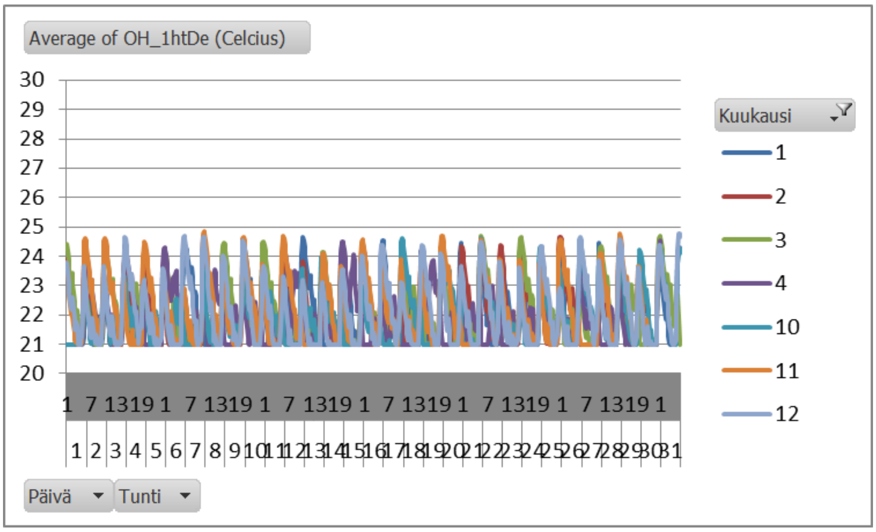



**Figure A20.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

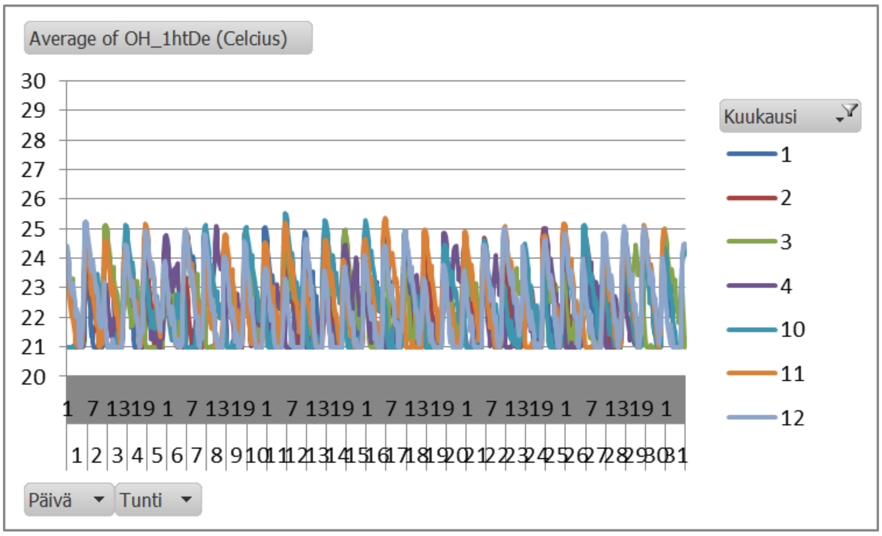



**Figure A21.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 22 °C, charge 9 kg.

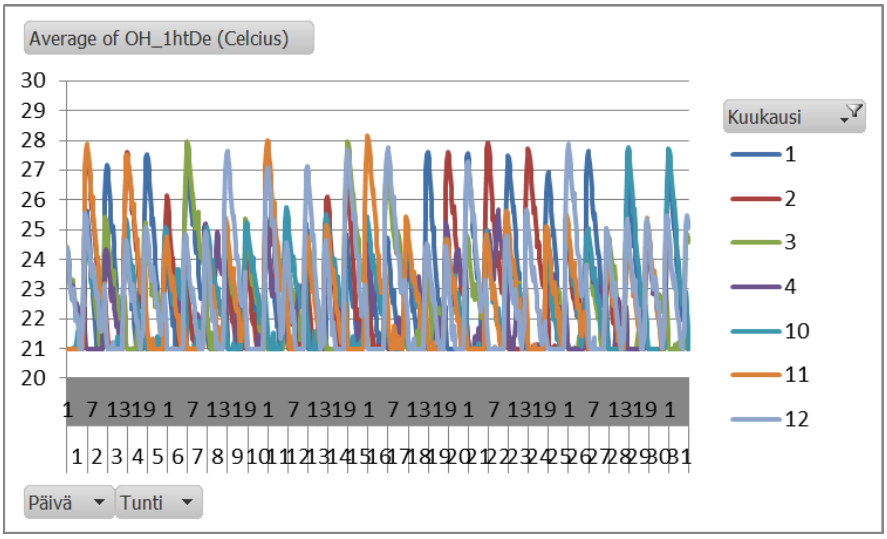



**Figure A22.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

### *Living room temperatures, fast appliance*

With the fast appliance, the living room temperature reached critical limits in all scenarios. Even with the smaller charge (9 kg) and the lowest maximum temperature (+21.5 °C), the living room temperature exceeds the acceptable +24 °C for extended periods of time in many months (Figure A23). During the winter months, from December to February, the living room temperature is acceptable on more days, although there are also days when the temperature exceeds the maximum (Figure A24).

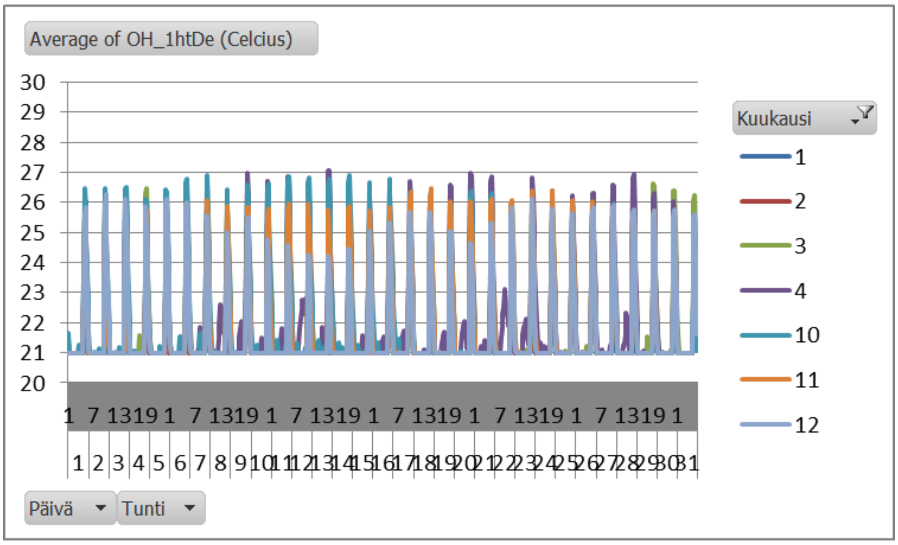



**Figure A23.** Living room temperatures during the heating season (October to April), fast appliance, room temperature maximum 21.5 °C, charge 9 kg.

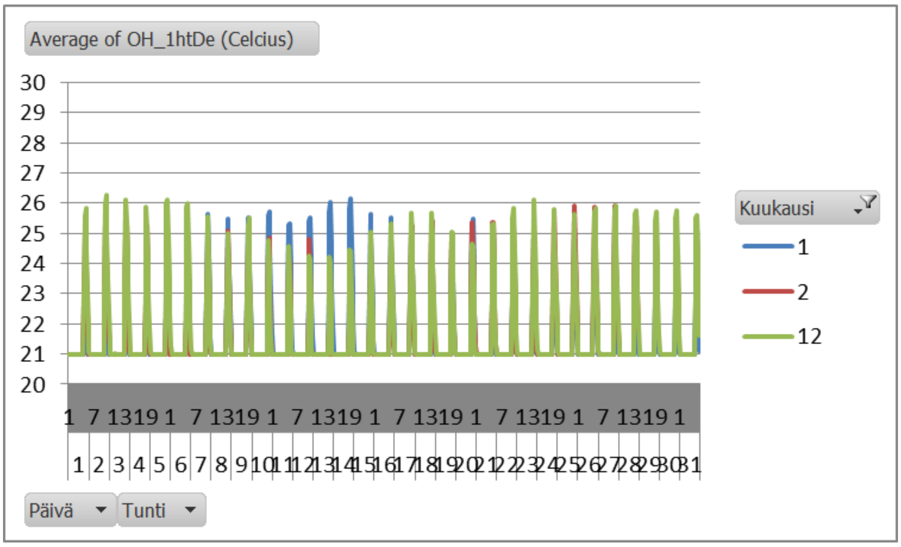



**Figure A24.** Living room temperatures during the heating season (December to March), fast appliance, room temperature maximum 21.5 °C, charge 9 kg.

## Two-storey passive building

Figure A25 shows the living room temperature without the appliance during the heating season, from October to April. The figure shows that the living room temperature varies quite a lot particularly in October and April, not remaining at the preset value of +21 °C. The deviations are due to the heat load (persons, devices and the sun) exceeding the heat demand. Compared to the single-storey old building and to the two-storey new building, this scenario shows a clear increase in the incidence and scope of temperature deviations.

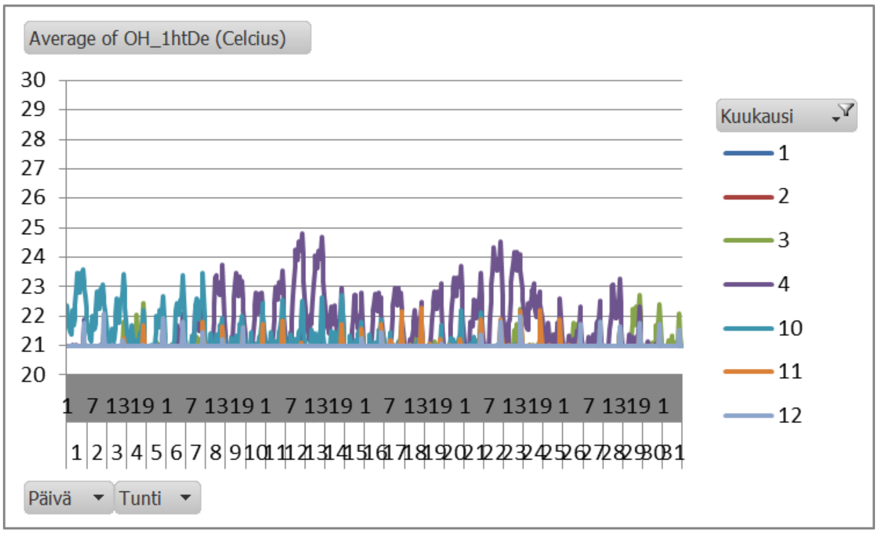



**Figure A25.** Living room temperatures during the heating season (October to April), appliance not in use.

### *Living room temperatures, very slow appliance*

With the very slow appliance, the living room temperature remains acceptable only in the scenario with the smaller charge (9 kg) and the lowest maximum temperature (Figures A26 and A27).

The living room temperature rises critically with the smaller charge and the highest maximum temperature value (9 kg and +25 °C). With the larger charge (18 kg) and the lowest maximum temperature (+21.5 °C), the living room temperature exceeds the acceptable +24 °C for extended periods of time (Figure A28).

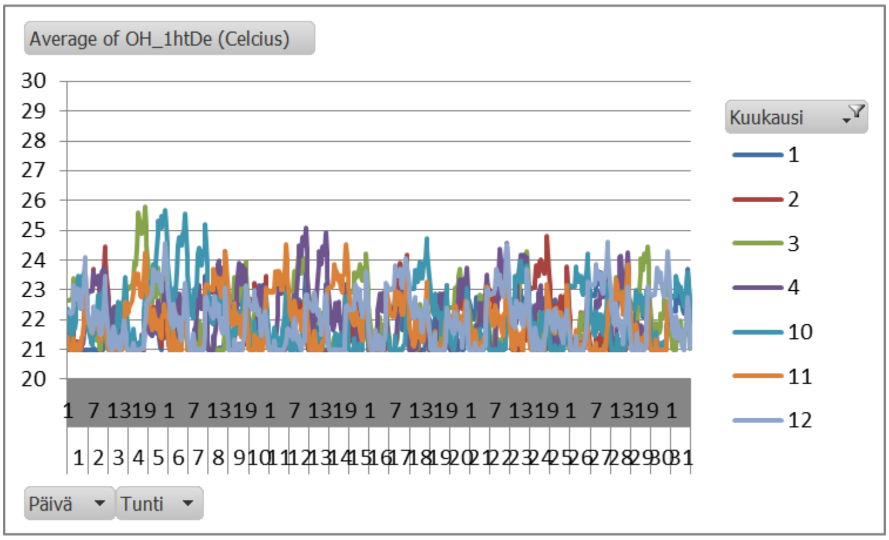



**Figure A26.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

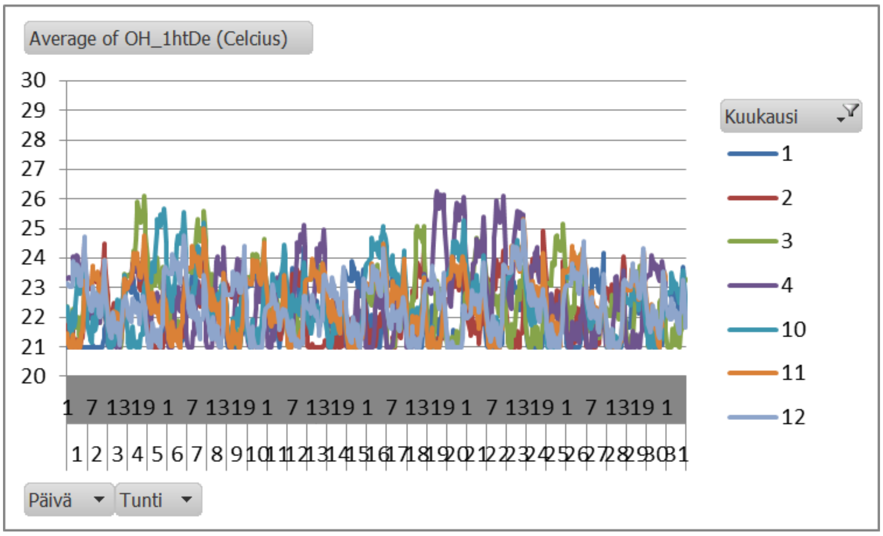



**Figure A27.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 22 °C, charge 9 kg.

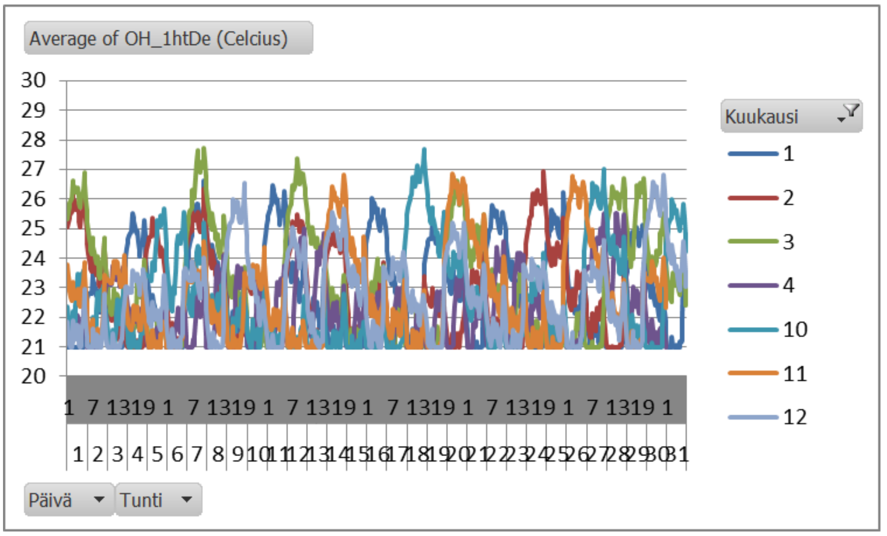



**Figure A28.** Living room temperatures during the heating season (October to April), very slow appliance, room temperature maximum 21.5 °C, charge 18 kg.

### *Living room temperatures, slow appliance*

With the slow appliance, the living room temperature remains acceptable only in the scenario with the smaller charge (9 kg) and the lowest maximum temperature (+21.5 °C), Figure A29.

The living room temperature approaches the limits of acceptability even with the smaller charge (9 kg) and the maximum temperature value of +22 °C, Figure A30.

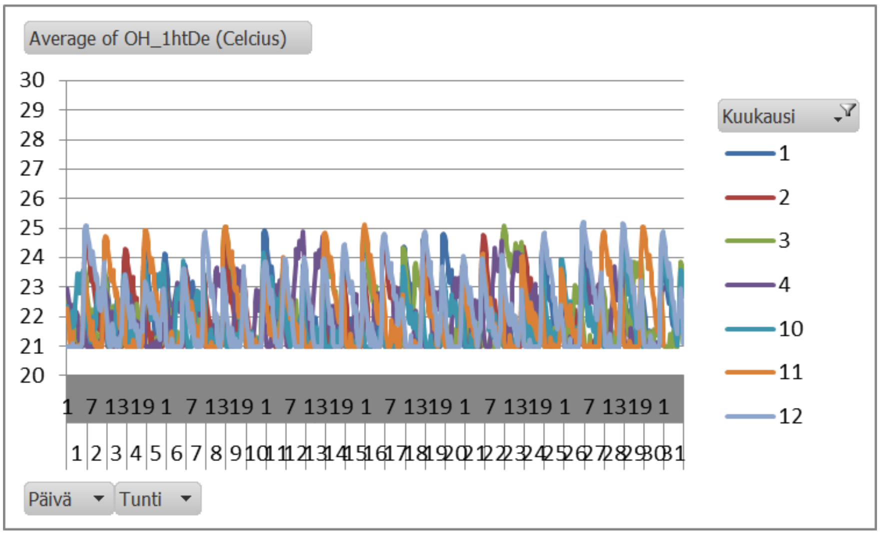



**Figure A29.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

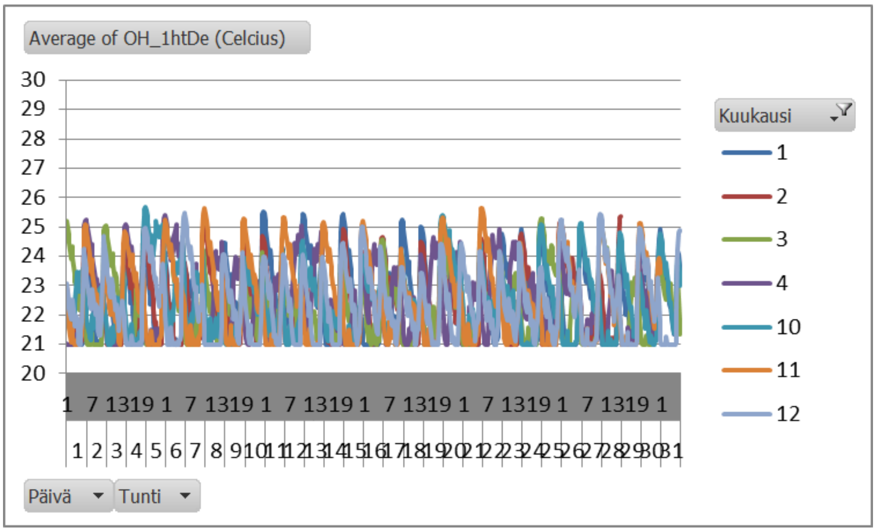



**Figure A30.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 22 °C, charge 9 kg.

### *Living room temperatures, slow appliance, Sodankylä weather*

The scenarios with Sodankylä weather yielded much the same results as those with Helsinki weather. The living room temperature remains acceptable only in the scenario with the smaller charge (9 kg) and the lowest maximum temperature

(+21.5 °C), Figure A31. The living room temperature approaches the limits of acceptability even with the smaller charge (9 kg) and the maximum temperature value of +22 °C in both Sodankylä weather and Helsinki weather (Figure A32).

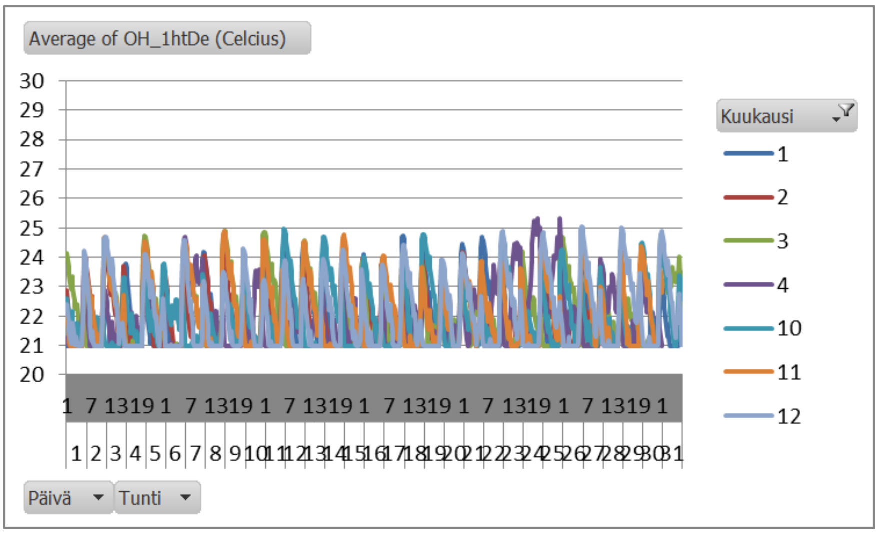



**Figure A31.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 21.5 °C, charge 9 kg.

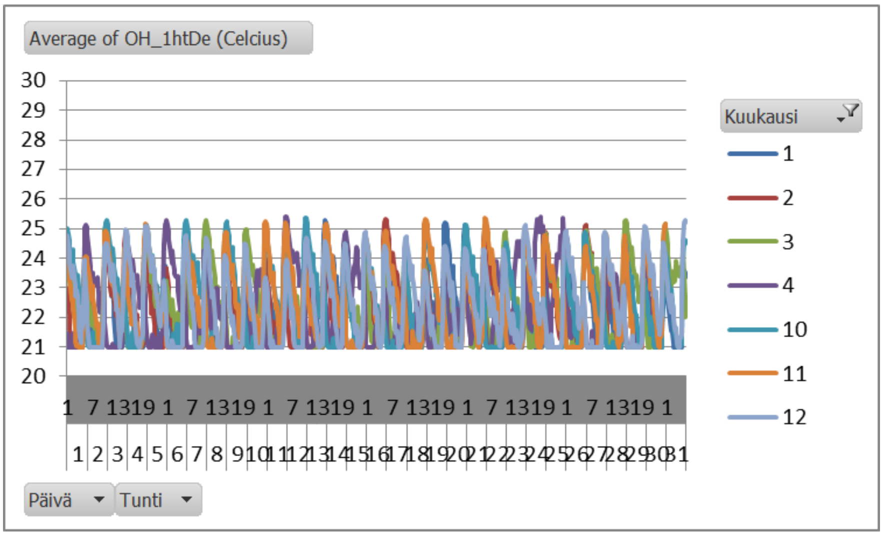



**Figure A32.** Living room temperatures during the heating season (October to April), slow appliance, room temperature maximum 22 °C, charge 9 kg.

*Living room temperatures, fast appliance*

With the fast appliance, the living room temperature reaches critical limits in all scenarios. Even with the smaller charge (9 kg) and the lowest maximum temperature (+21.5 °C), the living room temperature exceeds the acceptable +24 °C for extended periods of time in many months (Figure A33). In the winter months too (Figure A34), the temperature easily rises when the appliance is used.

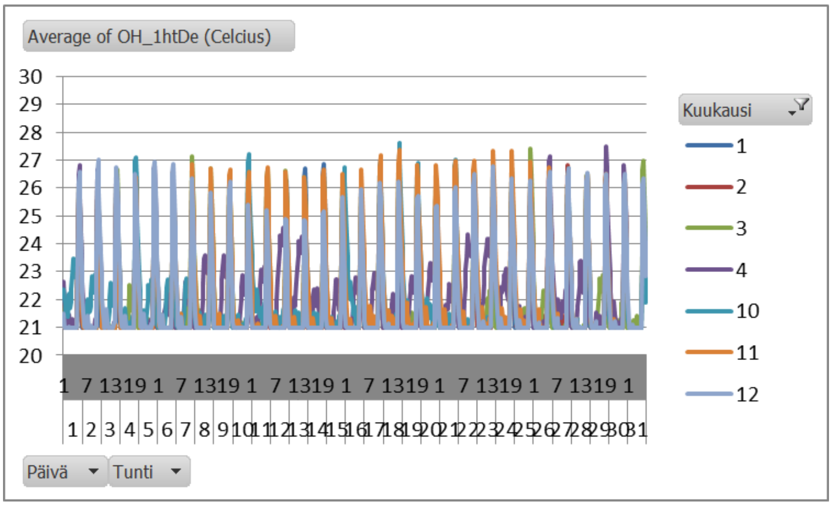



**Figure A33.** Living room temperatures during the heating season (October to April), fast appliance, room temperature maximum 21.5 °C, charge 9 kg.

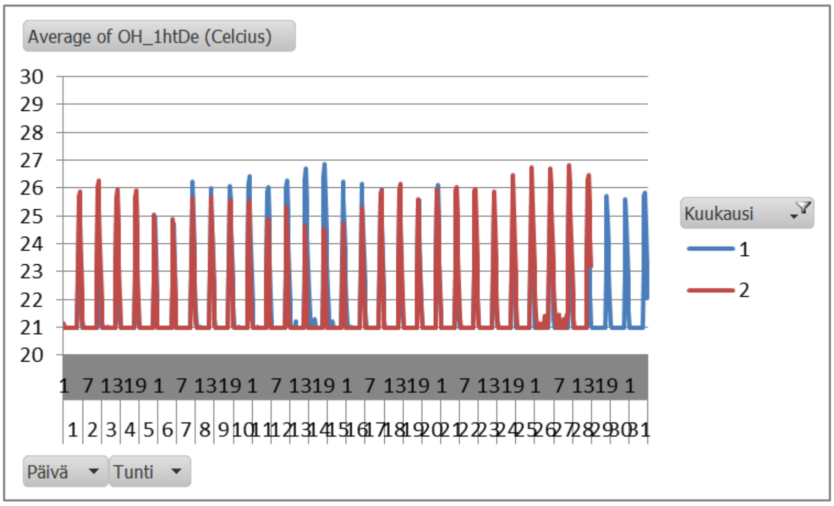
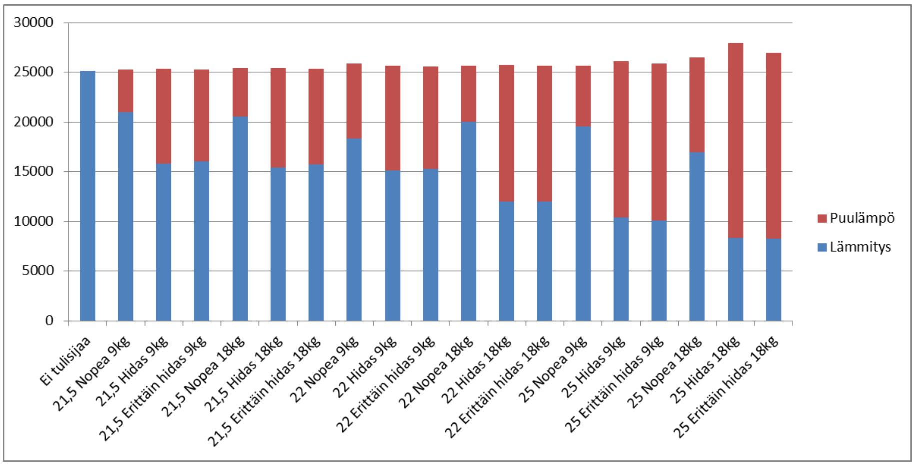



**Figure A34.** Living room temperatures during the winter months (January to February), fast appliance, room temperature maximum 21.5 °C, charge 9 kg.

# Appendix B: Total energy consumption for heating and appliance net output

The total energy consumption for heating the spaces in buildings in the analysis in all the scenarios are shown in the figures below (Figures B1–B4). For this purpose, 'total energy consumption' means the energy consumption for direct electric heating plus the heating energy released by the appliance into the space.




Wood burning
Heating system
No appliance :: 21.5 Fast 9 kg :: 21.5 Slow 9 kg :: 21.5 Very slow 9 kg :: 21.5 Fast 18 kg :: 21.5 Slow 18 kg :: 21.5 Very slow 18 kg :: 22 Fast 9 kg :: 22 Slow 9 kg :: 22 Very slow 9 kg :: 22 Fast 18 kg :: 22 Slow 18 kg :: 22 Very slow 18 kg :: 25 Fast 9 kg :: 25 Slow 9 kg :: 25 Very slow 9 kg :: 25 Fast 18 kg :: 25 Slow 18 kg :: 25 Very slow 18 kg

**Figure B1.** Total energy consumption for heating the spaces in a single-storey detached house with original structures.

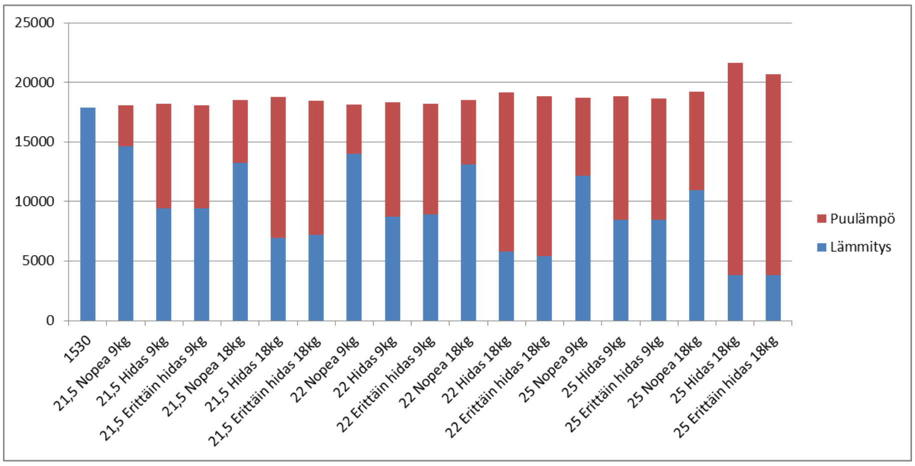



**Figure B2.** Total energy consumption for heating the spaces in a single-storey detached house with renovated structures.

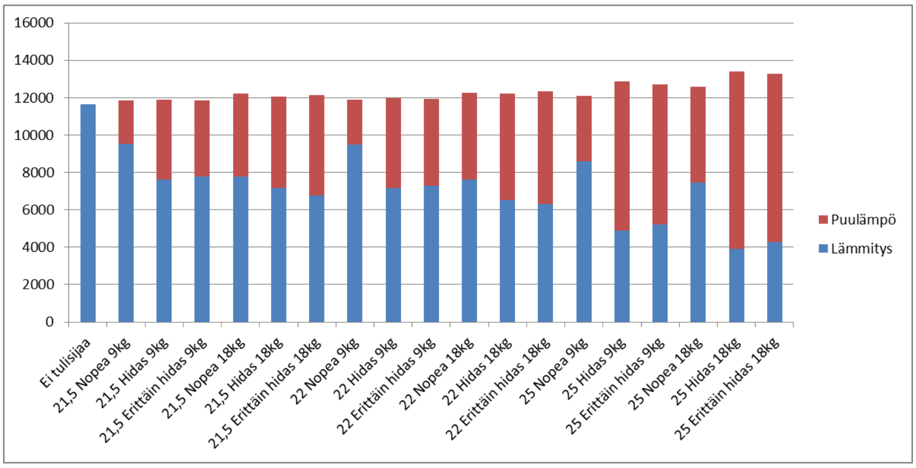



**Figure B3.** Total energy consumption for heating the spaces in a two-storey detached house built to the current building code.

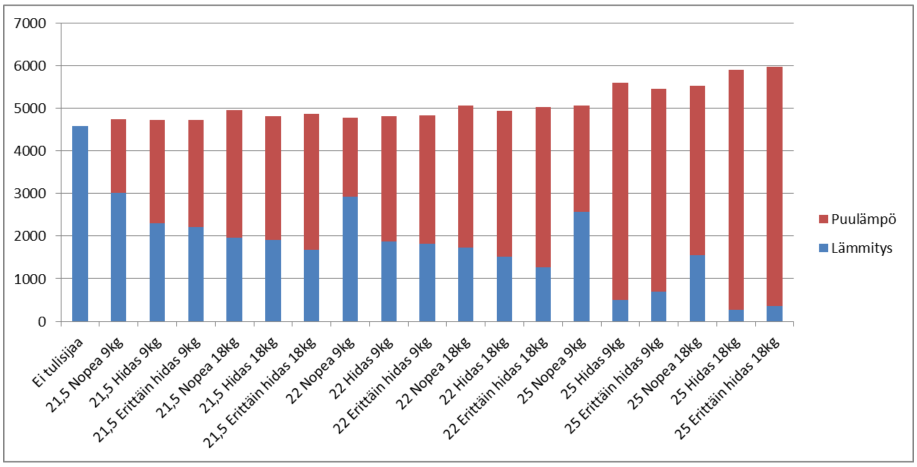
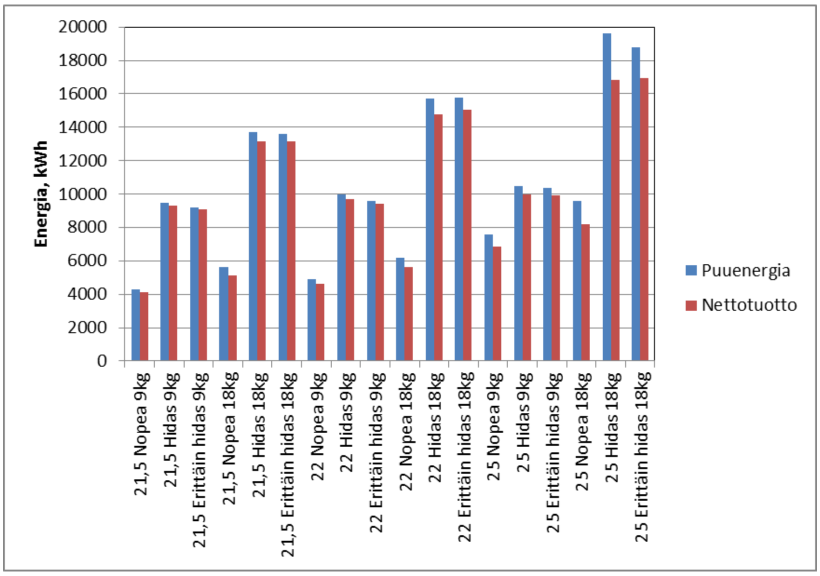



**Figure B4.** Total energy consumption for heating the spaces in a two-storey detached house built to a passive-house standard.

#### Heating energy output from appliances

The heating energy net output of the appliances and the heating energy released by the appliances into the space are shown in Figures B5–B8. Net output is the difference between the heating energy consumption without the appliance in use and the heating energy consumption with the appliance in each scenario. Wood energy is the heating energy that the appliance would release into the space if the combustion efficiency were 100%. The difference between the wood energy and the net output is the additional heat loss caused by the appliance in the form of a higher indoor temperature.




Energy, kWh
Wood burning :: Net output
21.5 Fast 9 kg :: 21.5 Slow 9 kg :: 21.5 Very slow 9 kg :: 21.5 Fast 18 kg :: 21.5 Slow 18 kg :: 21.5 Very slow 18 kg :: 22 Fast 9 kg :: 22 Slow 9 kg :: 22 Very slow 9 kg :: 22 Fast 18 kg :: 22 Slow 18 kg :: 22 Very slow 18 kg :: 25 Fast 9 kg :: 25 Slow 9 kg :: 25 Very slow 9 kg :: 25 Fast 18 kg :: 25 Slow 18 kg :: 25 Very slow 18 kg

**Figure B5.** Heating energy net output with various appliances and the heating energy released by each appliance (wood energy) in a single-storey detached house with original structures. The difference between wood energy and net output represents the heat loss in the heat release from the appliances.

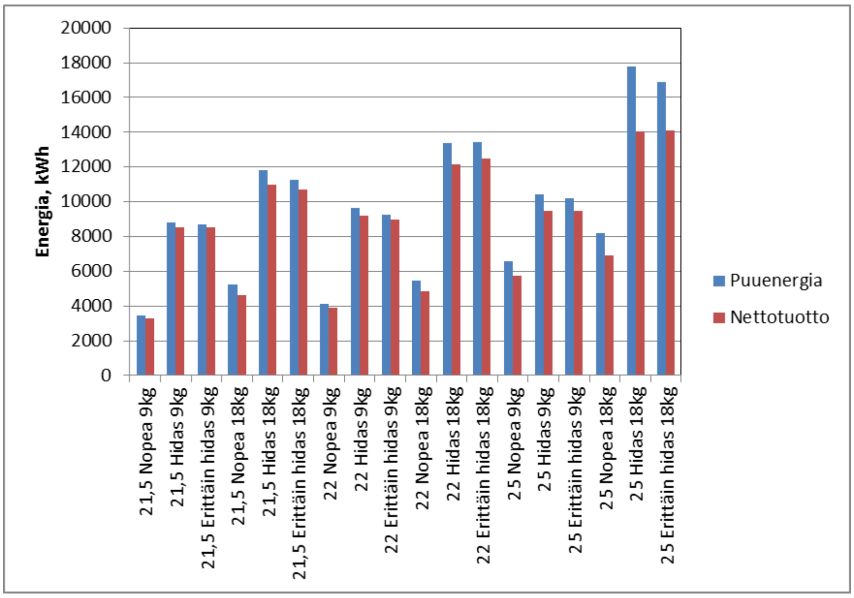



**Figure B6.** Heating energy net output with various appliances and the heating energy released by each appliance (wood energy) in a single-storey detached house with renovated structures. The difference between wood energy and net output represents the heat loss in the heat release from the appliances.

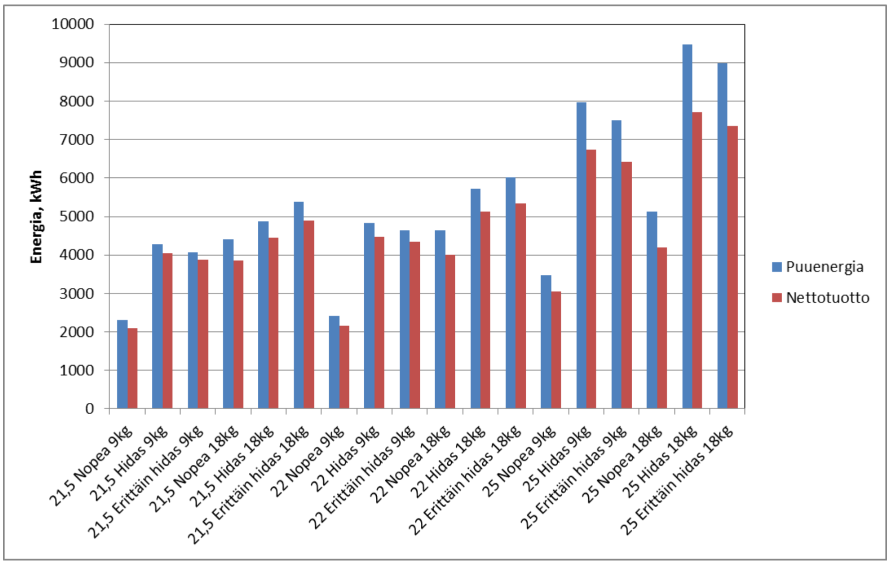



**Figure B7.** Heating energy net output with various appliances and the heating energy released by each appliance (wood energy) in a two-storey detached house with structures built to the current building code. The difference between wood energy and net output represents the heat loss in the heat release from the appliances.

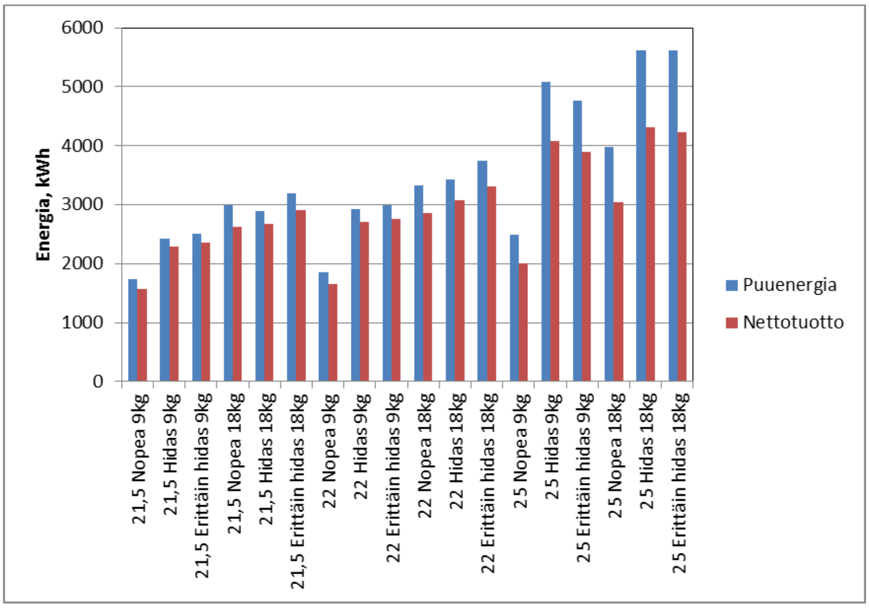
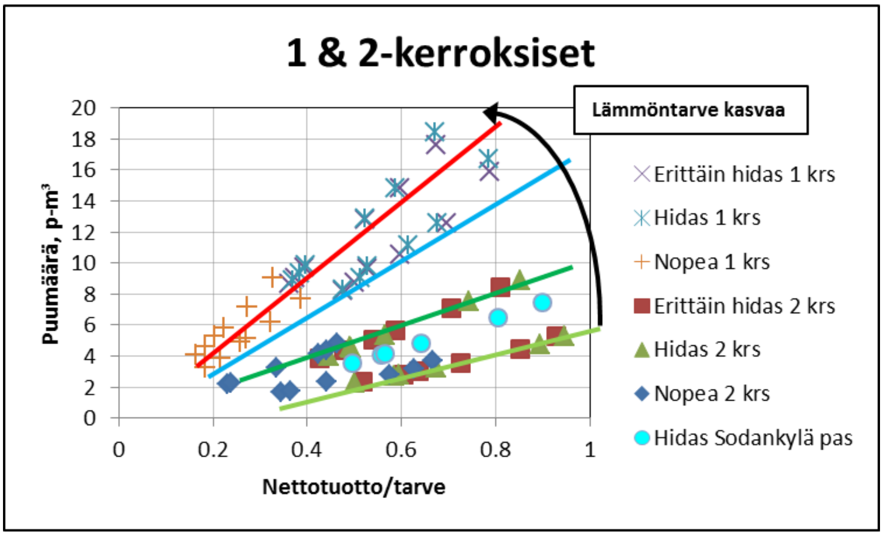



**Figure B8.** Heating energy net output with various appliances and the heating energy released by each appliance (wood energy) in a two-storey detached house with structures built to passive house standards. The difference between wood energy and net output represents the heat loss in the heat release from the appliances.



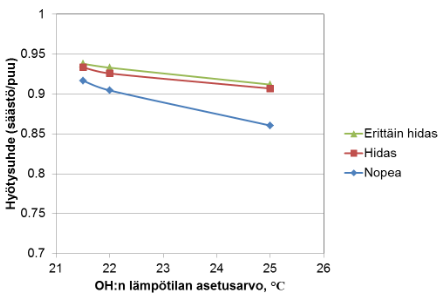

1-storey and 2-storey
Wood, stacked cu.m
Heating demand increases
Net output / demand
Very slow 1-storey :: Slow 1-storey :: Fast 1-storey :: Very slow 2-storey :: Slow 2-storey :: Fast 2-storey :: Slow Sodankylä passive

**Figure B9.** Volumes of wood corresponding to relative heat release in all computed scenarios. The assumption is that the appliance has a combustion efficiency of 80% and that the specific energy of the wood is 1,330 kWh per stacked cu.m.

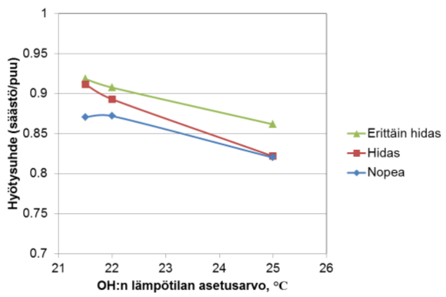
# Appendix C: Heat release efficiency of the appliances analysed

The heat release efficiency of the residential solid fuel burning appliances analysed takes into account the heat loss caused by the increasing indoor air temperature. The regulation efficiency of the actual heating system and the efficiency of the vertical thermal layering of indoor air also affect the heat release efficiency. In the simulations conducted, the non-ideal properties of the regulation system were included in the VTT Talo computation, and a precise PI regulation was used for computing. By contrast, it is not possible to simulate vertical thermal layering in VTT Talo, so this effect was entered as a constant efficiency of $\eta_{jakauma} = 0.95$.

Figures C1–C5 show the computed heat release efficiency values for the appliances in all simulation scenarios.




charge 9 kg




charge 18 kg

Efficiency (savings/wood)
Specified living room temperature maximum, °C
Very slow :: Slow :: Fast**Figure C1.** Heat release efficiency values for the single-storey building as a function of the maximum temperature for appliance burn. The figure shows values for a) charge 9 kg and b) charge 18 kg.

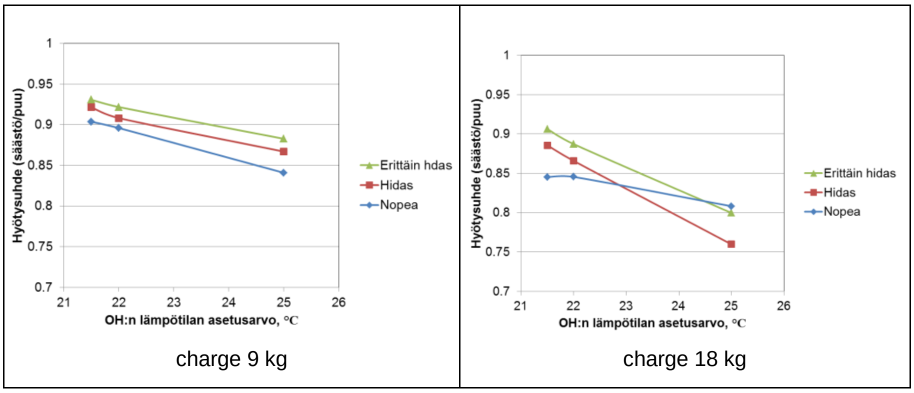



**Figure C2.** Heat release efficiency values for the single-storey renovated building as a function of the maximum temperature for appliance burn. The figure shows values for a) charge 9 kg and b) charge 18 kg.

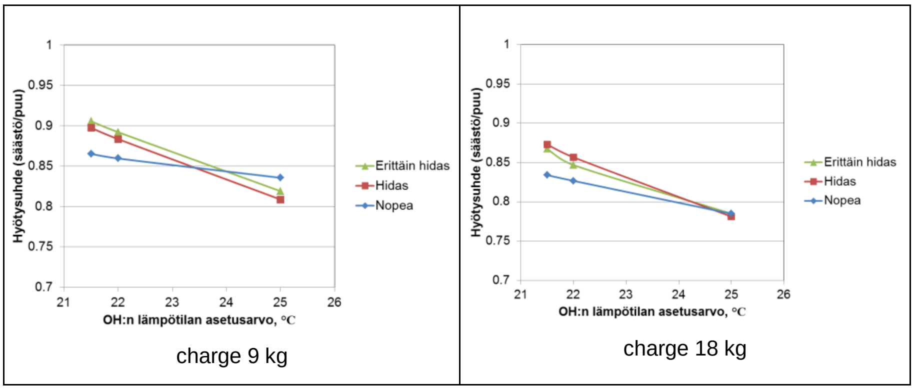



**Figure C3.** Heat release efficiency values for the two-storey building built to current code, as a function of the maximum temperature for appliance burn. The figure shows values for a) charge 9 kg and b) charge 18 kg.

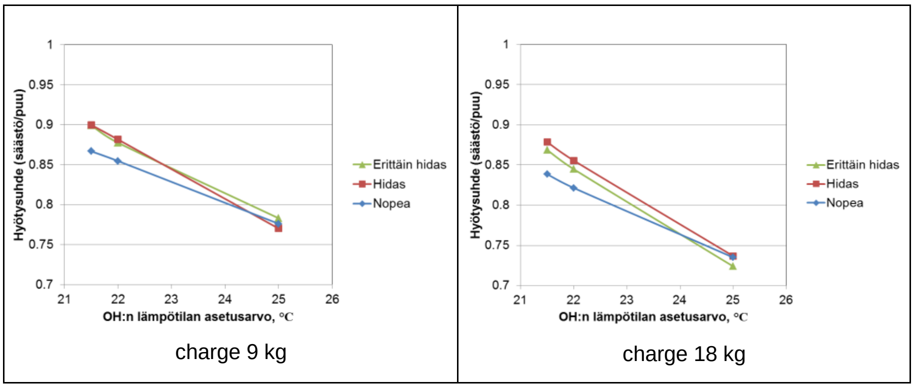



**Figure C4.** Heat release efficiency values for the two-storey passive building, as a function of the maximum temperature for appliance burn. The figure shows values for a) charge 9 kg and b) charge 18 kg.

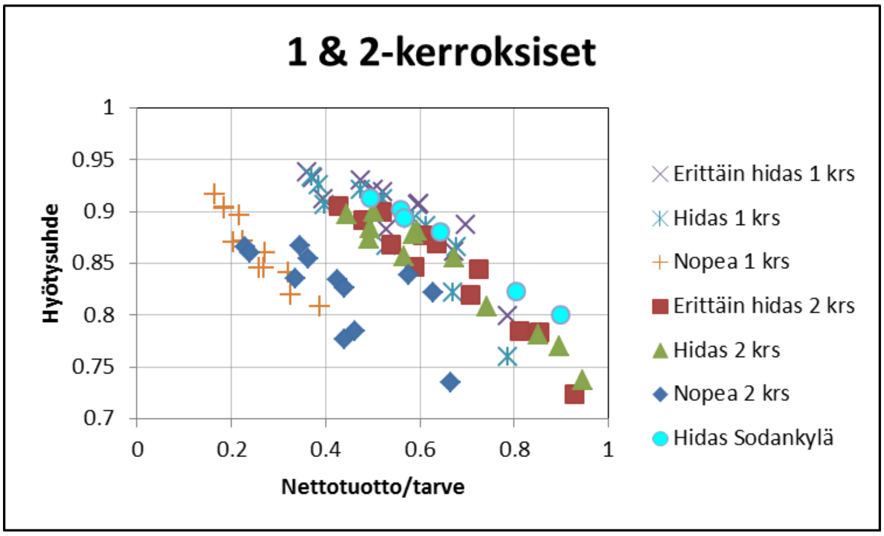


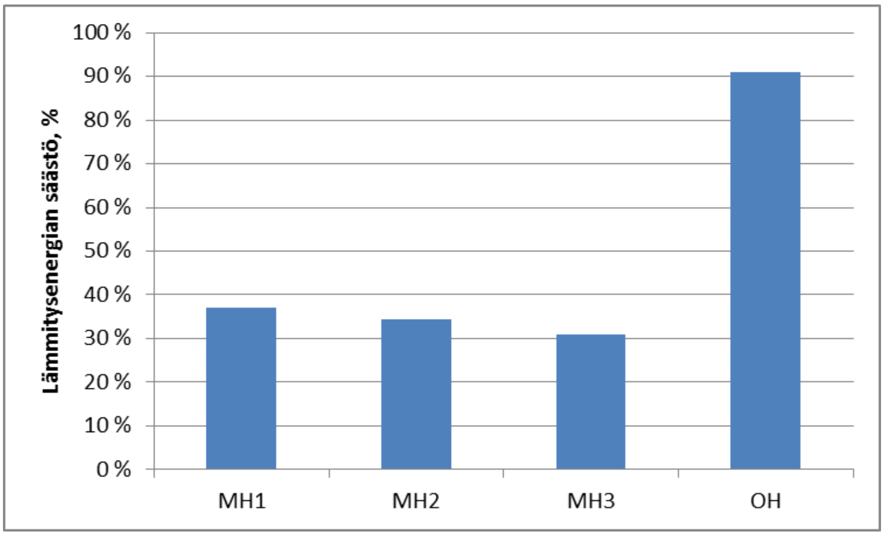

**Figure C5.** Heat release efficiency values in all computation scenarios.

# Appendix D: Heat distribution

Using a residential solid fuel burning appliance directly increases the indoor temperature of the room in which the appliance is located. As the temperature rises, air flow between rooms increases because of the temperature differential, and convection aims to equalise this differential by conveying the heat from the appliance to adjacent rooms. How the heat from the appliance spreads to other rooms depends on the architecture of the building, e.g. whether the dwelling is on one or more levels. Heat distribution also depends on whether connecting doors are closed or open. The following illustrates the distribution of heat from an appliance by example, featuring the buildings and appliances used in the simulations.

## Single-storey old building

In the single-storey building, the appliance is based on a large open space that combines living room, kitchen and entry hall. Also, the bedroom doors were open for the simulation, so the heat from the appliance was easily distributed throughout the building. Figure D1 shows how, in one scenario, the appliance affected the heating of adjacent rooms by the main heating system.




Savings in heating energy, %
Bedroom 1 :: Bedroom 2 :: Bedroom 3 :: Living room

**Figure D1.** Change of heat release from the main heating system in various rooms: very slow appliance, charge 18 kg, living room maximum temperature 22 °C.

The results show that the heat is effectively distributed through the open doors from the living room to the adjacent bedrooms and that the heating output of the main heating system decreases by more than 30% compared with the situation where the appliance is not in use.

## Single-storey renovated building

This building has the same room arrangement as in the previous section, and the bedroom doors were open for the simulation.

In this scenario, the heating output of the main heating system in the bedrooms drops by almost half compared with the situation where the appliance is not in use (Figure D2).

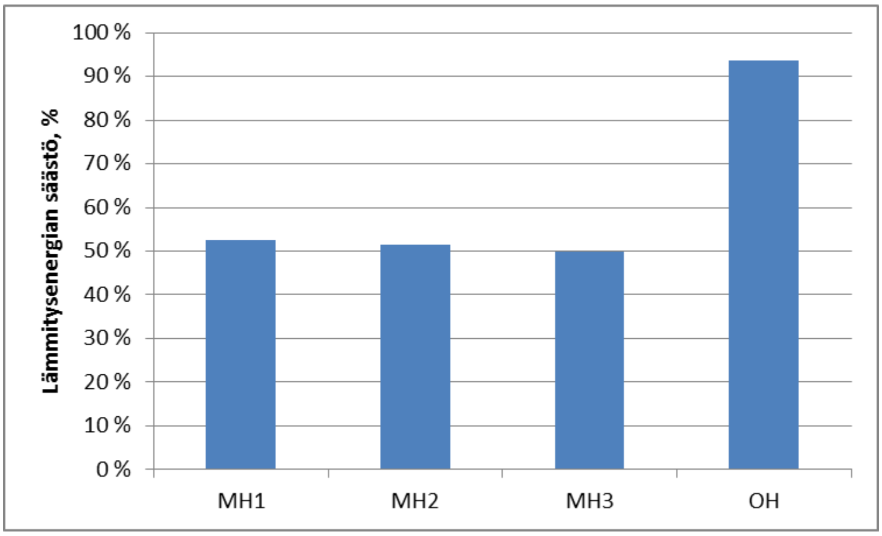



**Figure D2.** Change of heat release from the main heating system in various rooms: very slow appliance, charge 18 kg, living room maximum temperature 21.5 °C.

## Two-storey new building

In the two-storey building, the bedrooms are upstairs and the appliance is in the living room downstairs. Although the bedroom doors were open in these simulations too, the heat does not spread upstairs as easily as to adjacent rooms on the same level. In the two-storey building, using the appliance also affects the ventilation intake reheating demand through the extraction ventilation heat recovery system.

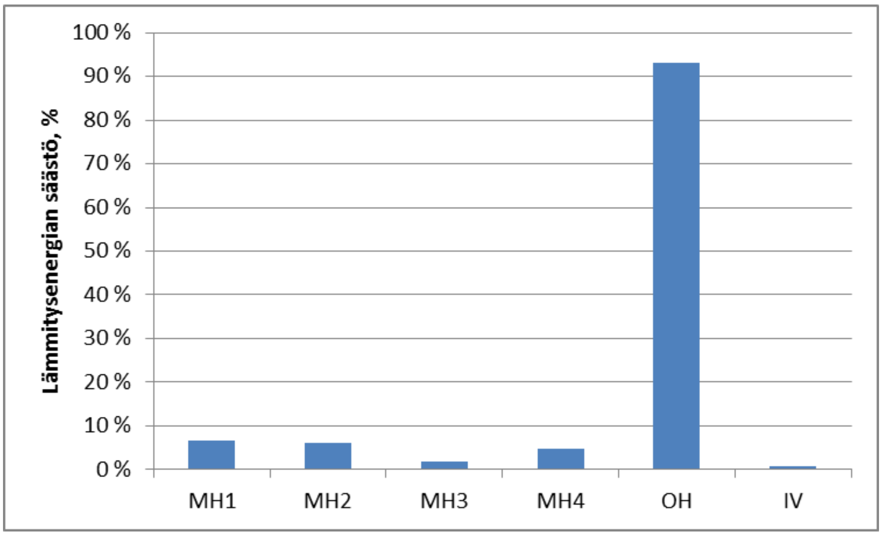



**Figure D3.** Change of heat release from the main heating system in various rooms: very slow appliance, charge 9 kg, living room maximum temperature 22 °C.

The results show that the heating output of the main heating system decreases considerably in the bedrooms, by almost 10%. The ventilation heating demand decreases only marginally, by about 1%.

## Two-storey passive building

Here, too, the bedroom doors were open, and extraction ventilation heat recovery was in operation.

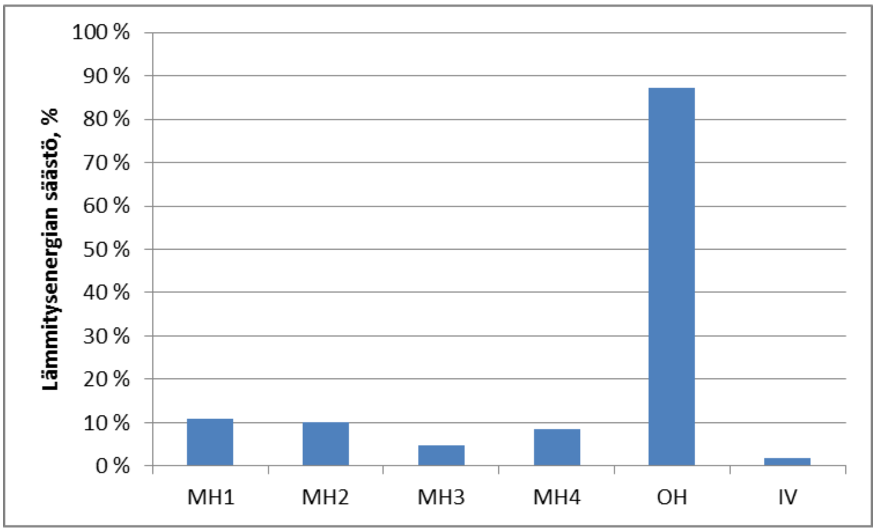



**Figure D4.** Change of heat release from the main heating system in various rooms and reduction in ventilation reheating demand when the appliance is in use: very slow appliance, charge 9 kg, living room maximum temperature 21.5 °C.

The situation is very similar to that in the two-storey new building: the heat from the appliance is slow to spread to the bedrooms upstairs, while the ventilation heating demand decreases only by about 2% (Figure D4).